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Method for Controlling Master-Slave Robots using Switching and Elastic Elements

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Abstract— **A new type of master-slave control methodology, which has the merits of both unilateral and bilateral ones, is proposed. The methodology is built on switching the unilateral feedback controls of position and force as required using switching and elastic elements. Proposed methodology not only eliminates the demerits of bilateral control, but also supplies the mechanical force feedback to the operator. It utilizes a feature of human factor that direct displacement feedback is not as important as visual and force feedback. Effectiveness of the proposed method is confirmed by experiments using a developed simple single axis master-slave arm system. Driving test of the experimental devices and sensory evaluations are conducted. As a result, it is confirmed that the methodology successfully provides the sense of touch to the operator of the system.**

Keywords— **Master-slave system, Force feedback, Control.**

I. Introduction

TELE-ROBOTICS is a promising technology for tele-operation using master-slave robot systems in the field of medical, welfare, extreme-environment, space-environment and virtual reality. Many sophisticated master-slave robot systems have been proposed. Some of them are already commercialized. For example, PHANToM by SensAble Technologies [1], [2] is a device for measuring six degrees of freedom motion of an arm and, at the same time, giving a force feedback of three axes, which is usually used for the input devise for virtual reality and for the master robot for the telerobotics. Da Vinci by Intuitive Surgical [3], [4] is a surgical master-slave robot system having two fingers on two arms and can realize highly dexterous manipulation. Both of them and some other master-slave robot systems and haptic devices [5]-[8] show enormous ability. However, they have a limitation in size and cost because they use electromagnetic motors with which electric power should be supplied as an input power for supplying feedback force to an operator of the master robot when the slave robot is in contact with an object. In this situation, slave robot is just in contact with the object and is stationary. It seems to be reasonable if the actuator of the master robot is just stopped and force feedback is applied mechanically instead of electrically for preventing signal noise due to the feedback and for simplifying the system. However, previously developed master-slave systems did not try to stop the master robot in a mechanical way when the slave robot is in contact with an object. Previously developed methods for controlling the master-slave robot are divided into two categories; i.e., a unilateral control system and a bilateral control system. The former is not to apply a force feedback. Although the system has advantage to have simple mechanism and controller, it has disadvantage not to have force feedback needed for dexterous manipulation. The latter is to apply a force feedback control electrically. Conceptual figure of the bilateral system is shown in Fig. 1(a). Although the mechanism and controller become complicated, dexterous manipulation can be conducted using the bilateral one. However, electrical force feedback causes an oscillation due to noise. In order to apply the precise force feedback electrically, the entire system becomes large and expensive.

In this paper, we propose a new method for controlling a master-slave robot arm, which has the merits of both unilateral and bilateral ones, i.e., construction and controller of the proposed system is simple, and the force feedback to the operator of the system is provided. The methodology is based on the judgment of contact/non-contact condition of the slave robot followed by the switching of the objectives of unilateral feedback control between position and force. Conceptual figure of proposed methodology is shown in Fig. 1(b). Large and stable stationary limiting torque

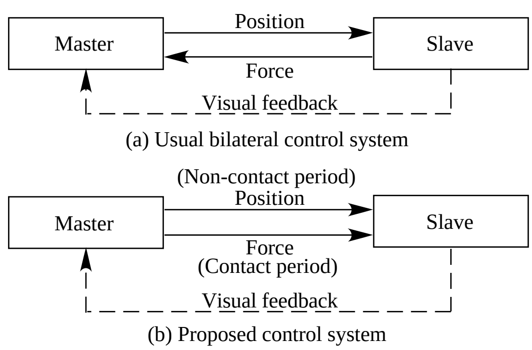

Fig. 1. Conceptual figures of systems

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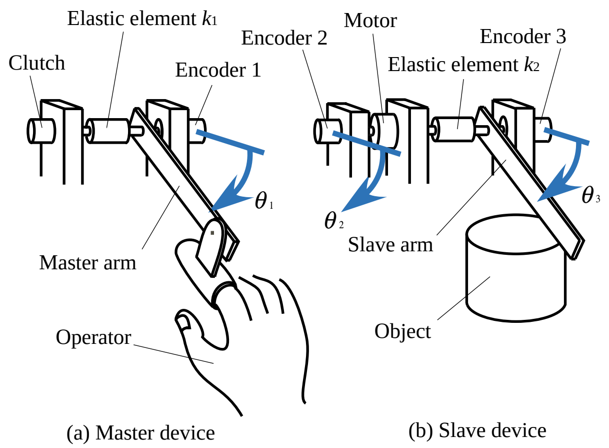


