Evaluation of the Different Master Device Approaches for a Model-Based Space Teleoperation System

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Abstract

In the teleoperation, a master-slave approach which can display both motion and force information to an operator is quite effective. However, it is not used for the space robotic teleoperation from the ground, since it becomes unstable due to the communication time delay problems. Therefore, a joystick has been a popular control device in such space teleoperations until now. Instead, the master-slave approach can be applied to a model-based space robotic teleoperation employing the virtual reality technologies. In our previous works, a model-based space teleoperation system having robustness against modeling errors has been demonstrated using a real space system Engineering Test Satellite VII (ETS-VII). This approach has lead to a new possibility of the employment of the master-slave approach into the model-based space robotic teleoperation. In this paper, the operability of both the master-slave and the joystick approaches is evaluated. Furthermore, we evaluate a force joystick approach too which is another control method in our teleoperation system. From the results, we could conclude that the master-slave is the best control approach for the contact tasks in which the directions of motion of the slave arm and the operator's input force are different.

1 Introduction

Generally, it is thought that a master-slave approach which can display the position and the force information of the slave system to an operator is an effective method in the teleoperation. However, the master-slave approach has not been used in the space teleoperation system until now [1], [2], since the bilateral system generally becomes unstable due to the indispensable communication time delay. The few stable bilateral systems under the communication time delay also have been proposed [3], [4], the operator can not get the easily understandable force information. Instead, a joystick that cannot display the force information is used as the master device in the space shuttle where no time delay exists. The joystick has been used in many space teleoperation projects like ETS-VII and is also supposed to be used in the international space station [5], [6], [7].

In our previous work, we have proposed a mixed force and motion commands-based space teleoperation system with robustness against the modeling errors [8]. Our system is one of the model-based teleoperation systems. The force and position information are calculated in the virtual world on the ground-based computer and can be stably and sharply displayed to an operator. Furthermore, we have also developed a novel and compact 6-DOF haptic interface to use as a master device [9]. In our ETS-VII experiments, we performed the surface-tracking and peg-in-hole tasks using this teleoperation system and the haptic interface [10]. Actually, although the modeling errors existed, the above tasks could be performed safely. From these ETS-VII experiments, it could be concluded that the master-slave approach displaying the force and position information can be successfully used for the space robotic teleoperations with the communication time delay.

Until now, at the planning stage of ETS-VII, a comparison between the joystick and the master-slave approaches was executed. This comparison conducted qualitative evaluations using the questionnaire to the operators. Therefore, we need to reevaluate the above controls quantitatively too. In this paper, the operability of these approaches is evaluated for the model-based space robotic teleoperation. Moreover, a force joystick approach [11], which is one of the control methods in our model-based space teleoperation system is also evaluated. From the above results, we could conclude that the master-slave is the best control approach for the contact tasks in which the directions of motion of the slave arm and the operator's input force are different.

2 Teleoperation methods

In these experiments, we adopt a model-based space robot teleoperation system. Therefore, the operator actually teleoperates the slave arm's model (virtual arm) in the virtual space model developed in the ground station computers. The slave arm's force and motion information which is displayed to the operator are calculated by the virtual space model. Therefore, the force and position information can be stably and sharply displayed to the operator.

The operator executes the tasks using the master-slave (MS), the joystick (JS) and the force joystick (FJ) modes. The details of these modes are described in this section.

A recently developed compact 6-DOF haptic interface device is used as a common master controller. A compact 6-axis force/torque sensor is integrated in the grip of this master device. All the modes are controlled by the force/torque data from this sensor. For instance, we use the haptic interface as a master device, as a joystick and as a force joystick by changing the control modes.

2.1 MS mode

The motions of both the virtual arm and the haptic interface device are simulated exactly. Therefore, the operator can feel the force and the motion information of the slave arm through the haptic interface.

2.2 FJ mode

The haptic interface is not moved at all and only the force/torque sensor data are used to create the commands.

2.3 JS mode

The haptic interface is allowed to move with the compliance control as a 3-DOF joystick realizing one axis of position and two of orientation.

