Development of Knife-Shaped Interaction Device Providing Virtual Tactile Sensation

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Abstract. We have been developing "ToolDevice," a set of devices to help novice users in performing various operations in a mixed reality (MR) space. ToolDevice imitates the familiar shapes, tactile sensation, and operational feedback sounds of hand tools that are used in everyday life. For example, we developed BrushDevice, KnifeDevice, TweezersDevice, and HammerDevice. Currently, KnifeDevice is insufficiency in force feedback. This paper proposes a tactile feedback model for cutting a virtual object utilizing two vibration motors and the principles of phantom sensation. We built a prototype to implement the proposed feedback model, and confirmed the usability of our model through an experiment. Finally, we redesigned KnifeDevice and implemented the tactile sensation on the basis of the results of the experiment.

Keywords: Mixed Reality, ToolDevice, phantom sensation, tactile sensation.

1 Introduction

We have been developing "ToolDevice" (Fig. 1), a set of devices to help novice users in performing various operations in a mixed reality (MR) space. ToolDevice imitates the familiar shapes, tactile sensations, and operational feedback sounds of hand tools that are used in everyday life.

In previous studies, we developed a handcrafting system [1][2] and a painting system [3][4] using ToolDevice. With TweezersDevice (Fig. 1c), used for picking up and moving virtual objects in the handcrafting system, we utilize a braking mechanism that uses a solenoid to provide force feedback when users pinch a virtual object. As for BrushDevice (Fig. 1a), used in the painting system, a reaction force mechanism helps a user to perceive tactile sensation when a user touch an object with the device [4]. These force feedback mechanisms are designed to be similar to that provided by the corresponding real world tools.

However, KnifeDevice (Fig. 1b), used for cutting virtual objects, had not exhibited such force feedback mechanism yet, because it is difficult to provide a reaction force of similar amplitude with that of a real knife operation by itself. Now, a user can cut virtual objects by placing them on a table and performing the cutting operation with

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KnifeDevice. KnifeDevice already has a vibration motor to provide simple tactile feedback to show whether the device make contact with a virtual object. However, it is hard to feel and understand various virtual objects with different shape from their tactile feedbacks. An alternative tactile feedback whose mechanism can be built-in in a compact space is required.

This paper proposes a tactile feedback model for cutting a virtual object utilizing two vibration motors and the principles of phantom sensation. It provides similar sensation with that of real-world cutting by combining visual and tactile sensation. We also propose four methods to imitate real-world tactile sensations. We built a simple prototype implementing the proposed feedback model, conducted an experiment to compare the four proposed tactile sensation methods, and confirmed the usability of our model. Finally, we redesigned KnifeDevice and implemented the tactile sensation on the basis of the results of the experiment.

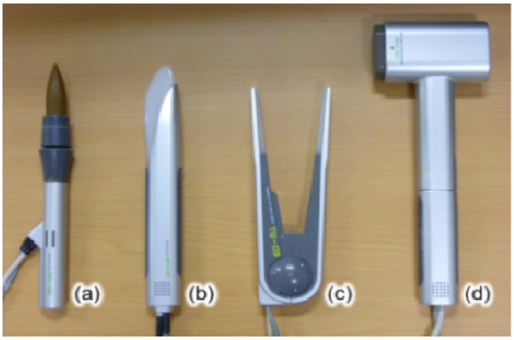

Fig. 1. (a) BrushDevice, (b) KnifeDevice, (c) TweezersDevice, (d) HammerDevice

2 Related Work

Tanaka *et al.* proposed a technique for representing forces acting on a virtual knife while it cuts a virtual object by using a haptic display called PHANToM to create tactile sensations [5]. PHANToM is a device that can provide haptic and tactile sensation in detail to the user by controlling the motion of the user's hand. However, PHANToM is required to be grounded, restricting the user's movements within the range of the mechanical linkages. Therefore, it is necessary to have a haptic display that provides much flexibility.

