Virtual Object Manipulation System with Substitutive Display of Tangential Force and Slip by Control of Vibrotactile Phantom Sensation

Tatsuya Ooka and Kinya Fujita

Tokyo University of Agriculture and Technology

ABSTRACT

We propose a substitutive multi-degree-of-freedom force display method that utilizes vibrotactile phantom sensation (VPS), in which the tangential force is substituted by the VPS position displacement and the slip is displayed as the oscillatory displacement of the VPS position. Based on the proposed method, we prototyped a virtual object manipulation system that consists of two 20 mm x 20 mm x 20 mm fingertip-wearable devices with four vibrating pins, a magnetic tracking system, a potentiometer for finger position measurement, and a physics simulator. The preliminary experiments demonstrated the feasibility to display the mass of an object, the slipping-down of an object between fingers, and the reaction torque induced by the rotation of the object-grasping hand.

KEYWORDS: vibrotactile display, phantom sensation, tangential force, slip

INDEX TERMS: H.5.2 [Information Interfaces and Presentation]: User Interfaces— Haptic I/O

1 INTRODUCTION

Manipulation of an object is a task that is highly dependent on haptic information. In order to attain precise object handling in a virtual environment, the normal and the tangential forces as well as the slip between the finger and the object are required. Grounded fingertip force display devices, whether manipulator-type or string-type such as SPIDER [1], provide the multi-degree-of-freedom force display function. However, they have a more complicated structure and more limited range of motion than other options. Several types of pseudo-force display devices have been proposed for a more simple structure and greater range of motion. Fingertip tightening devices [2][3] are typical examples that were made smaller by limiting the display information within the normal force at the fingertips. In compensation for a simple structure, the pseudo-force display devices, including the devices based on other principles, lack the functions to display tangential force and slip.

On the other hand, vibrotactile stimulation have been studied to assist haptic perception of contact state change [4][5]. Fingertip vibrotactile display devices have been developed such as texture display by using a pin array [6], slip display by using an electrostatic actuator [7] as well as Braille display. 3D direction display through the palm has also been attempted by controlling the stimulus position using multiple vibrotactile stimulators [8]. Furthermore, vibrotactile phantom sensation (VPS) and apparent movement, both of which allow stimulus position control with a limited numbers of stimulators have been applied to induce a sensation of rubbing at the palm [9] and so on. The conventional studies have utilized the vibration as a simple event cue or a navigational cue. Much of the haptic information during continuous physical interaction has not been displayed. Therefore, demand has arisen for a device that can display multi-degree-of-freedom force and slip that allows users to feel the weight and slip of a grasped object.

In this paper, we propose a substitutive display method for multi-degree-of-freedom force and slip that utilizes VPS. The dynamic changes of normal force, tangential force, and slip applied to the fingertip are substituted by controlling the magnitude and the position of the VPS. We also report on a multi-fingered virtual object manipulating system based on the proposed method and the results of the virtual object manipulating tasks which require the perception of tangential force and slip.

2 CONCEPT OF VIBROTACTILE SUBSTITUTION

The concept of the VPS substitution is shown in Fig. 1(a). The delicate change of contact force, while holding an object with fingers, is haptically perceived mainly by slow adaptive receptors such as Merkel disks. Fast adaptive receptors, such as Pacinian corpuscle, contribute to the perception of drastic contact state change such as contact or release [10]. If the magnitude and the position of the high-frequency VPS are dynamically controlled, the user is considered to perceive the change of the VPS through only fast adaptive receptors, even if the changing frequency is low. Therefore, although the contributing mechanoreceptors are limited and different from the ones for static force perception, the

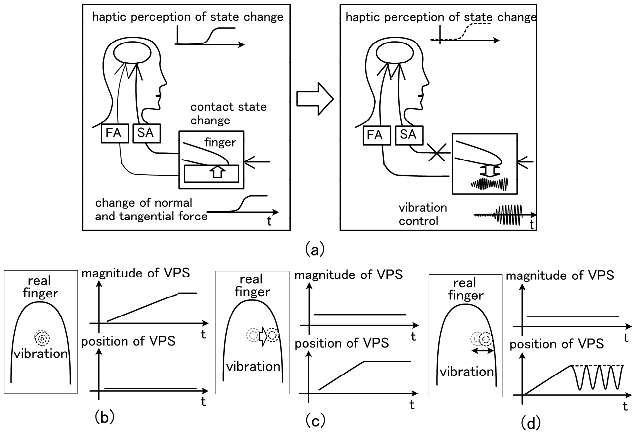

Figure 1. (a) Conceptual diagram of the vibrotactile substitution of the change of contact force. Proposed substitution methods of (b) normal force, (c) tangential force and (d) slip.

