Grasping Force Control in Master-Slave System with Partial Slip Sensor

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***Abstract* - This paper discusses the development and control of the master-slave system capable of grasping an object with unknown coefficient of static friction. Partial slip information is known to be essential for conducting stable grasping in teleoperating system. The developed partial slip sensor contains strain gages in several ridges placed on the curvature contact surface of the elastic body. By measuring strain velocity of each ridge with the strain gages, the vibration that occurs due to the partial slip can be detected. We developed the master-slave system with the slave robot uses the developed sensor to detect a partial slip and automatically controls the grasping force. When an operator intentionally decreases the grasping force applied to the master device in order to release an object, the suppressor suppresses grasping force that is automatically increased by the slave robot. Through the grasp manipulation experiment, the validity of the developed system was confirmed.**

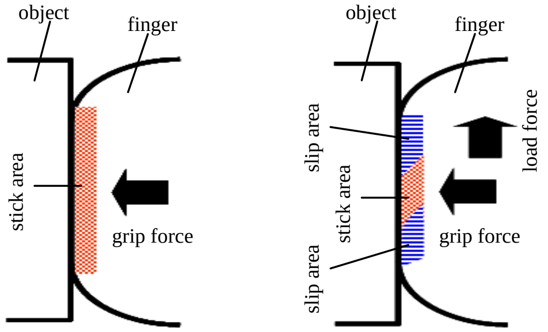
Index Terms* - *master-slave system, partial slip, grasping, manipulation

I. INTRODUCTION

A master-slave system controls a robot to reproduce an operator’s movement. By using a robot hand as a slave robot, human’s dexterous manipulation can be conducted at remote places. As a control method of a master-salve system, force feedback bilateral control has been studied and implemented. Therefore, most of the pilot studies on a master-slave system used a slave robot with a force sensor to measure a force applied to it. However, not only a force sensation, but also a tactile sensation is thought to be important in order to conduct a stable and dexterous manipulation.

Human beings are sensing partial slip which occurs on the contact surface of fingertip with the mechanoreceptors to realize a stable grasping of an object[1][2][3]. As shown in Fig.1, partial slip occurs when a fingertip is pressed and slid on a plane surface, refers to a contact condition between fingertip and an object in which part of a contact area slips while the other part sticks. Humans can increase the grasping force before the grasped object slips off from the fingers because the afferent signals from mechanoreceptors that are sensitive to the increase of slip area, which occurs due to a partial slip, provoke unconscious increase of grasping force. Several grasping methods for robot fingers have been proposed based on the partial slip sensation. Tremblay et al.[4] detected the partial slip of robot finger by sensing the micro vibration with the accelerometer. However, total slip often occurs immediately after the micro vibration. Thus, further improvements in sensor design are needed for conducting manipulation tasks. Maeno et al.[5] developed the elastic sensor capable of detecting a increase of partial slip on a contact surface, and proposed the grasping control method based on the change of stick/slip area ratio. Ikeda et al. proposed the grip force control method using the elastic finger with the CCD camera to realize the vision-based partial slip feedback[6]. These pilot studies stated the effectiveness of measuring the change of the contact condition between a robot finger and a grasped object to conduct the stable grasp. However, these studies considered about the grasping method for the autonomous robot fingers, and did not clarify the versatility of utilizing the grasping method for a master-slave system. In addition, the effectiveness of these methods for detecting the partial slip and controlling the grasping force was clarified only in the regulated circumstance; constant grasping and uplifting velocity.

In the present study, the designing and development of the partial slip sensor which can detect the partial slip during the active grasping motion is discussed. Next, the method is proposed for controlling grasping force of slave robot using the partial slip information that is detected with the developed partial slip sensor. Then, the cooperative control method for coordinating the output of the autonomous grasping force controller and the commands from the master device is proposed. At last, proposed methods are implemented to the master-slave system. The validity of the developed system is confirmed by the grasping manipulation experiment.