2.4 Control methods

The main feature of our mixed force and motion commands-based space teleoperation is that tip velocity commands are generated by the operator exerted forces on the master device and the motion information of both the virtual and the slave arms. However, we cannot manipulate the velocity control and change the control modes between the contact and the non-contact for the slave arm on ETS-VII. Therefore, the master and the virtual arms are controlled by the end-tip velocity and the slave arm is controlled by the position under compliance control. The control methods for the virtual arm, the slave arm and the reference position of the slave arm are the same as used in our ETS-VII experiments [10]. The reference position of the slave arm is added in the tip position of the virtual arm to realize of the operator's force. Therefore, the slave arm can compensate for the modeling errors without generating large forces. Here, we describe the control method for the master device only as follows:

- MS mode
  - in contact motion

$$\dot{x}_m = k_f(f_{ref} - f_{va}) \tag{1}$$

  - in non-contact motion

$$\dot{x}_m = k_v f_{ref} \tag{2}$$

$$f_{ref} = f_m + k_d(\dot{x}_{va} - \dot{x}_m) + k_p(x_{va} - x_m) \tag{3}$$

- FJ mode

$$\dot{x}_m = k_{fj}(x_{fj} - x_m) \tag{4}$$

- JS mode

$$\dot{x}_m = k_{jsp}(x_{js} - x_m) + \frac{f_m}{k_{js}} \tag{5}$$

here,

x_m, x_{va}: the tip position of the master and the virtual arms respectively,

x_{fj}: the position bound on the master arm,

x_{js}: the reference point for the master arm,

$\dot{x}_m$, $\dot{x}_{va}$: the reference tip velocities of the master and the virtual arms respectively,

f_m: the force/torque sensor data of the master arm,

f_{va}: the virtual reaction force,

f_{ref}: the position restraint force for the certification of the master arm backdrivability,

k_f, k_v: the force and velocity gains of the master arm respectively,

k_d, k_p: the damping and position gains for f_{ref} respectively,

k_{fj}: the restraint gains of the master arm,

k_{js}, k_{jsp}: the stiffness and the position gains of the master arm respectively.

In these experiments, we control the position variation only, while the posture is fixed in the initial state.

3 Experimental system

Our teleoperation system named as DARTS (Dual-Arm Robot Teleoperation in Space) is used as the experimental system [11]. This system consists of the space and the ground systems. An overview of the system is shown in Fig. 1. The appearance of the space system is shown in Fig. 2. We use only a left arm of the dual slave arms. The communication time delay in this communication loop is set at 6 seconds.

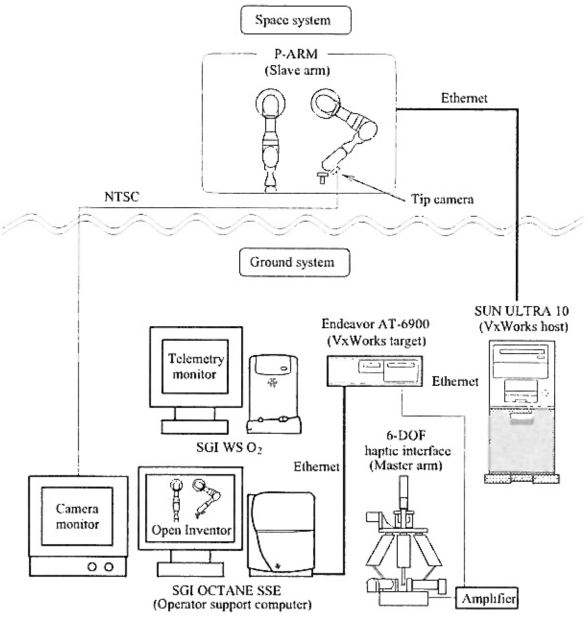

Figure 1: Overview of the system.

4 Details of the experiments

The operability in the MS, FJ and JS modes is e-valuated for the model-based space robotic teleoperation. For this purpose, two different operators execute these experiments. The experiments are the surface-tracking and the peg-in-hole tasks which are the same as in our previous ETS-VII experiments [10]. Each operator executes the above tasks ten times for each mode to minimize the evaluation errors.