2-24-16 Nakacho, Koganei, Tokyo 184-8588 Japan
{50008646107@st, kfujita@cc}.tuat.ac.jp

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adequate display of VPS and visual information in response to virtual environment is expected to assist the haptic perception of the contact state change..

The proposed idea is to substitute the forces and slip by controlling the applied vibration to the palmar surface of the fingertip as shown in Fig. 1(b, c, d). The normal force is substituted by the vibration magnitude, similar to the previous studies [3][4], that is most intuitive, as shown in Fig. 1(b). On the other hand, the substitution of the tangential force with normal-direction vibration is considered to be more difficult. We focused on the fact that the tangential force generates the shear deformation of the finger pad and generates the small displacement almost proportional to the force. Therefore, we assumed that the tangential force can be alternatively displayed by controlling the position of the VPS as shown in Fig. 1(c). Furthermore, displaying the slip between the fingertip and the manipulating object is important in addition to displaying the normal and tangential force to support haptic interaction between users and the virtual environment. So-called slip is a stick-slip micro vibration between the palmar surface of the fingertip and manipulating object. Therefore, we hypothesized that the slip is alternatively displayed by the oscillatory modulation of the VPS position that represents the tangential force as shown in Fig. 1(d).

3 PROTOTYPE DEVICE AND OBJECT MANIPULATION SYSTEM

3.1 Prototype Device

The prototyped fingertip-wearable device is shown in Fig. 2. The prototyped device has four pins for inducing two-dimensional VPS at the palmar surface of the fingertip. Each pin was attached to a vibrating coil (700 rolls, 4 mm dia. x 8 mm) that is located around a neodymium magnet (4430 G, 3 mm dia. x 8 mm) and was driven through 0.12 mm thick rubber film. The distance between the pins was experimentally determined at 8 mm, the maximum distance for fused phantom sensation. The maximum stroke of the free-vibrating pin, which is driven by the maximum driving voltage, is 0.24 mm. The weight of one device without cables is 14 g.

The four vibrations need to be recognized clearly as a fused single vibration. At the same time, the vibration frequency is required to be sufficiently high as the carrier wave for the amplitude modulation to display slip. Therefore, the driving frequency and the modulation frequency were experimentally set at 200 Hz and 50 Hz, respectively. The modulation depth was controlled in proportion to the friction coefficients as well as the slip velocity.

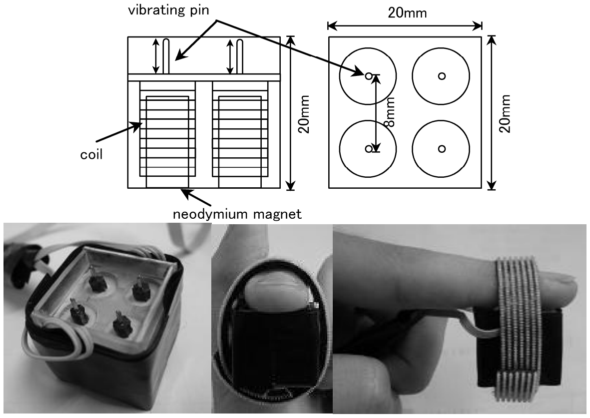

Figure 2. Structure of the prototyped fingertip-wearable VPS display device.

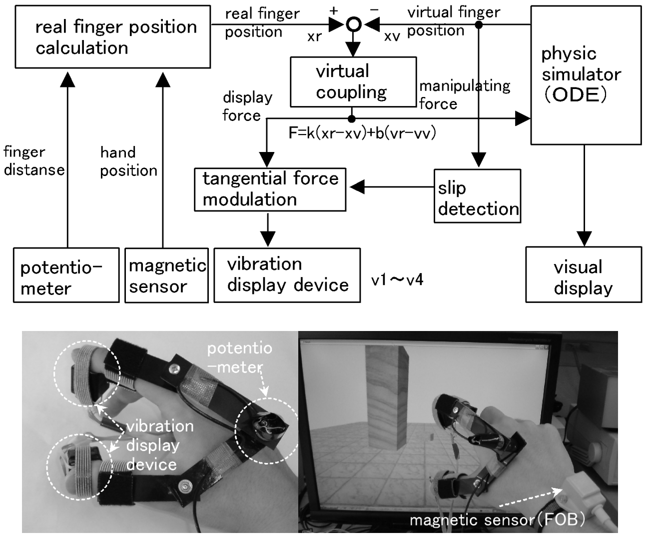

Figure 3. Block diagram and configuration of the multi-fingered virtual object manipulation system.