(a) Grip force is applied (b) Grip and load force is applied

Fig.1 Schematic view of the distribution of stick/slip area on the contact surface between the finger and the object

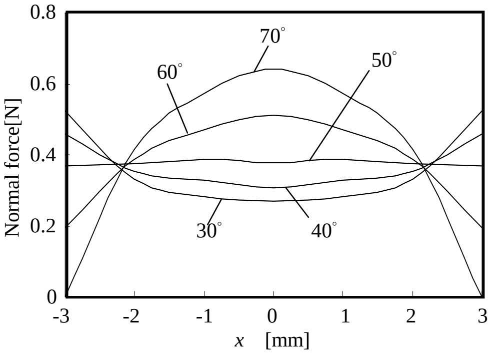


Fig.2 Normal force distribution[6]

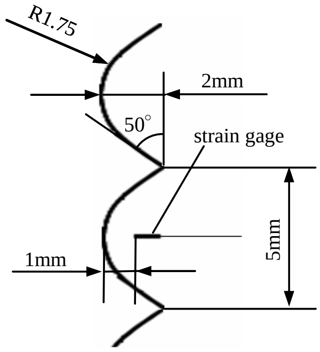


Fig.3 Cross section of ridges

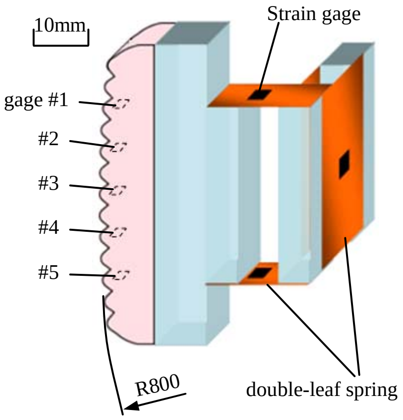
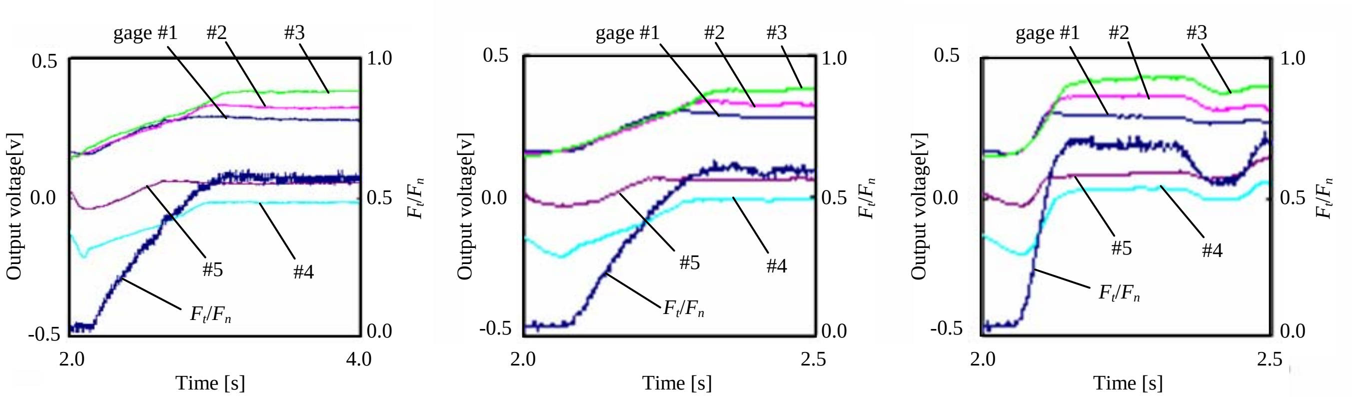


Fig.4 Overall view of sensor



(a) velocity at 1mm/s

(b) velocity at 5mm/s

(c) velocity at 20mm/s

Fig.5 Output of strain gages and force sensor

II. SENSOR

A. Design and Development

The sensor is designed to measure the force applied to the sensor and the vibration that occurs due to the partial slip. It consists of the force sensor part and the slip sensor part. The force sensor part is made of two double-leaf springs made of phosphor-bronze plates with strain gages. It is capable of measuring the total normal force and tangential force that are applied to the sensor.