Fig. 2. Outline of proposed system

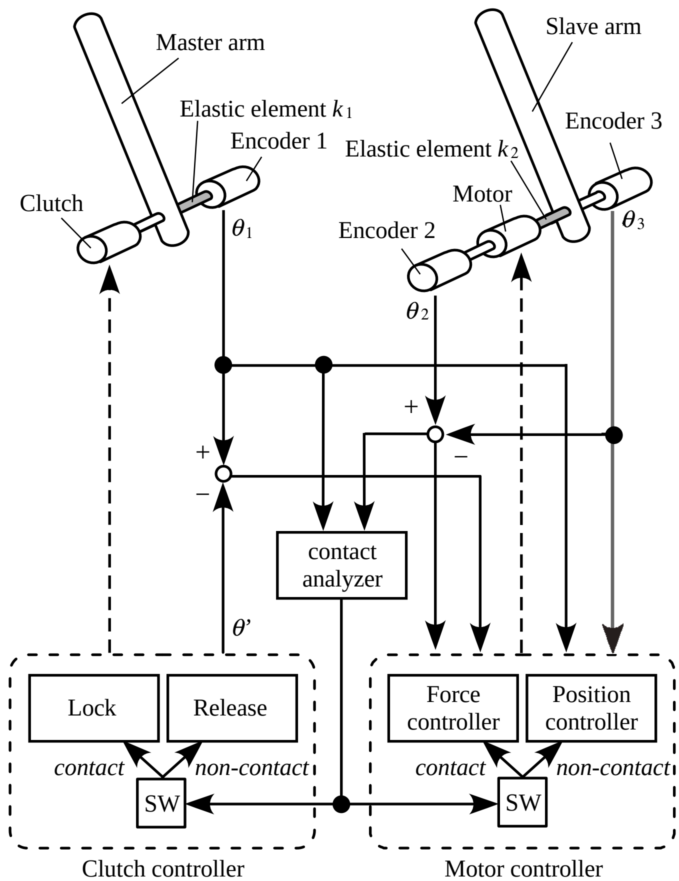


Fig. 3. Block diagram of system

can be applied by use of the ultrasonic motor because it is a frictionally driven motor and need no electric power to keep it stationary. So the ultrasonic motor is suitable for the switching element because it can make the master arm stationary when the slave arm is in contact with an object. Mechanical clutch is also suitable for the switching element. The force feedback to the operator is applied mechanically as an elastic force of the elastic elements instead of electrical feedback control. This method also utilizes a feature of human factor, that is, displacement information from visual feedback is superior to that from one's sensation [9]. Lightweight and well-controlled master-slave robot can be supplied using the proposed method.

II. Method

Since the previously developed unilateral and bilateral master-slave systems have potential problems as mentioned above, a new type of master-slave system and its control methodology are proposed in this chapter. The proposed system is based completely on different idea from previous ones as shown in Fig. 1. The system utilizes the switching elements including ultrasonic motors, clutches and the elastic spring elements. The system well uses both the visual sensation and force sensation of human beings.

A. System Configuration

Fig. 2 shows the outline of proposed system for a single DOF application. A master device consists of an encoder, an arm, an elastic element, a clutch and a shaft. The one side of the axis of the clutch is connected to the rotational axis of the device. The other side is fixed. Although the clutch can be replaced by an ultrasonic motor, we use the clutch to simplify the explanation and initial test. A slave system consists of two encoders, an arm, an elastic element, a motor and a shaft. A frame of reference in Fig. 2 is common in use in this paper. k_1 and k_2 in Fig. 2 represent torsion spring coefficients of the elastic elements. The elastic elements are used as one of the features of the system. An elastic factor is not generally thought to be a suitable factor for precise system, however, we dare to pay attention to an elasticity for novel master-slave system. The control methodology is mentioned in the next section.

A.1 Control Methodology

The elasticity is well used in the proposed system so as not to produce any oscillations of the master arm even when the operator feels a reaction force. Block diagram and flowchart of the proposed control methodology are shown in Fig. 3 and Fig. 4, respectively.