Kamuro *et al.* proposed Pen de Touch [6], which uses the non-binding force feedback mechanism. It provides force feedback for friction, reaction force, etc., thus enabling users to perceive the contact sensation and hardness of virtual objects. They developed a 3D modeling system [7] using Pen de Touch. Similarly, in this study, we also aim to develop a mechanism that provides non-binding force feedback.

Phantom sensation is known as a pseudo-tactile skin sensation perceived in an arbitrary place when two or more stimuli are provided simultaneously. The principles of phantom sensation were discovered by Von Békésy [8] and can be implemented using vibration motors inside a device [9][10]. Using this method, a tactile feedback mechanism could be small and the user can move his/her hand freely. Using the principles of phantom sensation, we developed and implemented a tactile feedback model for KnifeDevice.

3 Tactile Sensation

3.1 Analysis of Acting Forces While Cutting

In this study, we focus on a slicing action where a knife cuts an object not by pressing it but by moving through it. While cutting, forces are applied onto the knife from the user's hand and the object being cut. The forces consist of horizontal friction force and vertical resistance force act on the knife. Vertical resistance force (Fig. 2) is the result of the object's resistance and the vertical friction acting on the knife (lateral friction). Highly adhesive objects such as cheese and rice cakes have high lateral friction. On the other hand, non-adhesive objects such as wood and paper have low lateral friction. In this study, we assume that the objects being cut have low adhesivity; therefore, lateral friction could be negligible.

Fig. 3 shows the forces acting on the knife. When the knife is moved in the direction of movement, P is the force applied by the user, and F is the object's resistance. Therefore, the following forces are being applied to the knife: F_n is the cutting force and F_f is the kinetic friction force. F_n and P_n act vertically on it. We define r_1 as the distance between the fulcrum and the point of load and r_2 as the distance between the fulcrum and the point of effort. As long as the knife does not rotate, the moment of forces is balanced, and the equilibrant is defined as follows:

$$r_1 F_n - r_2 P_n = 0 \quad (1)$$

To cut an object, P needs to be greater than F. As P increases, the movement becomes faster. However, this has no impact on the forces acting vertically. Therefore, we assume that P has no impact on the perceived feedback.

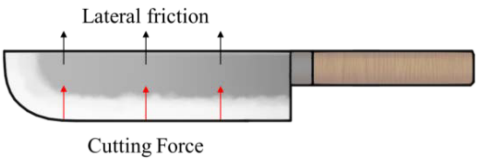

Fig. 2. Cutting force in vertical direction

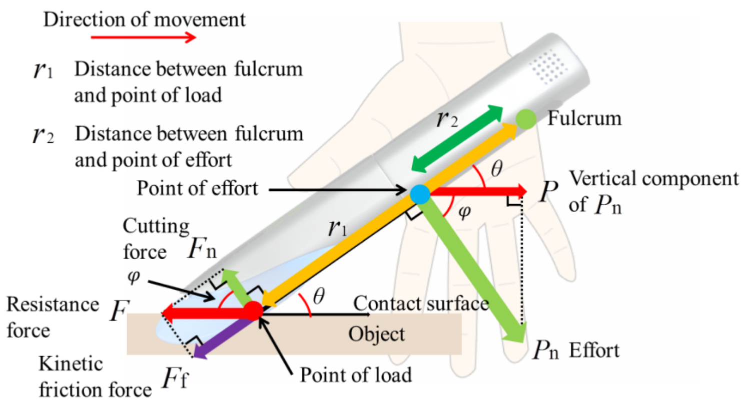

Fig. 3. Forces acting on KnifeDevice

3.2 Tactile Feedback Model

Because we use the same wooden material for all virtual objects in our handcrafting system, we can assume that F is always constant during the cutting operation. At this time, F_f does not change and F_n is defined by θ (angle between KnifeDevice and surface of the virtual object) (Eq. 2) and φ (angle between the normal vector of KnifeDevice and surface of the virtual object) (Eq. 3).