The partial slip sensor is formed with the silicon rubber which elastic modulus is 0.22MPa. The surface of the sensor that touches the object is curved in macro-scale. Because of these characteristics, normal force applied to the sensor will be large at the center of the sensor and small at the edge of the sensor when the sensor is pressed on to the object. Therefore, when the tangential force is applied to the sensor, the partial slip occurs at the edge of the sensor before the total slip occurs. There are ridges placed along the surface of the sensor in order to detect the vibration more easily when the partial slip occurs. Sato et al. conducted the simulation to derive the shape of the ridge that is most effective for detecting the slip[7]. As shown in the results in Fig.2, the distribution of the normal force at the surface of a ridge is most balanced when the angle of the ridge is 50 deg, means that each ridge will shift to the total slip phase without going thorough the partial slip phase. With this result, the ridges of the sensor were designed as shown in Fig.3. The overall view of the developed sensor is shown in Fig.4. To detect the vibration that occurs due to the partial slip, the strain gages are embedded beneath the ridges. Each strain gage is numbered as shown in Fig.4.

B. Partial Slip Measurement Experiment

Using the developed sensor, partial slip measurement experiment was conducted. As previously discussed, the partial slip sensor for master-slave system must be able to detect the partial slip at various grasping speed. The sensor was pressed to the acryl plate until the normal force applied to the sensor became 4N, and then moved along the plate at the speed of 1, 5, and 20mm/s. When the relative displacement between the sensor and the plate reaches at the certain amount, the partial slip occurs. During the experiment, the output voltage of the strain gages beneath the ridges and the force applied to the sensor was measured. The results are shown in Fig.5. When the sensor moved and the tangential force was applied to the sensor, the output voltage of each strain gage and F_t/F_n both increased, where F_t/F_n is the ratio of tangential