A.2 Contact analyzer

First, the angular positions, θ_2 and θ_3, obtained using the encoders in the slave system are compared with each other in order to distinguish whether the slave arm is in contact with arbitrary object or not, i.e., they become different when the arm is in contact with the object according to the deformation of the

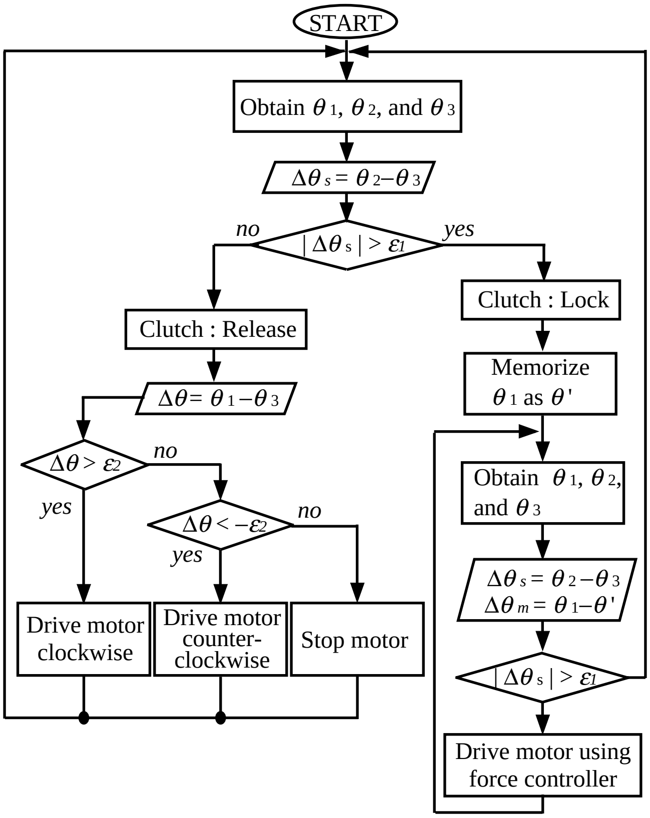


Fig. 4. Flowchart of proposed control methodology

elastic element in the slave device. The contact/non-contact condition is transmitted to clutch and motor controllers. If the arm is not in contact with the object, the angular position of the slave arm is controlled to agree with that of master arm. On the other hand, if the salve arm is in contact with the object, a reaction force at the finger of the operator is reproduced between the slave arm and the object.

A.3 Non-contact period

During the period when the slave arm is not in contact with any object, the clutch is operated to be unlocked, and the angular position of the slave arm (θ_3) is controlled to agree with that of master arm (θ_1) using a position controller, for example, a PID controller. Then, the elastic elements do not deform because the end of the elements are completely free.

A.4 Contact period

When the slave arm becomes to be in contact with an object, the control method is switched to be force control according to TABLE I. During the contact period, the clutch is operated to be locked, and the reaction force the operator feels is reproduced at slave arm. At this moment, the elastic element in the master

TABLE I
SWITCHING OF CONTROL

	Non-contact period	Contact period
Clutch	Release	Lock
Ultrasonic motor	Controlled to be $\theta_1 = \theta_3$	Controlled to be $k_1 \cdot (\theta_1 - \theta') = k_2 \cdot (\theta_2 - \theta_3)$
Control method	Position control	Force control

device does make sense.

The clutch in the master system is locked just after the slave arm becomes to be in contact with the object, and the locked angular position is memorized as θ'. Next, the angles of torsion of elastic elements for the master and slave systems, $\Delta\theta_m$ and $\Delta\theta_s$ in Fig. 4, are obtained using θ_1, θ', θ_2 and θ_3 in the motor controller. When the elastic element of master device is twisted by the operator's pressing force, the operator passively feels reaction force represented by $(k_1 \cdot \Delta\theta_m)$. If the $\Delta\theta_s$ is larger than the threshold ϵ_1 decided in advance, it is controlled using the motor in the slave system to be

$$k_1 \cdot \Delta\theta_m = k_2 \cdot \Delta\theta_s \tag{1}$$

Namely, the operator only feels the passive reaction force by the torsion of the elastic element without active ones. Then, the operator does feel the reaction force generated in the slave arm without feeling any oscillations of the master arm due to the electrical characteristic.