$$F_n = F\cos\varphi \tag{2}$$

$$\varphi = \pi - \left(\theta + \frac{\pi}{2}\right) \quad \left(0 \le \theta \le \frac{\pi}{2}\right) \tag{3}$$

During the cutting operation, P needs to be constantly greater than F; P is calculated using Eqs. 1–3 and F. In this study, the minimum value of P (minimum force required to cut an object) is considered for tactile sensation. In other words, the maximum resistance force is used to represent tactile sensation.

When the contact point between the knife edge and object's surface is fixed, the fulcrum point, point of effort, and point of load are static. At this time, F, r_1, and r_2 are constant, while P increases in proportion to θ. On the other hand, when the contact point is changed and θ is fixed, r_1 changes depending on the point of load. At this time, F, r_2, and θ are constant, while P increases in proportion to r_1. On the basis of this observation, we consider θ and r_1 as the only factors that change P. In other words, we use these factors as parameters to control the vibration for presenting tactile sensation.

Vibration has several elements such as position, amplitude, and interval. However, with regard to interval, it is difficult to apply the duration of vibration or that of absence of vibration to our model. Therefore, we only change the amplitude and position of vibration while providing tactile sensation.

The position and amplitude in this context refer to the perceived position and amplitude of vibration when using the principles of phantom sensation, as described in chapter 2. To change the amplitude of the perceived vibration, the amplitudes of both the vibration motors are synchronized.

3.3 Prototype

We built a prototype (227 mm long) with two vibration motors (Linkman, 7AL09WA), one at each end of the device (Fig. 4). These vibration motors can be energized at 256 levels (from 0 to 255); the higher the voltage provided, the greater the amplitude of vibration. We conducted a preliminary study with three students in their twenties. The result showed that they did not perceive amplitudes less than level 30. They also did not accurately distinguish all amplitudes of vibration, so the levels were reduced to 16 (from 30 to 255 separated in steps of 15).

In Eq. 4, M_1 and M_2 are the amplitudes of the two vibration motors, and X is the position of the perceived vibration. When M_1 and M_2 are changed to 16 levels, X is also changed to 16 levels as follows:

$$M_1 = X \quad (0 \leq X \leq 15) \tag{4}$$

$$M_2 = 15 - X \quad (0 \leq X \leq 15) \tag{5}$$

3.4 Methods of Changing Pseudo-vibration

Pseudo-vibration is defined as the position of vibrations perceived on the basis of the principles of phantom sensation. We proposed the following four methods to change the position and amplitude of pseudo-vibration. These methods are combinations of angle and contact position used for changing the amplitude and perceived position of vibration.

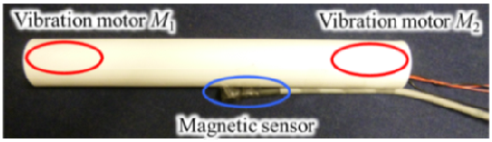

Fig. 4. Prototype

(1) The amplitude of pseudo-vibration changes depending on the angle between KnifeDevice and the object's surface (angle ∝ amplitude).
(2) The perceived position of pseudo-vibration changes depending on the angle between KnifeDevice and the virtual object's surface (angle ∝ perceived position).
(3) The amplitude of pseudo-vibration changes depending on the position of contact between KnifeDevice and the virtual object's surface (contact position ∝ amplitude).
(4) The perceived position of pseudo-vibration changes depending on the position of contact between KnifeDevice and the virtual object's surface (contact position ∝ perceived position).