1. Surface-tracking task

   This task is carried out using a peg and a tracking-surface board. In start, the operator teleoperates the peg to exert a force of 20 N along the z-direction against the surface and this tracks the curved surface maintaining this force. The operator can check this force at the telemetry monitor.

2. Peg-in-hole task

   This task is also carried out using the same set-up. The diameter of the peg is 18.0 mm and the clearance in the hole is 0.02 mm. The starting position is 20 mm to the x-direction, -20 mm to the y-direction and 20 mm to the z-direction from the center of the hole respectively.

5 Results of the experiments

5.1 Surface tracking

The results of the surface-tracking task executed using the MS, FJ and JS modes of the master arm, are

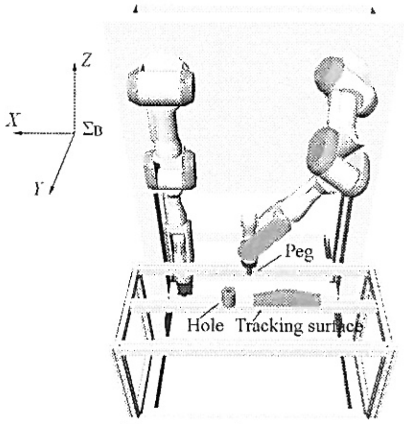

Figure 2: Space system.

shown in Figs. 3, 4 and 5 respectively. These figures show the results of one operator only. In the MS and FJ modes, the control commands are generated from the force/torque data of the master arm. However, in the JS mode, these are generated from the position and rotation of the joystick. Therefore, we compare the forces of the master and slave arms in the MS and FJ modes. While in the JS mode, we compare the force of the slave arm and both the position and rotation of the joystick.

The profiles of both the virtual arm's position and the slave arm's position are almost coincident in all of these three modes, shown in Figs. 3, 4 and 5. The profiles of the slave arm's forces are also similar in all modes. The standard deviations for the z-direction force of both the master arm and the slave arm in all experiments are shown in Fig. 6 and Fig. 7 respectively. These standard deviations are average of ten experiments for both each operator and each mod-e respectively. The standard deviations of both the master and slave arms in the MS mode is the smallest of all modes clearly. The standard deviations of the master and slave arms in the FJ mode is smaller than that of in the JS mode. Therefore, it can be said that the input force of the operator in the MS mode is the most stable, and this force in the FJ mode is more stable than that in the JS mode.

Moreover, all operators expressed the MS mode as the most comfortable one, while the JS mode as the most inconvenient one.

Here, we describe about the motion and the force directions of both the master and the slave arms in the surface-tracking task. Fig. 8 shows the motion of the slave arm and the input force direction. In moving up the surface, the operator should pull up the slave arm in the z-direction and exert the force along the minus z-direction at the same time. We describe the details in each mode as follows.

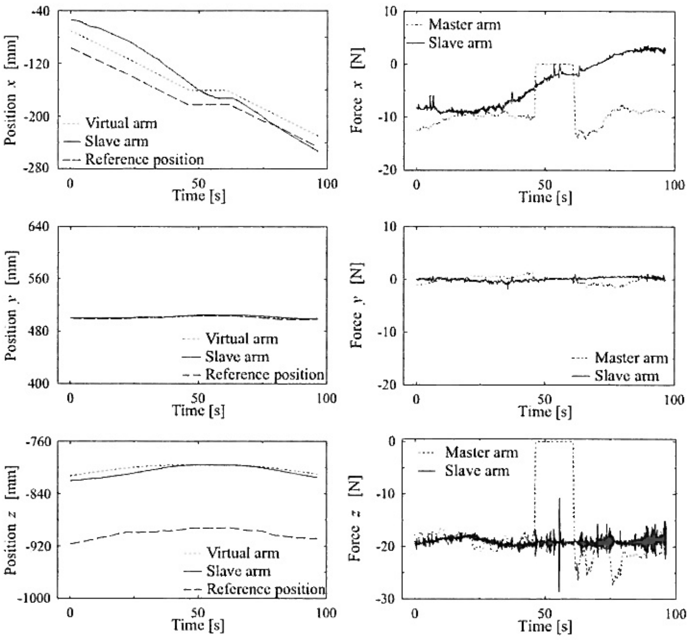

Figure 3: Surface-tracking task in the MS mode.