As you can easily point out, the angular positions of the master and slave arms during the contact period are different if the stiffness of the object is different from that of the elastic element in the master device. However, there is a fascinating report for influence of visual sensation under the master-slave system [9]. The report says that humans mainly perceive the stiffness of objects from the combination of visual displacement and haptic force information, whereas the direct displacement information is rarely used. Hence, the proposed method is thought to make the operator perceive the stiffness of objects using visual feedback. Furthermore, if the torsional rigidities of elastic elements in the master and slave systems are selected to be different, scaling of reaction force can be conducted using the same methodology. However, the method cannot provides the reaction force by active motion of the object because the information about reaction force is sent from the master device to the slave device as shown in Fig. 1(b). Whenever the object doesn't move actively, the method has much availability. This mehod is especially suitable for tele-operation having time delay, for example, operation by use of internet, because unstability due to the delay of force feedback never occours since no control signal is sent from the slave system to the motor driver of the master sys-

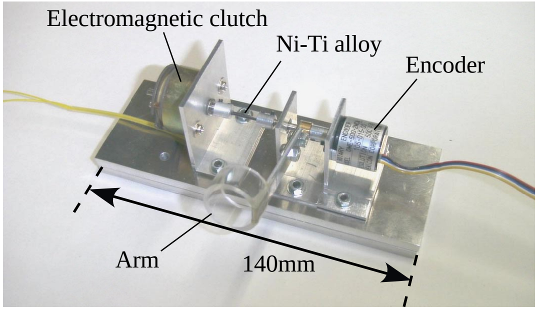


Fig. 5. Master device

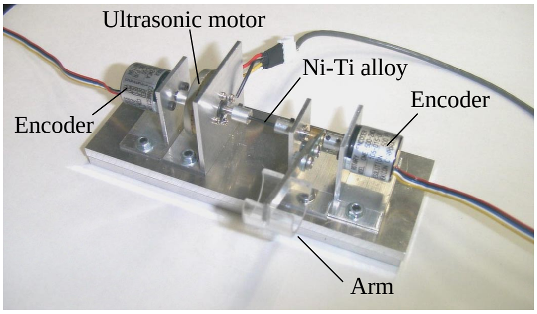


Fig. 6. Slave device

tem as shown in Fig. 1. Although the above explanation is based on the single-DOF system, the proposed methodology can be easily extended to a multi-DOF system because the whole master-slave system consists of simple components.

III. Experimental Device

Simple single axis experimental devices are developed to confirm appropriateness and effectiveness of the proposed methodology. According to the illustration of Fig. 2, master and slave devices, and an entire system are respectively developed as follows.

A. Master Device

The developed master device is shown in Fig. 5. The master device consists of an electromagnetic clutch (ASA ELECTRONICS, MB2-P24), encoders (NEMICON, OME-A), shafts, an arm, couplings and an elastic element. As the elastic element, we adopt Ni-Ti alloy shaft for a torsion-bar spring. The Ni-Ti alloy, called super elastic alloy, has wide elastic region. The Ni-Ti alloy shaft and the other shafts are 1.5 mm and 3 mm in diameter, respectively. The length of the arm is 50 mm. The couplings are used for connecting the axis of electromagnetic clutch, shafts and Ni-Ti alloy shaft. For the non-contact period mentioned in the section II-A.3, the electromagnetic clutch is kept unlocked. Then, the arm, handled by the operator, rotates freely around the axis of the electromagnetic

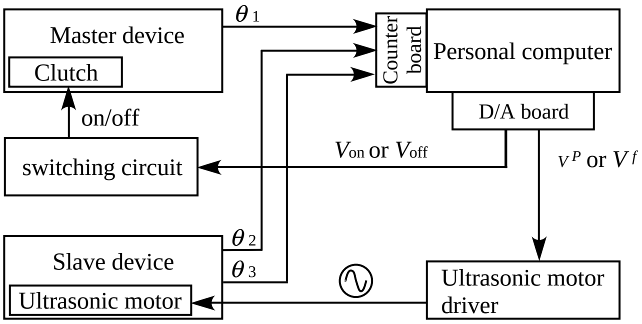


Fig. 7. System configuration

clutch. On the other hand, for the contact period, the clutch is operated to be locked, and the operator feels the reaction force generated by the twisted Ni-Ti alloy shaft.

B. Slave Device

The developed slave device is shown in Fig. 6. The slave device consists of an ultrasonic motor (SHINSEI USR-30-B4), encoders (NEMICON OME-A), shafts, an arm, couplings, and a Ni-Ti alloy shaft. The ultrasonic motor has features such as high response and high driving torque at low rotational speed, so it is possible to drive the axis directly. The maximum driving torque of the motor is 0.1 Nm. Aims for adopting the couplings and Ni-Ti alloy shaft are the same as that mentioned in the section III-A. For the non-contact period, the ultrasonic motor is driven so as the position of arm to follows that in the master device. On the other hand, for the contact period, the motor is driven so as the reaction force against a contact object to be the same as the reaction force felt by the operator in the master device.