In (1), P increases in proportion to θ. Therefore, the amplitude is set to 0 when θ is minimum, and the amplitude is set to 15 when θ is maximum. In (2), the amplitude is set to 0 when the point of load is at the blade end. The amplitude is set to 15 when the point of load is at the front edge. In (3), as θ increases, the force acting on the front edge increases. Therefore, pseudo-vibration is located at the front edge when θ is maximum. The vibration is provided at the device end when θ is minimum. In (4), pseudo-vibration is provided at the front edge when the point of load is at the front edge. The vibration is provided at the device end when the point of load is at the blade end.

4 Experiment

4.1 Objective

We conducted an experiment to evaluate the usability of our proposed method. Specifically we analyzed the tactile sensation perceived when touching on a virtual object and slicing the virtual object with the knife. We also compared our proposed methods with the simple vibration method (the standard method) in which the amplitude of vibration is constant.

4.2 Environment

Fig. 5 shows the system configuration. We use a binocular see-through head mounted display (HMD; Canon VH-2002), which enables users to perceive depth. The HMD is connected to a video capture card (ViewCast Osprey-440) that captures input videos from the cameras built into the HMD. The position and orientation of the HMD and the device are tracked using Polhemus LIBERTY, a 6DOF tracking system equipped with magnetic sensors. A transmitter is also used as a reference point for the sensors.

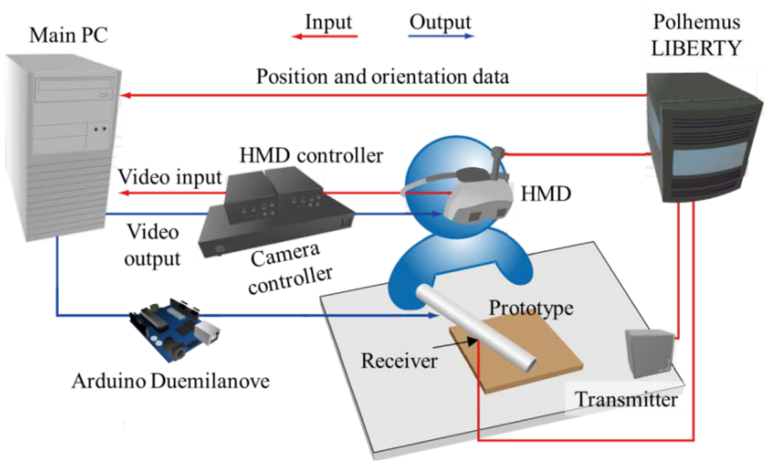

Fig. 5. System architecture

For creating an MR space, we first set the video captured by Osprey-440 as the background and then created a virtual viewing point in OpenGL by obtaining the position and orientation of the HMD from Polhemus LIBERTY. To control the vibration motors, we use the Arduino Duemilanove.

In the experiment, a red bar is rendered to indicate the front edge of the knife. When the knife comes into contact with the virtual object, a white sphere is rendered to indicate the contact point between the knife and the object.

4.3 Procedure

In this experiment, the subjects are required to perform the following four movements for the standard method and each of the aforementioned combinations (Fig. 6):

(a) Touch a flat surface at 0, 45, and 90 deg
(b) Trace a flat surface
(c) Trace an angular surface
(d) Trace a curved surface