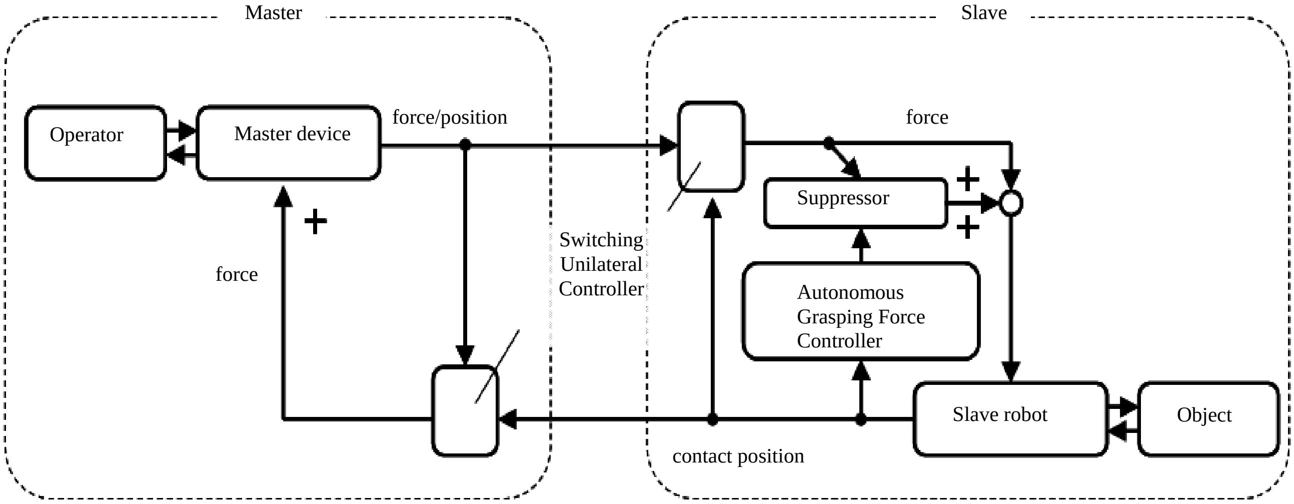


Fig.6 Block diagram of proposed control method

and normal force applied to the sensor. The gage #1 and #5 are the outmost strain gages, and gage #3 is the strain gage in the center of the contact surface. Each result shows that as the F_t/F_n increased due to the movement of the sensor, the output of the strain gages located at the edge of the sensor shifted in the state of equilibrium. Then the output of gage #3 and F_t/F_n shifted in the state of equilibrium at the same time. These results shows that the partial slip started at the edge of the sensor, and the total slip occurred when the ridge at the center of the sensor slipped. From the results, we decided to detect the partial slip by measuring the time derivative of the output voltage of strain gages embedded beneath the ridges.

III. PROPOSED CONTROL METHOD

The proposed method consists of autonomous grasping force controller, switching unilateral controller, and suppressor. The block diagram of the proposed control method is shown in Fig.6.

A. *Autonomous Grasping Force Control Method*

The total slip occurs when F_t/F_n applied to the sensor exceeds the static friction coefficient. The stable grasping can be conducted if the grasping force is controlled so that F_t/F_n is always less than the static friction coefficient. Therefore, there were pilot studies that involves with the direct measurement of the static friction coefficient[8][9]. However, in these studies, the robot must slips off the object before conducting the grasp. The previous discussion suggested that the developed sensor is capable of detecting the partial slip which occurs before the total slip. For the autonomous grasping force control of slave robot, we measure F_t/F_n at the moment when the partial slip occurs, and use it as the target value to control the grasping force so that F_t/F_n never exceed the target value. Since the target value of F_t/F_n is always less than the static friction coefficient, robot hand never slips off the object. This method is also useful against the sudden disturbance applied to the object during the grasp.

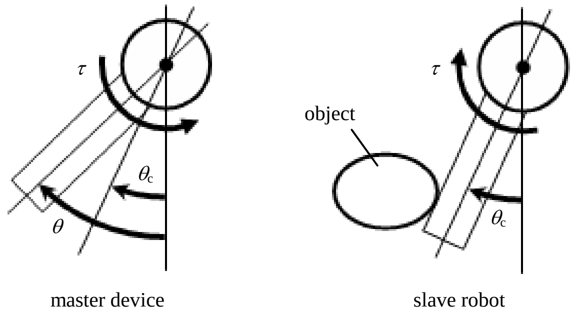


Fig.7 Master-slave system with switching unilateral control method (slave robot is in contact with an object)

B. *Switching Unilateral Control Mehotd*

In the proposed control method, the slave robot would automatically change the grasping force when the operator's command from the master device is inadequate for the stable grasping. If the regular force feedback bilateral control system is used, the reaction force of the output of the autonomous grasping force controller will be applied to the master device, as if it is the disturbance. To avoid this problem, the switching unilateral control was implemented. The switching unilateral control is based on the control method proposed by Yamano[10]. For simplification, the single degree of freedom link model is used in the following explanation. Assume that the DC motor is attached on the joint of the link model. The switching unilateral controller switches the control method based on whether the slave robot is in contact with an object or not. Fig.7 shows the link model of the master-slave system in the condition that the slave robot is in contact with an object. When the slave robot is not touching an object, position information is sent to the slave robot from the master device, and position control is conducted. When the slave