C. Entire System

Entire experimental system is constructed as shown in Fig 7. Output pulse signals from the encoders are converted into counted values in a counter board (CONTEC, CNT24-4D(PCI)). Then, the angular positions, θ_1, θ_2 and θ_3, are calculated from the counted values in the personal computer. The rotational speed and direction of the ultrasonic motor and lock/release state of the clutch are calculated according to the proposed methodology. Commands for the ultrasonic motor driver and the switching circuit are sent through a D/A board (CONTEC, AD12-8(PCI)). The ultrasonic motor driver determines the parameters of input signals for the ultrasonic motor.

IV. Experimental Results

Results for the experiments using the proposed methodology and the developed devices are shown

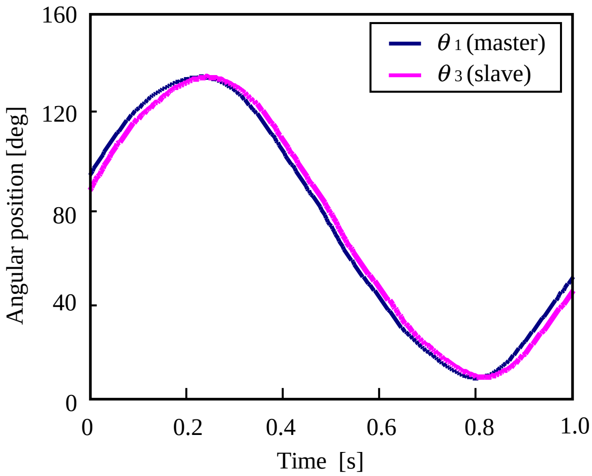


Fig. 8. Result for position control (non-contact period)

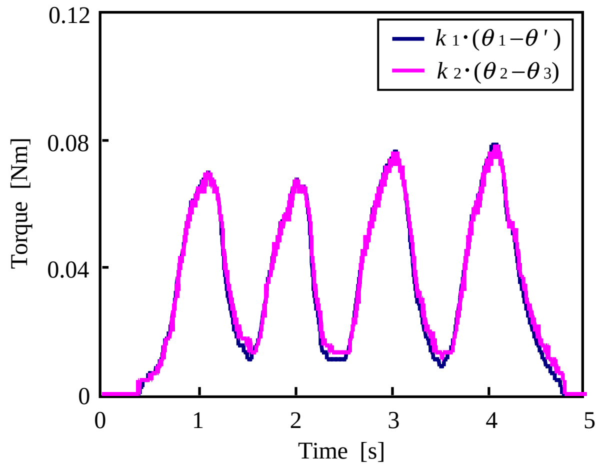


Fig. 9. Result for force control (contact period)

in this chapter. The unilateral feedback controls of position or force are selected according to non-contact/contact condition of the slave arm against an object. First, an experiment on unilateral position feedback control under the non-contact condition is conducted. Second, an experiment on unilateral force feedback control under the contact condition is also conducted. Then, sensory evaluations on ten subjects are conducted to confirm availability of the proposed methodology to provide the sense of touch to the operator.

A. Experiment for Non-Contact Period

While the arm of the slave device is not in contact with any objects, the angular position of the slave arm is controlled to be the same as that of the master arm as mentioned above. For controlling the velocity of ultrasonic motor, a proportional feedback,

$$V^p = K_p^p \cdot (\theta_1 - \theta_3) + n^p \tag{2}$$

is used, where, V^p is a command voltage for the ultrasonic motor driver which determines the rotational speed of the motor from 0 rpm to 300 rpm, K_p^p is a proportional feedback gain, and n^p is a bias for the unilateral position feedback control. Fig. 8 shows the experimental results for position control, where the proportional feedback gain K_p^p and the bias n^p are 0.020 and 0.36, respectively. The angular position of the slave arm successfully follows that of the master arm.