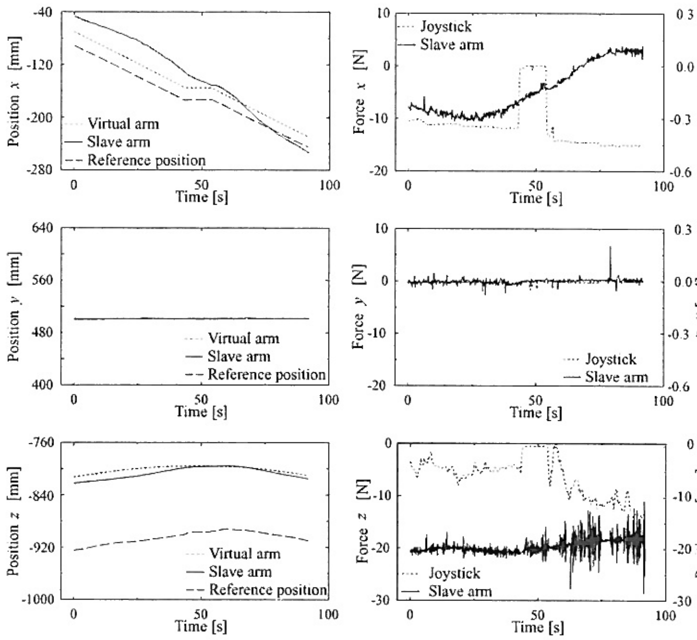

Figure 5: Surface-tracking task in the JS mode.

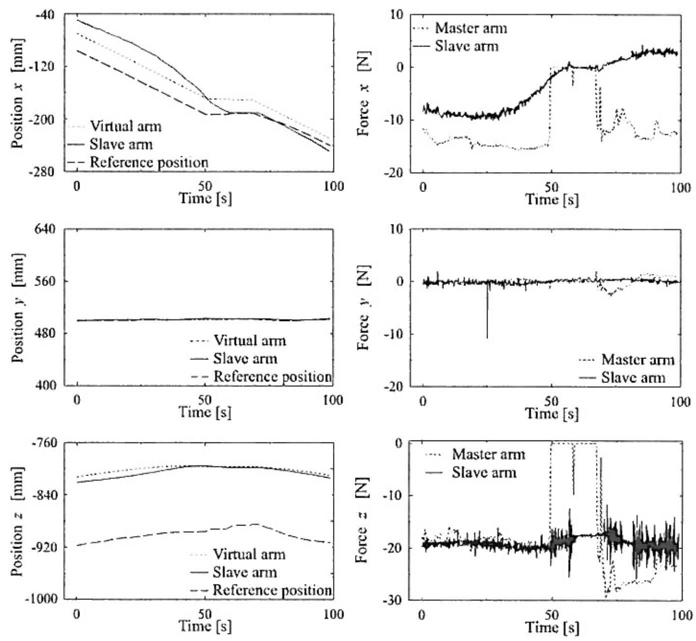

Figure 4: Surface-tracking task in the FJ mode.

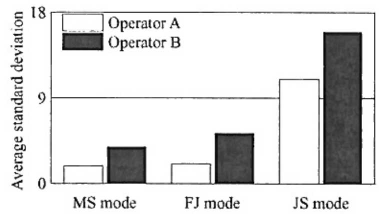

Figure 6: Average standard deviation of the master arm's forces in the surface-tracking task.

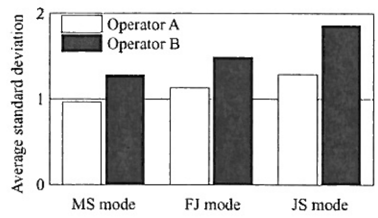

Figure 7: Average standard deviation of the slave arm's forces in the surface-tracking task.

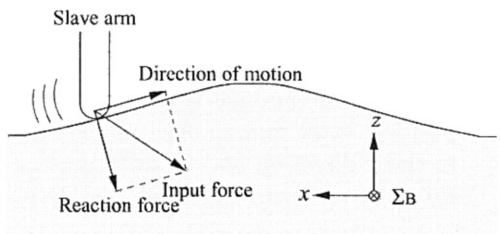

Figure 8: Motion and forces in the surface-tracking task.

