A Pseudo-Force-Feedback Device by Fingertip Tightening for Multi-Finger Object Manipulation

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ABSTRACT

This paper proposes a multi-finger pseudo-force-feedback device that induces tactile sense to each fingertip by its tightening. The compact and lightweight device design was realized by limiting the display sense to tactile only, in contrast to the conventional force-feedback devices stimulate both tactile and proprioceptive receptors by representing the reaction force. A prototype device that tightens the fingertip using geared motor was developed. The device was controlled with open-loop control architecture with high-voltage initial acceleration pulse in order to reduce the delay. The contact prediction algorithm was also implemented to reduce the influence of the delay. The experimental evaluation demonstrated that the influence of the delay is negligible in natural grasping, and the recognition is possible in wide range of object size.

Keywords: force feedback device, tactile, pseudo-force display, fingertip tightening

1 INTRODUCTION

Handling of an object is a task that heavily depends on the haptic information related to the status between the fingers and the object. Obviously, manipulation with fingers becomes difficult if the reaction force from the object can not be perceived. Numbers of grounded force-feedback devices [1-3] have been developed, and some of them are commercially available. The manipulator-based grounded force display devices generally have higher rigidity and some of them have function to represent 6 degree-of freedom force.

However, the multi-device coordination of this type of haptic device is difficult because of the interference between the manipulators. Therefore, that is not suitable for multi-finger object operation. There is another type of force-feedback device using tensile force of strings [4], but it has the similar interference problem of the strings.

Recently, another kind of force-feedback devices such as a device using gyroscopic effect, have been proposed [5,6]. They have an advantage to display the world coordinate force without mechanical grounding. However, the display of continuous force is essentially difficult, and it is still too large to wear on each fingertip.

Exoskeleton-type ungrounded force-feedback devices for multi-finger direct manipulation have also been developed [7-10]. The fingertip reaction force is generated by pulling the wire using a motor or pushing the attachment using a pneumatic actuator. These devices allow users to feel the reaction force from the grasping virtual object through their fingers. However, the devices require motors or compressors as the power source and wires or tubes for power transmission. The device application time is also a problem with this kind of complicated wear-on device.

On the other hand, there are some vibro-tactile devices that are attached on fingertips or palm [11][12]. These devices allow users recognize contact or non-contact status by providing a vibration. However, the sensation represented by the device is a substitution and obviously different from the sense induced by the contact with an actual object. In summary, it is still a challenge to display accurate reaction forces to each finger with a lightweight device in any kind of force-feedback device.

This study noticed the haptic sense consists of tactile and proprioceptive senses. If the tactile sense is properly displayed, it is expected it may induce the sufficiently similar sense as the actual contact, even if the proprioceptive sense is not displayed. Based on this hypothesis, a compact multi-finger pseudo-force-feedback device by fingertip tightening was developed.

2 CONCEPT

The mechanical contact to an object induces two kinds of sensations as shown in figure 1. The first is the proprioceptive sense that is perceived by muscle spindles or tendon organs. The proprioceptive sense provides the internal information that is related to muscle force or joint position. Another one is the tactile sensation perceived by the cutaneous mechanoreceptors. The tactile sense is external information because it is induced by the contact with outer object. Basically, the force-feedback device induces both two sensations by generating actual force.

In order to provide the proper proprioceptive sensation, the haptic device is required to counterbalance the muscle contractile force. Therefore, the higher-powered actuator is needed, and it prevents the size reduction of the device.

The reaction force, while a user touches an object as shown in figure1, is perceived by the tactile mechanoreceptors as well as the tendon organs. The tactile mechanoreceptor provides the one important part of the force sensation. It is expected the tactile sense, which is provided at proper timing to the user’s motion, practically represents the reaction force, even if the proprioceptive sense is not provided. Therefore, this study discusses the possibility of pseudo-force-display by stimulating the tactile receptor only using a prototype device. The prototype pseudo-force-display device was designed as a fingertip tightening mechanism for multi-finger object handling.

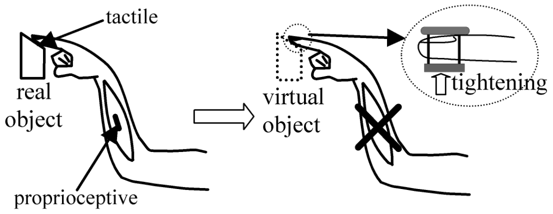

Figure1: The concept of pseudo-force-display by fingertip tightening

3 SYSTEM DESIGHN

3.1 Structure of the Device

The structure of the device is shown in figure 2. The fingertip is tightened by rolling up the contact belt using a motor. A

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geared motor was utilized to reduce the size and to obtain the enough torque. The simple device design allowed the reduction of the size and the weight.