3.2 Virtual Object Manipulation System

After examining the basic property of the proposed substitutive display method, a two-fingered virtual object manipulation system was prototyped. The block diagram and the configuration of the system are shown in Fig. 3. The hand position of the user is detected by a six-degree-of-freedom magnetic sensor (FOB, Ascension) attached at the back of the hand, and the distance between the thumb and the index finger is detected by a potentiometer. Based on these data, the positions of the thumb and the index finger are calculated. In the virtual environment, which is simulated by the physical simulator, two boxes were set as the proxies of the two fingertips. The two proxies allow users to manipulate the virtual objects. The virtual environment is simulated using a general-purpose physics simulation library ODE. Because ODE is based on an analytical method and requires manipulation force as input, the virtual coupling (VC) that consists of elasticity and viscosity is utilized. The manipulation force for simulation and the displayed force are calculated from the distance between the real finger and the proxy using VC. The VC parameters were experimentally adjusted for distinct contact recognition and simulation stability (elastic coefficient k = 800 N/m, viscous coefficient b = 30 N/m).

4 EXPERIMENTS

4.1 Basic property of vibrotactile substitution

In order to verify the possibility of displaying the contact state change by controlling VPS, the basic properties of the proposed method were experimentally examined. At first, the correlation between the VPS magnitude and the position and strength of the perceptive sense of normal force and tangential force were experimentally examined in order to investigate the performance to display the contiguous change of contact force. Seven subjects were required to voluntarily reproduce the perceived normal or tangential force by pushing the force sensor after the VPS stimulation was applied at their palmar surface of the index fingertip. The linear correlation for each subject (average correlation coefficient 0.72 ± 0.12) was confirmed as expected with some degree of individual deviation.

Second, to investigate the possibility of object handling assistance through the substitutive slip display, the complex reaction time was evaluated by using a slip discrimination task from simple increase of tangential force. The two types of VPS stimulations were applied in random order synchronized with computer graphics (CG), which the touching virtual object slips or moves minutely in the tangential direction. The subjects were required to push the force sensor as quickly as possible only if they felt the slip. In the same way, the reaction for real slip or increased tangential force was examined by using a linear actuator. Ten subjects performed the tasks under the following five conditions: VPS slip with/without CG, real slip with/without CG, CG alone. The correct reaction rate of VPS slip without CG was 90%, and the average reaction time was 550 ms. The reaction time was shortened to 220ms in the tasks without the necessity of discrimination of slip and tangential force. The possibility to recognize and react to the VPS slip has been demonstrated.

4.2 Multi-fingered manipulation tasks

The multi-fingered multi-degree-of-freedom fingertip force display system is expected to be able to assist tasks that require the recognition of a complex state change. Therefore, the following two virtual object manipulating tasks were performed.

4.2.1 Slip Down of Grasped Object

The task is to grasp and lift a virtual object and then let it slip down by decreasing the grasping force. The subject is expected to perceive the normal force as the grasp reaction force at first, the tangential force induced by the mass of the object after lifting up, and slip of the object at last. The mass of the manipulated virtual object was 2.0 kg, the size was 7 cm x 7 cm x 20 cm and the friction coefficient between the proxy and object was 0.85.

A typical example of the displayed force during the task is shown in Fig. 4. The y-axis forces (normal force) for the thumb and index finger at the beginning are the grasp reaction force. The x-axis forces (tangential force) are induced by the mass of the manipulating object. The decrease of the grasping force reduced the friction force and the object starts slip at about t = 1.6 s as seen in Fig. 4(c). The oscillatory modulated tangential forces, depending on the relative velocity and friction constant between the proxy and manipulated object, are observed in Fig. 4(a, b).

