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Contact Task by Force Feedback Teleoperation Under Communication Time Delay

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1. Introduction

Space robot systems are performing and expected to perform important missions, for example, large-scale structure on-orbit construction (as in the International Space Station or the Solar Power Satellite) and on-orbiting servicing tasks in Low Earth Orbit (LEO). It is difficult to develop an intelligent robot, which performs various tasks autonomously in complex environments. Current technology makes necessary to rely on human operator for providing overall task guidance and supervision, and for handling special situations. The benefits of teleoperation of a space robot have already been proved many times by Shuttle Remote Manipulator System, which is operated by astronauts inside the spacecraft to perform complex tasks, such as satellite handling and repairing (Ravindran, R. & Doetsch K. H., 1982).

Controlling space robots from ground is potentially much more effective than controlling them in space (Sheridan, T. B., 1993). There are many advantages: first, the total hourly cost of a ground operator is orders of magnitude lower than that of an astronaut in space; second, ground control stations can have greater computing resources available; third, ground teleoperation permits to reduce crew workload; and forth, ground control permits terrestrial scientists to perform remotely experiments, etc. Hence, ground control of space robots seems very attractive, but on the other side there are some important drawbacks or limitations that must be overcome: (i) communication time delay; (ii) a low communications bandwidth; (iii) lack of telepresence with difficult control in operation.

Under such a condition, special attention should be paid to contact forces and torques when performing contact task with a space-based manipulator teleoperated from ground. Therefore, the manipulator should be controlled autonomously with compliance feature. Note that some sort of compliance feature on the manipulator, either active or passive, is effective for contact task. Compliance is useful to cope with the error caused by an imperfect model. It can reduce execution time and overall forces applied upon the environment. The only problem is that it consists of an automatic remote feature and the operator can get confused if not fully aware of its behavior. Experimental researches for teleoperation have been well studied. The robot in the German space robot experiment, ROTEX, which was teleoperated both from within the space shuttle by an astronaut and from ground by an operator, was equipped with a force/torque sensor (Hirzinger, G. et al., 1993). In addition, ground-based experimental studies on teleoperation under time delay have been performed

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as in (Hannaford, B., 1994), (Funda, J. et al., 1992), (Hirata, M. et al., 1994), also under time varying (Hirche, S. & Buss, M., 2004). The Engineering Test satellite VII, which was launched at the end of 1997 by the National Space Development Agency (Oda, M. et al., 1998), performs the most recent experiment for space teleoperation.

This paper describes experimental analysis of a new strategy for space teleoperation under communication time delay, which makes it possible for an operator to notice contact through force reflection of a hand controller. In experiment, contact force display and command input of a hand controller were focused. Organization of the paper is the following. Section 2 explains the concept, the algorithm, and virtual images of the proposed approach. Section 3 introduces our teleoperation system for experiment. Teleoperation experiment of vertical contact to target is described in section 4 and section 5, in order to examine effectiveness of force contact display and command input, respectively. Section 6 describes teleoperation experiment of tracking task.

2. Important Teleoperation by Force Reflection

2.1 Concept of the proposed approach

In teleoperation for a space-based manipulator from ground, a ground operator sends a command to the manipulator, which executes it. After duration of communication time delay, the operator receives telemetry data as a result of manipulator motion. Then, the current telemetry data is result of the command data sent before duration of the time delay, when sending the current command. In the proposed teleoperation approach, difference of the current command and the current telemetry is displayed to the operator by force reflection through a hand controller. The manipulator is moving or begins to move when an operator feels force reflection. On the other hand, when contact force is applied to the manipulator, it is added to force reflection of the time delay. In operation without contact, force reflection becomes to be zero when receiving telemetry data expressing that the manipulator finishes its motion. Under condition of contact, force reflection continues to be applied even if the manipulator stops its motion. Also, an operator feels change of force reflection when contact of the manipulator occurs, when a contact force applied to the manipulator is reduced, and when the manipulator is moving. Thus, the operator can know conditions of the manipulator. In order to apply the proposed approach, autonomous compliance control has to be used for the remote manipulator.

2.2 Force feedback algorithm

Figure 1 shows a data flow chart of the proposed approach. The following kinds of data are defined:

x_c : "command" operated by joystick;

x_r : "reference" point for compliance control ;

x_t : "telemetry" as a result of manipulator motion;

f : contact force applied to a remote manipulator;

f_a : contact force used for force feedback calculation;

$\boldsymbol{F}$: force reflection on a hand controller.

Two kinds of f_a can be obtained from force sensor f and compliance calculation K (x_t - x_r), respectively, they are examined in section IV. M, C, K denotes parameters for compliance control. k_t is control gains for calculation of force reflection of a hand controller. Teleoperation computer calculates command x_c from hand controller operation. x_c is sent to remote computer and compliance control is performed by reference x_t (= x_c). x_t, x_r, f are sent from remote computer to teleoperation computer as telemetry data, which is used for calculation of force reflection F of a hand controller.