The driving motor starts to rotate the shaft when the virtual fingertip contacts with a virtual object. The shaft rolls up the contact belt, and the actual fingertip is tightened. The contact of the belt represents the contact of the fingertip with a virtual object. The shaft is driven in opposite direction when the virtual fingertip separates from the virtual object, to releases the fingertip from the contact belt.

The prototype device consists of 10mm diameter aluminum roll shaft, cotton-made 0.5mm thick contact belt, 0.5mm thick polyvinyl chloride contact plate, 1/75 reduction ratio geared motor (S.T.L. HS-GM21-ALG), and Velcro strap for the device fixation. The device weight is 18g per finger. The contact and non-contact statuses are shown in figure 3.

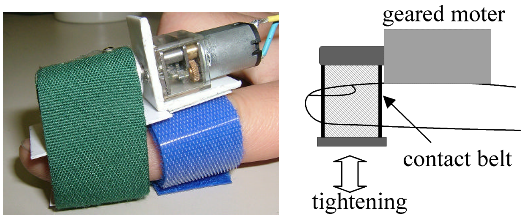

Figure 2: Structure of the device

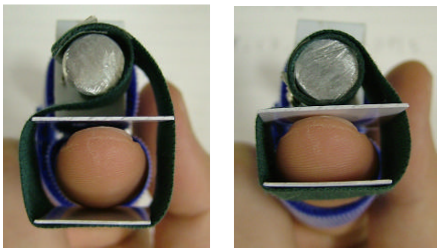

Figure 3: Non-contact and contact statuses

3.2 Device Control

In general, a force sensor is required to control the displayed reaction force accurately. However, the use of force sensor increases the device weight and adds electric wires. Thus, the advantage of the pseudo-force-feedback device is canceled.

Another force control method is an electric current control. The force can be indirectly controlled by controlling the motor current that is proportional to the motor torque. However, the friction of the developed device is high and the back-drivability is low because of the reduction gear. The contact force output after constant force output is discontinuous. Therefore, linear contact force control by the feedback control of the electric current was not applied.

In this study, the open-loop control of the applied voltage was utilized as shown in figure 4. The driving voltage was calculated from the desired force using the device property that was measured in advance. The linearity between the driving voltage and the contact force showed good linearity as seen in figure 7.

Furthermore, in order to decrease the time delay of motor output, at the switching from non-contact to contact state, higher voltage pulse was applied to accelerate the shaft rotation. The pulse driving voltage was 8V that was chosen as the maximum rating voltage of the motor. The driving pulse width was decided experimentally as 20ms that provides constant time delay independent from desired force.

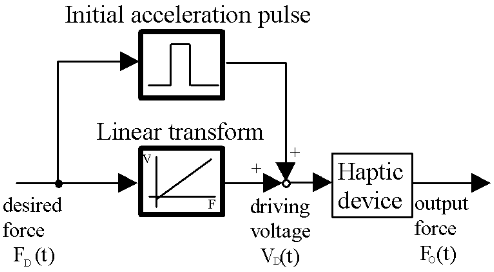

Figure 4: Block diagram of the controller

To obtain stable contact force, the repeatability of the shaft stop position after rewind motion is required. Hence, the rewind driving time was adjusted in proportional to the output force.

3.3 System Configuration

The simplest structure prototype system that has two pseudo-force-feedback devices for the thumb and the index finger was implemented to evaluate the feasibility of the proposed method as shown in figure 5. The distance between two fingertips was detected by the rotary potentiometer connected between the two finger-devices. The system predicts the contact with the virtual object based on the measured fingertip distance and outputs the required voltage at proper time. The contact prediction algorithm is described chapter 5. In this study, the performance to represent the contact and non-contact statuses were evaluated.

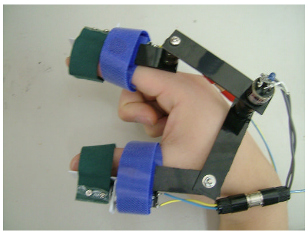

Figure 5: Prototype of pseudo-force-feedback display

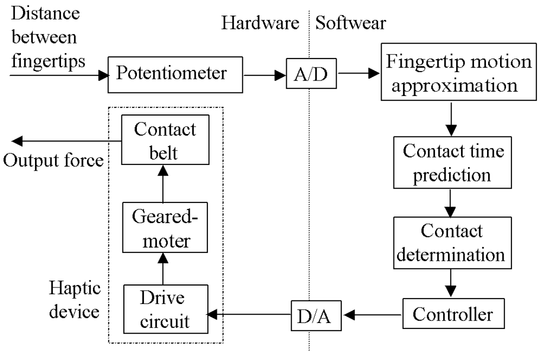

Figure 6: Entire system configuration

4 DEVICE SPECIFICATIONS

4.1 Linearity and Repeatability

The linearity and the repeatability were evaluated in 9 right-handed male subjects from 20’s to 30’s. A set of 5 trials per voltage was performed in each subject. The contact force between the fingertip and the contact plate was measured using a sheet-shaped force sensor, TEKSCAN Flexi-force. The results are shown in figure 7. As the average force variation was 17%, the practically sufficient linearity and the trial-by-trial repeatability was obtained.