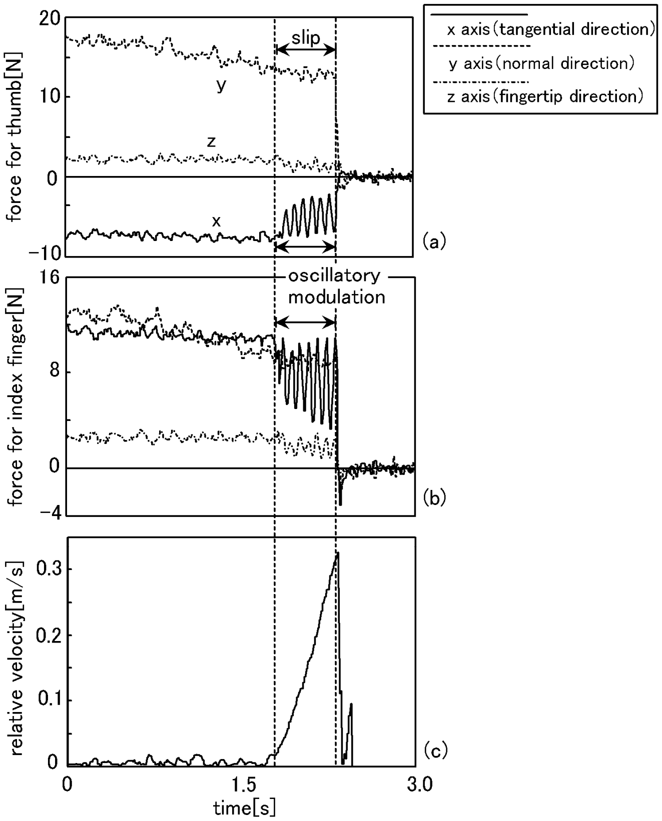

Figure 4. Example of slip down of grasping object task. (a, b) Displayed forces for thumb and index fingers, (c) relative velocity between object and finger.

4.2.2 Door Knob Turning

The task is to grasp a virtual door knob and turn it while the range-of-motion of the knob is limited. The torque caused by the knob rotation is expected to be perceived by the spatially opposite tangential forces at the thumb and the index finger. The virtual knob is a 9 cm x 9 cm x 9 cm cube. The rotation axis of the knob is fixed and the rotation angle is limited up to ±15 degrees. The minimal rotation torque of the knob was set at 0.1 Nm to allow users to perceive the reactive torque against the rotation.

The typical result is shown in Fig. 5. The grasping of the knob increased the normal force at the thumb and index finger as seen in Fig. 5(b, c). The following hand rotation, as seen in Fig. 5(a), increased the tangential forces in the same direction for both fingers (they are opposite in the spatial coordinate system). After the knob locking at about t = 6 s, the more rapid increase of the tangential force was observed that represents the increase of the reactive torque.

4.3 Subjective Evaluation

Six subjects were required to answer whether the state changes during the two tasks can be haptically recognized or not, such as the grasp reaction force, mass of the object, beginning of the slip, the torque from the object, and the locking of the object.

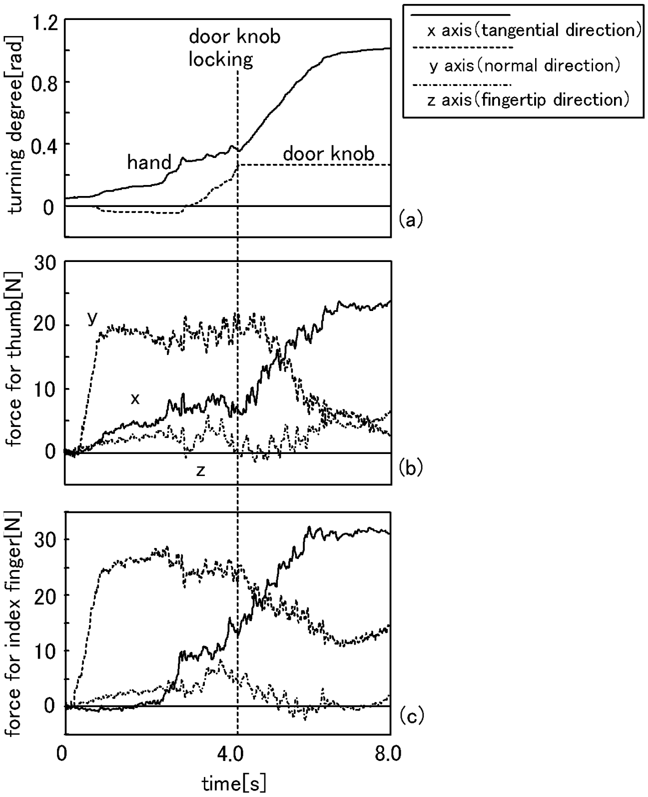

Figure 5. Example of door-knob-turning task. (a) Rotation angle of door knob and hand, (b, c) displayed forces for thumb and index fingers.