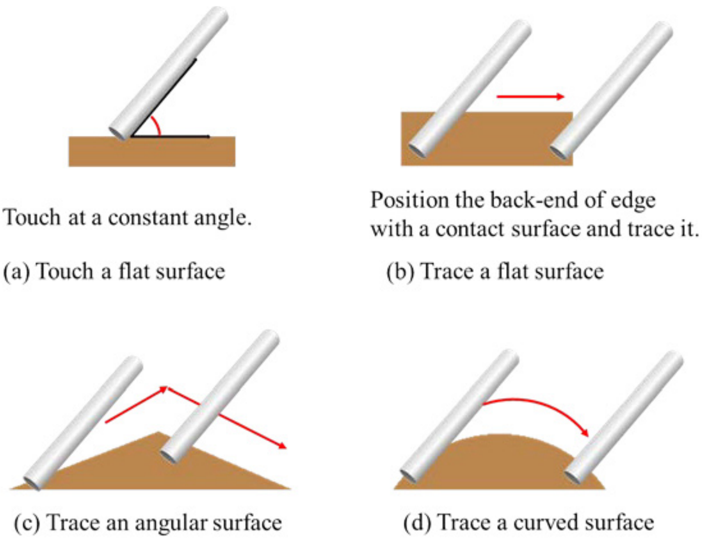

Fig. 6. Movements used in the experiment

The order of the four methods used for each subject is randomized. In addition, between the trials for each method, we ask the subjects to try the standard method for comparing. After each trial, the subjects evaluated the four methods on a five-point scale (1: lowest, 5: highest) and compared them to the standard method that had been rated as 3. Five students In their twenties were the subjects.

4.4 Result and Discussion

The results are shown in Fig. 7. The bars indicate the average score for each method. From these results, we can conclude that almost all our proposed methods performed better than the standard method. Angle ∝ amplitude (1) has the best score out of the four methods. Track an angular surface (c) has the best score for (a) to (d). The reason for this is that it was easy for the subjects to perceive an angular surface because the amplitude of the vibration increased when going through the angular part. On the other hand, the score of case (3)–(a) was lower than that of the standard method. One subject commented that he felt strange because the amplitude decreased as he pressed harder. As for the perceived position of the pseudo-vibration, two subjects did not perceive any change in position. They only perceived the change after they were told that the position could change. Thus, we conclude that the change in position might not be perceived without previous knowledge.

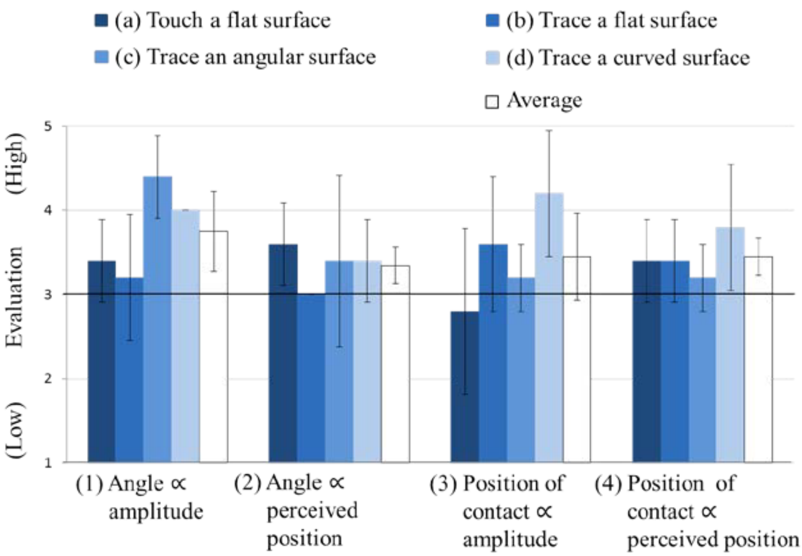

Fig. 7. Average score and standard variation

5 Implementation

5.1 Redesigned KnifeDevice

Fig. 8 shows the appearance and structure of redesigned KnifeDevice we developed. We confirmed the usability of our proposed method through our experiment and implemented it in KnifeDevice by mounting two large vibration motors at each end of the device. These motors have 256 levels of amplitude. In addition, to provide variety in the vibration in future, two smaller vibration motors were fitted into each end of the device.

Pressure-sensitive sensors are mounted with 256 levels (from 0 to 255) of sensitivity at the edge of the device and the gripper. By using these levels as input signals, users can turn on the tactile switch by applying a weak force on the table or cut objects in the air by gripping the device with a strong force.