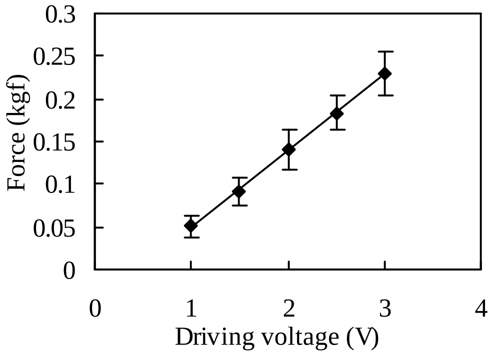

Figure 7: Relation between finger tightening force and driving voltage

The variation of the shaft position after the rewinding for finger release was also evaluated. The rewind time adjustment reduced the shaft position variation to 10 degrees. The variation of the fingertip contact force by rewinding was negligible.

4.2 Precision

The developed system uses the average model for desired force to driving voltage transform. Thus, there is a certain level of error by individual variation. The maximum error in 9 subjects was 54% at the representation of the minimum force, 0.5kgf. The personal calibration using force sensor will compensate the individual variation and allows accurate force control. The range of the pseudo-force that the developed device can provide was 0.5 to 0.23kgf.

4.3 Delay

The most important property of the haptic device is the response time. The time delay from the command output to the contact force rising was evaluated in the state transition from non-contact to contact state. The experiments were performed in 9 male subjects from 20s to 30s. One subject performed 5 times per one driving voltage.

The time delays without the high-voltage acceleration pulse varied from 100 to 600ms as seen in figure 8. The delays with the acceleration pulse were from 80 to 90ms, which was significantly decreased. The fluctuation with the driving voltage was also decreased in the latter condition compared to the former condition. The subject-by-subject variation was also decreased as confirmed in figure 9.

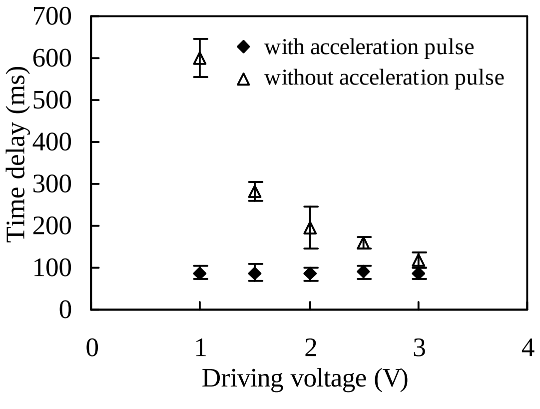

Figure 8: Relation between time delay and driving voltage

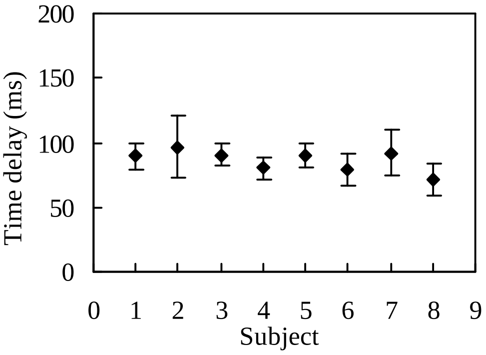

Figure 9: Time delay variation across subjects

5 CONTACT PREDICTION

It is known that several 10s milliseconds delay of force-feedback seriously influences the perception. There is concern that the device delay brings the user the inconsistency between the visual and the haptic sensation, because the device delay was 80 to 90 ms. In the developed prototype system, a contact prediction algorithm was implemented. The system predicts the contact time based on the users grasping motion and starts to drive the motor 80 ms before the predicted contact time.

5.1 Quadratic Function Approximation

The velocity of the fingertips change dynamically while human grasp an object. Therefore, the dynamic changing pattern of the fingertip position was approximated using a quadratic function. The fingertip position was acquired at 500 hz sampling rate. The quadratic function approximation was performed using the past N data. The position 80ms after the measurement was predicted by using the approximated function, and the contact determination was performed based on the predicted position. The number of the data for the approximation was dynamically changed as follows.