Furthermore, the subjects who recognized each state change were required to evaluate the clarity of it using a five-level scale.

Fig. 6(a) shows the event recognition rates in the slip down task. The event recognition rates of the mass and the slip were 100%. However, the clarity scores of the slip were relatively low, especially for the beginning of the slip. Fig. 6(b) shows the results of the knob turning task. The event recognition rate of the rapid torque increase after the lock was 100%. However, event recognition rates for the more mild torque increase during knob rotation and onset of the knob lock were relatively low. The clarity score of the door knob lock was lower than the other state changes.

5 DISCUSSION

In the experiments to examine the basic properties of the proposed substitutive force display method, the linear correlation between the VPS position and the tangential force sense was verified. The correct reaction rate of VPS slip without CG was 90%. The possibility of the substitutive VPS display of the contact force and slip has been demonstrated. One point to keep in mind is that the reaction time for VPS slip without CG was 200 ms slower than the real slip. The possible reason is that both tangential force and slip are substituted by the vibration while the real tangential force change is gradual and mainly perceived by the slow adaptive receptors.

In the slip down task, all the subjects perceived the mass and the slip. However, the clarity score for the beginning of the slip was low. The most possible reason is that the oscillatory modulation depth was insufficient because it was controlled in proportion to the slip velocity and the friction coefficient. In terms of event recognition assistance of contact state change from stable grasp to slip, other rules that allow more deep modulation need to be discussed.

In the knob turning task, all the subjects successfully felt the opposite tangential forces to the thumb and index finger as torque to the hand. However, some subjects failed to recognize the torque increase caused by the knob turning before the lock and the onset of the knob locking. The subjective clarity scores in these cases were low as well. It is supposed that the increasing rate of the tangential force was insufficient because of the insufficient elastic coefficient of VC. However, the parameters of VC are limited by several conditions, such as simulation stability, especially in the case where VC is used with an ungrounded force display device that allows finger penetration into the virtual object. Any method to enhance the state change needs to be introduced for clarity to improve.

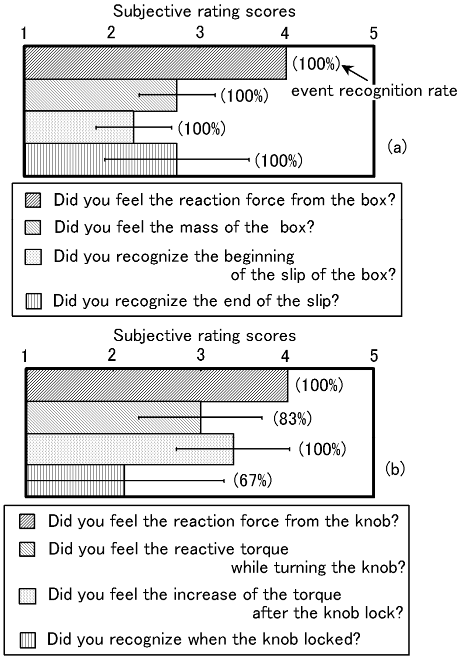

Figure 6. Subjective rating scores of clarity and event recognition rates. (a) Slip down of manipulated object, (b) door knob turning.

The weakness of the tangential force sense in the knob turning task was pointed out in the free interview with the subjects. The supposed reason is the insufficiency of the VPS position displacement. However, the distance between the pins was set to the maximum distance that induces VPS. Therefore, more pins are required to stimulate a wider area of the fingertip. A thinner VPS display device is also to be developed.

The feasibility to display multi-degree-of-freedom force and slip and to assist the object manipulation tasks has been demonstrated. More tasks of different types are to be examined toward practical multi-fingered manipulation, such as a task that requires the perception of the continuous change of tangential force, one that needs to distinguish slip velocity, one that requires the recognition of the direction of the reaction force vector, and so on.

6 CONCLUSIONS

This paper proposed a substitutive multi-degree-of-freedom force display method that utilizes VPS. A multi-fingered virtual object manipulating system based on the proposed method was prototyped. The feasibility of the perceptional assistance of contact state change such as slip down of the manipulated object and reaction torque induced by the rotation of the object-grasping hand was verified through the virtual object manipulation tasks. The future works are to improve the clarity of the state change and evaluate the task assistance effect in other manipulation tasks.

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