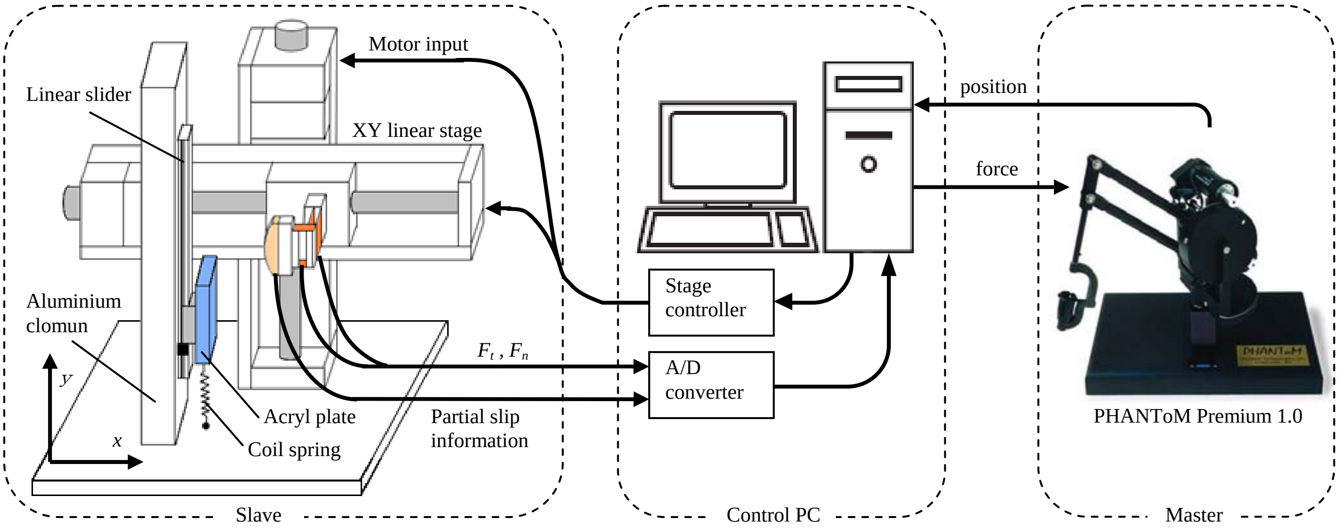


Fig.8 Overall view of the developed master-slave system

robot is in contact with an object as shown in Fig.7, the contact position information is sent to the master device from the slave robot. The master device generates the force that is calculated according to the contact position and its position as expressed in the equation

$$\tau = K(\theta - \theta_c) \tag{1}$$

where τ is the torque, K is the coefficient of the rigidity, θ_c is the contact position, and θ is the present position of the master device. The slave robot conducts the force control based on the force generated by the master device. With this control method, the position of the slave robot is corresponding to the position of the master device when the slave robot is not touching an object. And the force generated by the master device is corresponding to the force generated by the slave robot when the slave robot is in contact with an object. Switching unilateral control method was applied to the linear finger motion of the proposed master-slave system. The master-slave system with switching unilateral control is always stable because it does not send the contact force information directly to the master device. In the other hand, this control method has the weakness; it cannot be used to conduct the task that involves with the manipulation of an object which moves towards the direction of the force applied. However, in general occasion of grasping manipulation, the object is restrained by the thumb. Therefore, proposed method can be used for the present study.

C. *Suppressor*

For some manipulation tasks such as releasing the grasped object, robot fingers must be lifted from the object. In such an occasion, an operator operates the master device to lift the slave robot finger from the object, while autonomous grasping force controller increases the grasping force to maintain the contact with the object. Therefore these two operations may conflict. The suppressor is introduced to the proposed method to avoid such confliction. The suppressor controls the output of the autonomous grasping controller according to the commands from the master device. If the operator is intentionally reducing the grasping force to release the object, the suppressor suppresses the output of the autonomous grasping force controller. If the operator is not trying to release the object, the output of the autonomous grasping force controller is not suppressed. The algorithm for implementation of the suppressor will be described later.

IV. MASTER-SLAVE SYSTEM

A. *Structure*

For the master device of the system, we used PHANToM Premium 1.0, the haptic device manufactured by SensAble Technologies. For the slave robot, we used XY linear stage manufactured by SIGMA KOKI. The developed partial slip sensor was mounted on the driving part of XY linear stage as the finger of the slave robot. The overall view of the system is shown in Fig.8. The feedback cycle of the system is 1ms. The slave robot is capable of measuring the tangential and normal force applied to the sensor, and the partial slip that occurs at the surface of the sensor along y-axis. The output of the sensor is sent to the PC through an AD converter. This system consists of only one finger. In order to conduct the grasping manipulation, at least two fingers are needed. Therefore, we setup the aluminum column parallel to the surface of the sensor to substitute the thumb. During the grasping manipulation, the aluminum column supports the grasping force applied by the robot finger. As the object to grasp, acryl plate was mounted on the linear slider that was fixed along the aluminum column, thus the acryl plate can slid up when it is lifted. For applying the disturbance to the object, we connected the object to the ground with the coil spring. When the object is lifted up, the spring force will be applied to the object as the disturbance.