5.2 User Study

As explained in chapter 4, angle ∝ amplitude (1) is the best method for providing pseudo-vibration, so we implemented it in redesigned KnifeDevice. Then, we conducted an experiment to confirm whether the tactile feedback is useful when it is implemented in KnifeDevice itself. The subjects, who were three students in their twenties, were required to cut various virtual objects, such as a cuboid, a hexagonal column, and a sphere, on a desk or in the air, and rate the usability of KnifeDevice. Our tactile feedback model was proven to be useful by this user study.

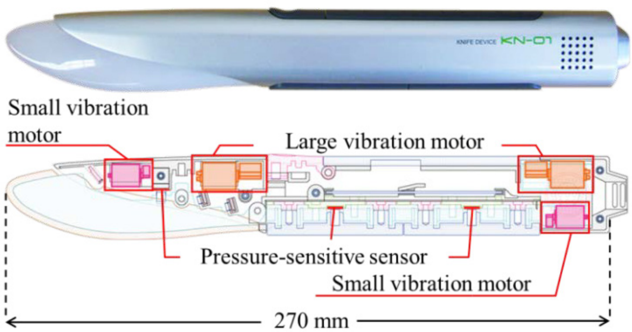

Fig. 8. Redesigned KnifeDevice

6 Conclusion and Future Work

In this paper, we proposed new methods to provide virtual tactile sensation while cutting a virtual object in the MR space. Our proposed methods utilize changes in the amplitude and position of vibrations in accordance with the angle between the device and virtual object's surface and the contact point between the device and object's surface. We implemented these methods in a simple prototype and conducted an experiment that compared the tactile sensations of the standard method in which the amplitude of vibration is constant against the four proposed methods. The results confirmed that almost of all our proposed methods provided better tactile sensations than those provided by the standard method. On the basis of the results of the experiment, we redesigned KnifeDevice. We conducted a user study and confirmed the usability of redesigned KnifeDevice. In future, we aim at improving tactile sensation by combining our proposed methods and using vibration motors of different intensities.

References

1. Arisandi, R., Takami, Y., Otsuki, M., Kimura, A., Shibata, F., Tamura, H.: Enjoying virtual handcrafting with ToolDevice. In: Proc. UIST 2012, pp. 17–18 (2012)
2. Arisandi, R., Otsuki, M., Kimura, A., Shibata, F., Tamura, H.: Implementation of metal-working mode in mixed reality modeling system using ToolDevice. In: CD-ROM Proc. STSS 2012 (2012)
3. Otsuki, M., Sugihara, K., Kimura, A., Shibata, F., Tamura, H.: MAI Painting Brush: An interactive device that realizes the feeling of real painting. In: Proc. UIST 2010, pp. 97–100 (2010)
4. Sugihara, K., Otsuki, M., Kimura, A., Shibata, F., Tamura, H.: MAI Painting Brush++: Augmenting the feeling of painting with new visual and tactile feedback mechanisms. In: Adjunct Proc. UIST 2011, pp. 13–14 (2011)
5. Tanaka, A., Hirota, K., Kaneko, T.: Virtual cutting with force feedback. In: Proc. VRAIS 1998, pp. 71–75 (1998)
6. Kamuro, S., Minamizawa, K., Kawakami, N., Tachi, S.: Ungrounded kinesthetic pen for haptic interaction with virtual environments. In: Proc. IEEE Ro-Man 2009, pp. 436–441 (2009)
7. Kamuro, S., Minamizawa, K., Tachi, S.: 3D haptic modeling system using ungrounded pen-shaped kinesthetic display. In: Proc. IEEE VR 2011, pp. 217–218 (2011)
8. von Békésy, G.: Sensory Inhibition. Princeton University Press (1967)
9. Seo, J., Choi, S.: Initial study for creating linearly moving vibrotactile sensation on mobile device. Proc. IEEE 2010, 67–70 (2010)
10. Kim, Y., Lee, J., Kim, G.: Extending ‘Out of the Body’ saltation to 2D mobile tactile interaction. In: Proc. APCHI 2012, pp. 67–74 (2012)