- MS mode

  The operator can get the information about both the direction of the slave arm and the direction of the force exerted by the master arm. Therefore, the operator can easily adjust the input force direction.

- FJ mode

  The operator cannot get the information about the direction of motion of the slave arm through the master arm. Therefore, the standard deviation of the master arm's force becomes larger than that in the MS mode.

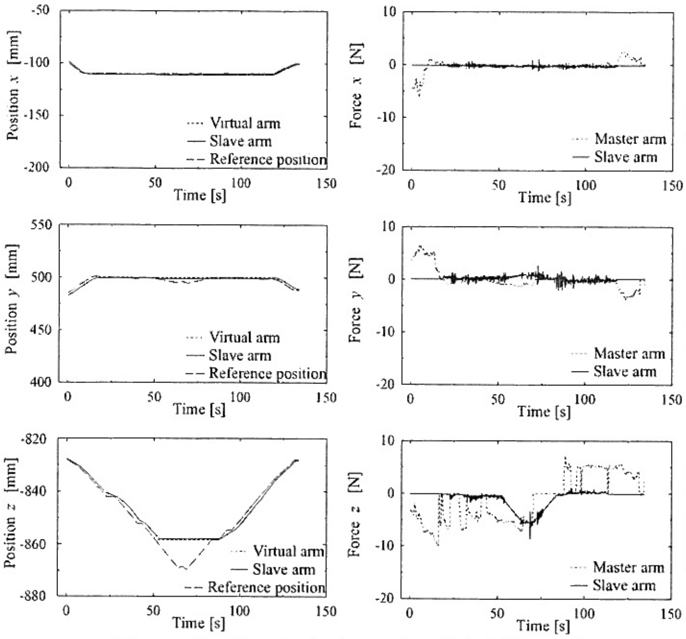

Figure 9: Peg-in-hole task with MS mode.

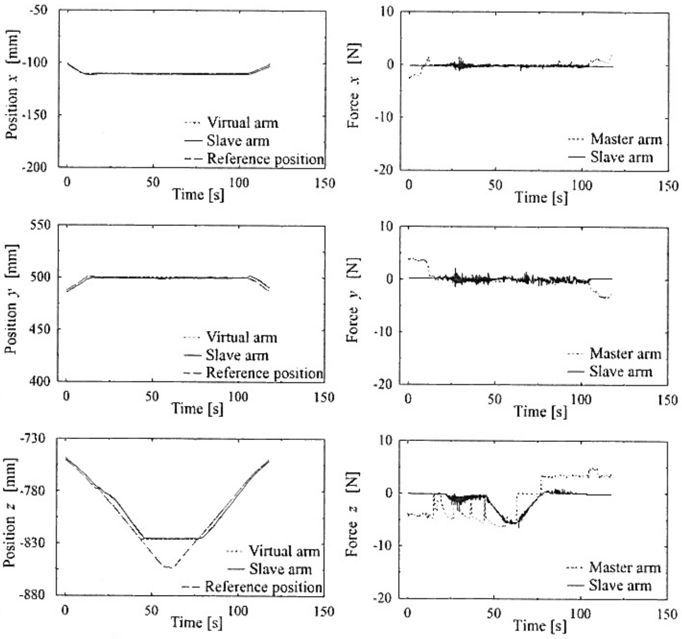

Figure 10: Peg-in-hole task with FJ mode.

- JS mode

  The operator cannot get the information about the direction of motion of the slave arm and the input force direction through the joystick. In this situation, it is very difficult to adjust the input force. Therefore, the standard deviations are biggest to the other modes. Thus, the JS mode is the most unstable of all modes.

From these results, it can be concluded that the MS mode is suitable for the contact tasks in which the direction of motion of the slave arm is different from that of the operator's input force command.

5.2 Peg-in-hole

The results of the peg-in-hole task executed using the MS, FJ and the JS modes of the master arm, are shown in Figs. 9, 10 and 11 respectively.