B. Setup of Controller

The proposed autonomous grasping force controller, switching unilateral controller and suppressor were implemented to the master-slave system. Switching unilateral controller was implemented along x-axis in Fig.8 to switch the control method when grasping force is applied to the object. The force feedback bilateral controller was implemented along y-axis in Fig.8, so the operator can feel the weight of the object. The algorithm of the suppressor is expressed by

$$Fss = Fsa\left[1 - sigmoid\left((Fm - \alpha)/\beta\right)\right] \quad (2)$$

where Fss is the output of the suppressor, Fsa is the output of the autonomous grasping force controller, Fm is the output of the switching unilateral controller, α and β are the constant values for adjustment of suppression. The sigmoid function is expressed by the following equation:

$$sigmoid(x) = \frac{1}{1+\exp(-x)} \quad (3)$$

V. VERIFICATION EXPERIMENT

A. Experimental Setup

To verify the validity of the developed system, the grasp manipulation experiments were conducted. For the verification of the autonomous grasping force controller, an object of unknown friction coefficient must be grasped without slipping even when a disturbance is applied to the object. In order to simulate such environment, the experiments were conducted with two different conditions; putting the powder on the object to lower the friction coefficient, and putting nothing on the object. The friction coefficient between the object and the sensor in those two conditions were measured preliminarily in order to judge if the total slip occurred during the grasping experiments. These values of friction coefficient were never used for the autonomous grasping control.

The experiment was conducted by 5 subjects. The task was to grasp the object by pressing the robot finger into the object, and lift up the object at certain height, then lower down the object and lease it. Each subject conducted the experiment three times with and without the autonomous grasping force controller. There were no practices before the experiments.

B. Results

The average success rate of grasping without slipping is shown in Table 1. With the autonomous controller, subjects always succeeded to grasp the object, meanwhile they often failed without the autonomous controller.

TABLE 1
SUCCESS RATE OF GRASPING (%)

autonomous controller	Object	
	with poweder	without powder
with	100.0	100.0
without	13.3	66.7