5.2 Dynamic Change of Approximation Data Number

The contact prediction using fixed number of data for the approximation showed less prediction performance. In the case of fast finger motion, the contact prediction delay increased if the data number was not adequately reduced. In contrast, when the fingertip ’ s motion was slow, the prediction error increased due to the velocity fluctuation and noise. Hence, the data number for the approximation was dynamically adjusted. When the fingertip velocity was fast, the number was decreased, while the data number was increased for slow motion.

The simplest data number control is to use the finger velocity. However, the velocity-based predication was insufficient in the faster motion due to the finger acceleration. Similar method using acceleration is seriously influenced by the noise.

Thus, an indirect method was applied. The approximation data number was adjusted depending on the time T from the grasping motion onset to the time that the finger velocity reaches a specified velocity (80mm/s). The data number was increased with T. The data number N was adjusted to make the approximation data length coincides with the half of T. The maximum and minimum data numbers were set as 100 and 15.

6 EVALUATION EXPERIMENTS

6.1 Influence of Delay

Firstly, a set of experiments were performed to evaluate the influence of the force-feedback delay. In the experiment, a computer-generated graphic image was displayed that is synchronized with the pseudo-force-feedback, as shown in figure 10. The red, darker, colored ball represents the user’s fingertip position, while the yellow, lighter, colored ball moves cyclically at constant velocity. The subjects were required to grasp the virtual object repeatedly to track the yellow ball using red ball. After the tracking task, the subjects were asked whether the haptic and the visual contact sensations were coincided or not. The target velocity was changed from 100 to 500mm/s at 50 mm/s step. The subjects were 8 male adults.

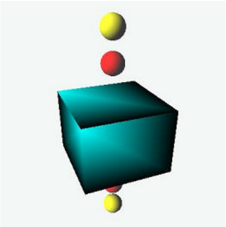

Figure 10: Computer-generated image used in the delay influence evaluation experiment

The maximum visual and haptic synchronized velocities are shown in figure 11. The sensation synchronized velocity without prediction was 250mm/s. The synchronized velocity with prediction was improved to over 400mm/s. The average fingertip velocity is 300 to 400mm/s in human regular grasping motion. It is confirmed that the practically sufficient response was attained.

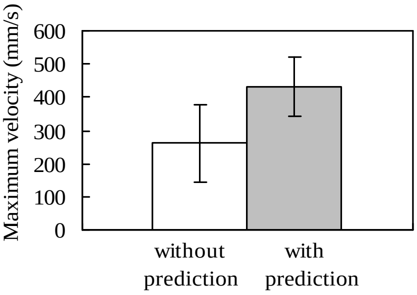

Figure 11: Maximum visual-haptic synchronized velocity

6.2 Recognition of Virtual Object Size

A set of object size recognition experiments were performed to examine the size representing performance of the system. In the experiment, a virtual object that has random size was displayed at first, without visual information. After that, the subject was required to choose an actual object that has the same size as the virtual object. The size of the virtual objects were 10, 25, 40, 55 and 70mm, while the size of the actual objects were 2mm and 5 to 80mm at 5mm step. Each 7 subjects performed 5 tasks per condition.

The displayed and recognized size of the virtual objects are illustrated in figure12. It is confirmed that the accuracy of the size recognition was improved by the contact prediction. However, in the case the virtual object was 70mm, the recognized size was smaller than the displayed size. This error appears the prediction delay due to the insufficient data number for the prediction.

In the case the displayed object was 10mm, the contact prediction increased the error of the recognized size. This error could be caused by the deceleration of the finger motion due to the human behavior to avoid the contact of fingers. Even the further contact prediction algorithm improvement is desired, the prototype multi-finger pseudo-force-feedback device demonstrated the performance to represent the wide range of size adequately.

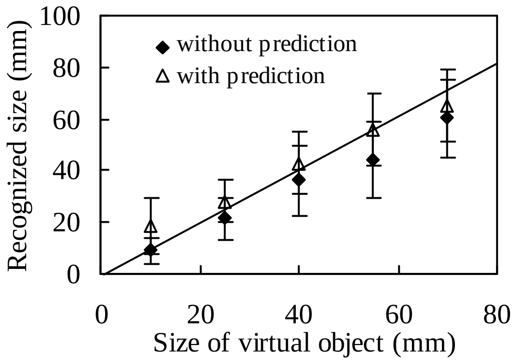

Figure 12: Displayed and recognized virtual object size

7 CONCLUSIONS

In this study, a multi-finger pseudo-force-feedback device by the fingertip tightening was prototyped. The pseudo-force-feedback concept attained compact and lightweight design of the device. The high-voltage initial acceleration pulse decreased the device delay. Furthermore, the contact prediction algorithm reduced the influence of the delay. The pseudo-force-feedback is expected to releases users from heavy mechanical devices and to allow easy-to-do multi-finger manipulation.

The finger tracking system that does not obstruct the advantage of the device and the continuous control of the displayed force are remained.

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