B. Experiment for Contact Period

While the slave arm is in contact with an arbitrary object, the reaction force the operator feels in the master device is reproduced at the slave arm against the object. Namely, the ratio of $\Delta\theta_s$ to $\Delta\theta_m$ should be equal to that of k_1 to k_2 in Fig. 2. For controlling the motion of the ultrasonic motor, rotational speed command voltage V^f is given to the motor driver as follows. While increasing the pressing force, the constant voltage (1.4 V) is given to emit enough force against the reaction force by torsion of elastic element. While diminishing the pressing force, the proportional feedback,

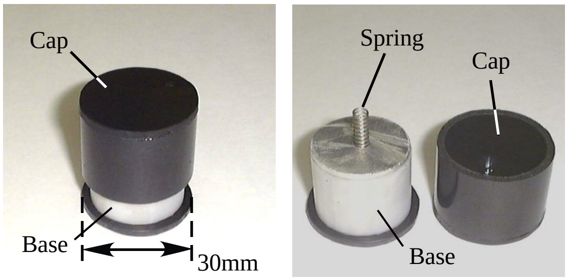
$$V^f = K_p^f \cdot (k_2 \cdot \Delta\theta_s - k_1 \cdot \Delta\theta_m) + n^f \tag{3}$$

is used, where, K_p^f is a proportional feedback gain, and n^f is a bias for the unilateral force feedback control. Fig. 9 shows the experimental results for force control, where the proportional feedback gain K_p^f and the bias n^f are 1.67 and 0.36, respectively. Both k_1 and k_2 are 0.012 Nm/deg. The reaction force at the slave arm successfully follows that at the master arm.

C. Sensory Evaluation

Since the position and force controls for non-contact and contact period, respectively, have been confirmed, sensory evaluations on subjects about object stiffness are conducted as the next step. The outline of the sensory evaluation is as follows. The master device is covered by opaque box in order not to be seen by the subjects during the experiments.

1. Four test objects, A, B, C and D, as shown in Fig. 10, are prepared. They are not distinguished visually because springs are covered by caps. Each of their spring coefficients are 0.13 N/mm, 0.21 N/mm, 0.33 N/mm and 0.83 N/mm, respectively.
2. Stiffness of six pairs of object selected from four test objects are tested by a subject using the developed devices. Then, the subject answers which object is felt to have higher stiffness between each pair.



(a) Entire view (b) Inner view

Fig. 10. Test object

TABLE II
RESULTS FOR SENSORY EVALUATION

Subjects	Percentage of correct answers [%]	Object selected in experiment (4)
1	94.0	C
2	100.0	C
3	100.0	D
4	100.0	D
5	100.0	B
6	94.0	D
7	100.0	B
8	100.0	A
9	100.0	B
10	100.0	C
Average	98.8	

3. Sensory evaluation of 2 is conducted for three times on one subject in random order.
4. Subjects are asked to select an object whose displacement looks the same as that of his/her finger.

TABLE II is the results for the sensory evaluations on ten subjects. Average of the percentage of correct answers is 98.8 % of 180 trials. The proposed methodology possibly provides the sense of touch to the subject using reaction force to his/her finger and visual feedback. The results for the experiment 4 varies, although the angular positions of master and slave arms become equal in case of the test object C. It means that the direct displacement feedback due to the kinesthesia has less importance to know the stiffness of the object than the visual sensation does. The result agrees well with the previously reported knowledge mentioned above [9].

V. Conclusions

A new control method for the master-slave system has been developed in this paper. First, theory of the new master-slave system is proposed. The system is constructed by switching and elastic elements. The elastic elements are not generally thought to be suitable elements for the precise system. However, it is the key element for the novel master-slave system as the proposed system well uses the feature of human sensation. Then, the experimental devices are developed for confirming the effectiveness of the proposed method. Finally, the basal driving test of the experimental devices and sensory evaluations are conducted. As a result, it is confirmed that the methodology successfully provides the sense of touch to the operator. The methodology is well suited to remote control robot system through internet which potentially has time delay, because information transmission cost is much lower than the former bilateral master-slave system.

Make use of the ultrasonic actuators including ultrasonic motors and ultrasonic clutches instead of the electromagnetic clutches used in this experiment is one of the most important issue for this method to be realistic in the future study, because the electromagnetic clutch we used is not silent and small enough, and takes over 10 ms to be switched. Moreover, the ability of the methodology while the object is dynamically moving should be understood in our future study. Then, lightweight and well-controlled master-slave robot can be supplied using the proposed method with introducing ultrasonic actuators. It means that this method and system can be applied to large-DOF dexterous robot arms/hands in the future study.

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