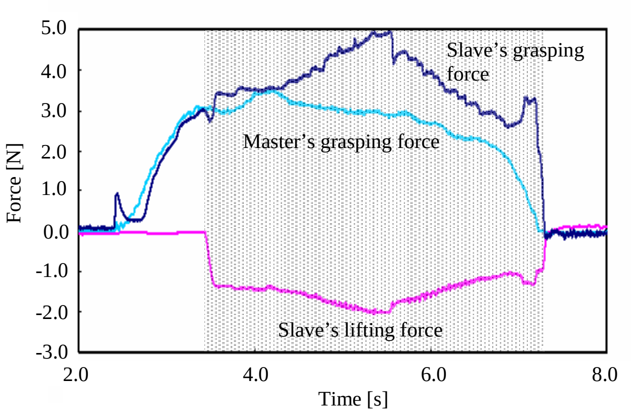


Fig.9 Force generated by the slave robot and grasping force applied by subject A

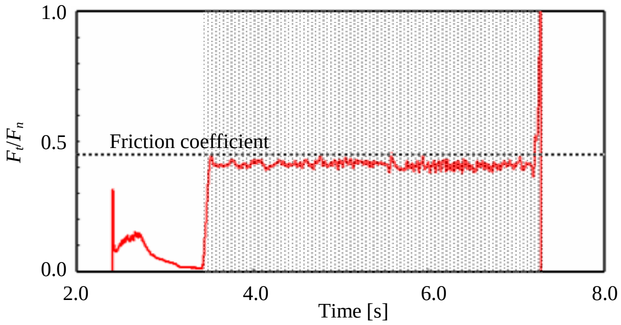
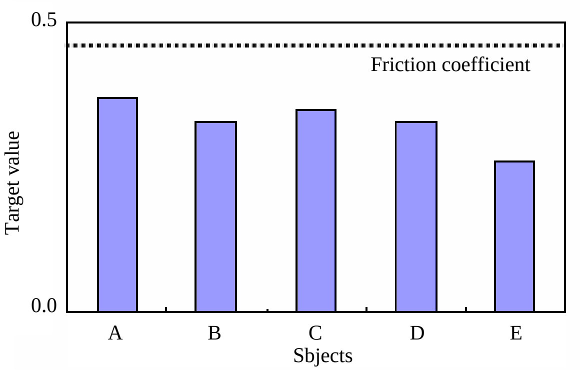
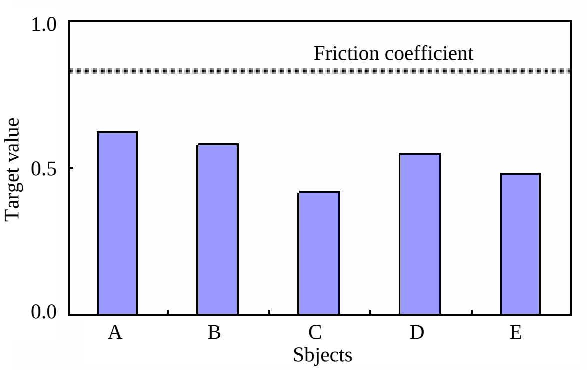


Fig.10 Ratio of tangential and normal force generated by slave robot

The result of subject A is shown in Fig.9. This experiment was conducted with the powdered object, and the autonomous grasping force controller. The shaded area indicates the time when the slave robot is lifting the object. Before the object was being lifted up, the grasping force generated by the slave robot was approximately equal to the force applied by the operator because of the switching unilateral controller. As the object was lifted up and the tangential force applied to the object increased, the partial slip occurred and the output of the autonomous controller was added to the output of the switching unilateral controller. As the result, the grasping force generated by the slave robot increased. When the operator decreased the grasping force to release the object, the grasping force generated by the slave robot also decreased due to the suppressor. Fig.10 shows the ratio of tangential and normal force generated by slave robot. Due to the autonomous grasping force controller, F_t/F_n never exceeds the friction coefficient 0.45, thus the slip between the object and the slave robot did not occur.



(a) Grasping the object without powder (friction coefficient: 0.45)



(b) Grasping the object with powder (friction coefficient: 0.81)

Fig.11 Target value for autonomous controller

Fig.11 shows the average of target values for the autonomous grasping force controller. As described in chapter 3, the target value for the proposed control method is the ratio of tangential and normal force applied to the sensor at the moment when the partial slip occurs. Here, if the target value is smaller than the friction coefficient between the sensor and the object, slip did not occur and stable grasp was conducted. For every subject in both conditions, target values are less than the friction coefficient. From these results, we can say that by using proposed system, the object of unknown coefficient of friction can be grasped without slipping.

In addition, the ratio of minimally required grasping force and the force generated by the slave robot was calculated by comparing the target value for the autonomous grasping force controller and the friction coefficient. According to the calculation, the slave robot of the developed system was grasping the object with the grasping force that was 1.2 to 2.3 times larger than the minimally required grasping force. On the other hand, human beings are known to grasp the object with the grasping force that is 1.2 to 2.0 times larger than the minimally required force. The result indicates that the developed system is capable of controlling the grasping force at the level of human grasping control ability.

VI. CONCLUSIONS

In this paper, we have discussed the development of partial slip sensor that can detect the partial slip at different driving velocity. Based on the partial slip information detected by the developed sensor, autonomous grasping force control method was proposed. The master-slave system with the developed sensor and proposed control method was developed. The result of grasping manipulation experiment shows that the developed master-slave system is capable of conducting the grasping of the object which friction coefficient is unknown, without slipping even when the disturbance was applied to the object.

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