The profiles of both the virtual arm's position and the slave arm's position are coincident in all these three modes, as shown in Figs. 9, 10 and 11. The profiles of the slave arm's forces are also very much similar in all modes. The forces of the master arm are also similar in both MS and FJ modes. Moreover, the change in the command using the joystick in Fig. 11 resembles to the force using the master arm in Fig. 9 and Fig. 10. In order to compare the generated forces developed by the slave arm in the z-direction, the overall absolute values in all the peg-in-hole experiments are shown in Fig. 12. These values are average of the ten trials for both the operators and for each mode. These values are very similar in all modes. However, the operators expressed that the MS mode is more tiring than the FJ mode, but the MS and FJ modes are better than the JS mode.

Here, we describe about the motion and the force directions of both the master and the slave arms in the peg-in-hole task. Fig. 13 shows the direction of motion of the slave arm and the input force direction. The approach to the hole is a free space motion. Therefore, no significant differences appear in the three modes. During the peg insertion, the direction of motion of the slave arm and the input force direction are the same. For this reason, the operator can easily adjust the input force direction along the hole surface, whether he/she can get the motion information of the slave arm from the master arm or not. Therefore, it is thought that no significant differences appear among the three modes even in this process.

From these results, it can be concluded that there is almost no difference between three modes in the tasks in which the direction of motion of the slave arm is the same as that of the input force. However, the operators expressed that the FJ mode is more convenient than the MS and JS modes. Therefore, the FJ mode are suitable for above task.

6 Conclusions

In this paper, we performed the surface-tracking and the peg-in-hole tasks in order to evaluate the operability of the MS, FJ and JS modes in the model-based space teleoperation. We utilized both the motion and

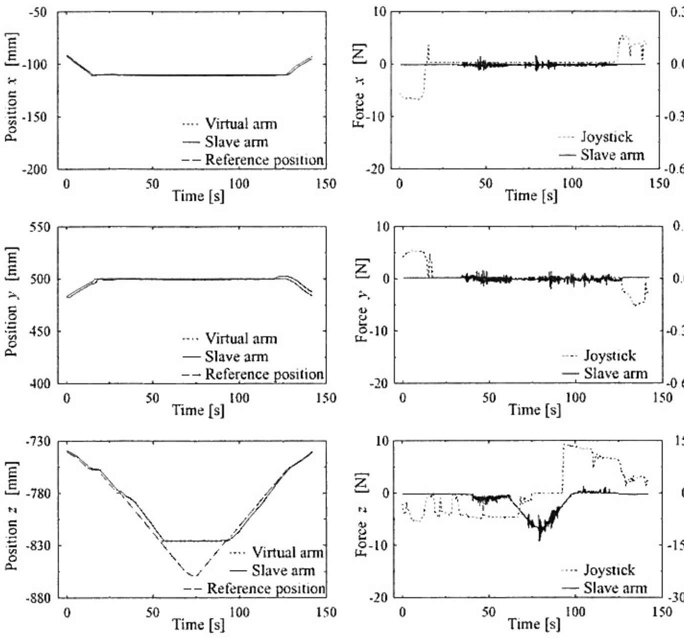

Figure 11: Peg-in-hole task with JS mode.

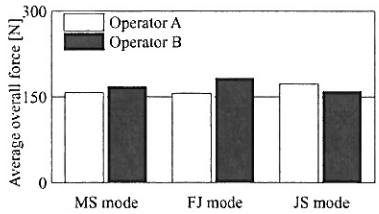

Figure 12: Average overall contact force of the slave arm in the peg-in-hole task.

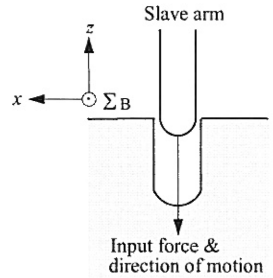

Figure 13: Motion and force in the peg-in-hole task.

force information from all arms for this evaluation. From the results, the MS mode appears to be the best control approach for the contact tasks which is the difference directions between the motion and the force of the slave arm, like the surface-tracking task. Moreover, the FJ mode is suitable for the tasks which is the same directions of the motion and the force of the slave arm, like the peg-in-hole task.

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