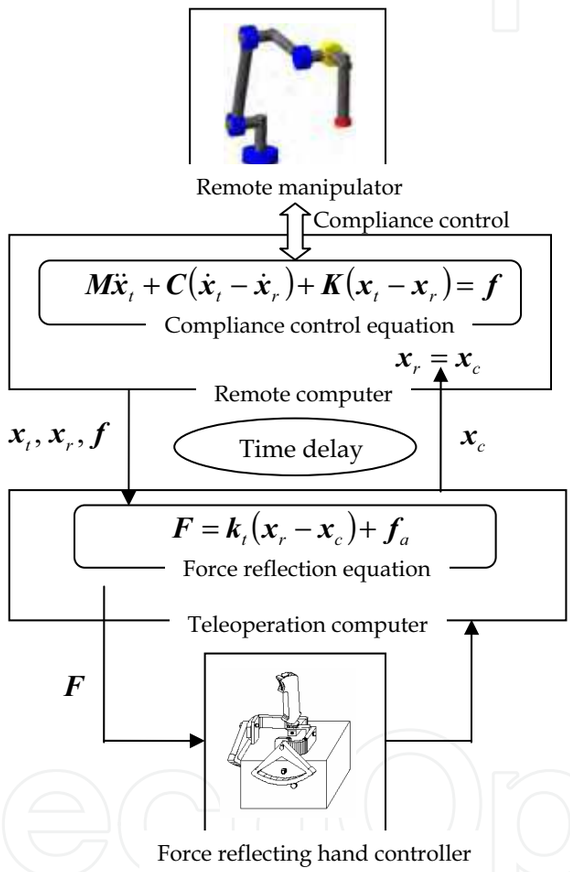


Figure 1. Data flow in force feedback teleoperation

2.2 Virtual feelings for operation

Figure 2 shows image of the proposed teleoperation approach without contact. A remote manipulator is operated as if the operator moves it through a virtual spring. The left figure shows command and telemetry manipulators. Sending command and receiving telemetry data configure them, respectively. The difference of command x_c and telemetry x_r of the

manipulator end tip positions are translated to extension of the virtual spring, which generates force reflection of communication time delay. As a result, the operator can recognize the time delay by extension of the virtual spring. The manipulator has executed the command when force reflection becomes to be zero, and then the operator feels no forces.

Figure 3 shows image when performing a contact task. The left side figure shows command x_c, telemetry x_t, and reference x_r manipulators. The reference manipulator denotes the command one sent before duration of the time delay. Both differences due to contact force and the time delay are translated to extension of the virtual spring, which generates force reflection. When the manipulator is moving, the operator feels that length of the virtual spring is changing, not constant. When the manipulator stops, and external force/torque is applied to the manipulator, the operator feels that the virtual spring is extended at constant length. Thus, the operator can know conditions of the manipulator.

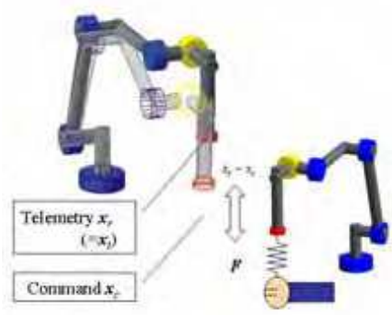


Figure 2. Virtual feeling of communication time delay without contact

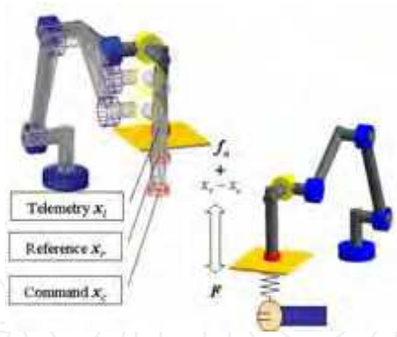


Figure 3. Virtual feeling of communication time delay with contact

3. Experimental System

Figure 4 shows the experimental teleoperation system. PA-10 (product of Mitsubishi Heavy Industry Ltd.), which is controlled on the MS-DOS, is used as a remote manipulator. Impulse Engine 2000 (product of Nissho Electronics Ltd.) is used as a hand controller. This is a joystick controlled on the Windows 2000 by an operation computer, and it has two

degrees of freedom, and also it can reflect forces to an operator. Figure 5 shows Impulse Engine 2000 in the left side and PA-10 in the right.

An operator inputs command through the joystick into the operation computer, and the command is buffered in the operation computer during duration of communication time delay, which is set for simulating space teleoperation from ground under the time delay. Then, the command is sent to the remote computer, and the manipulator executes it. As a result of manipulator motion, reference and telemetry data are sent from the remote computer to the operation computer. The joystick reflects force calculated on the operation computer based on information of telemetry data received from the remote computer, and the command input by the operator.

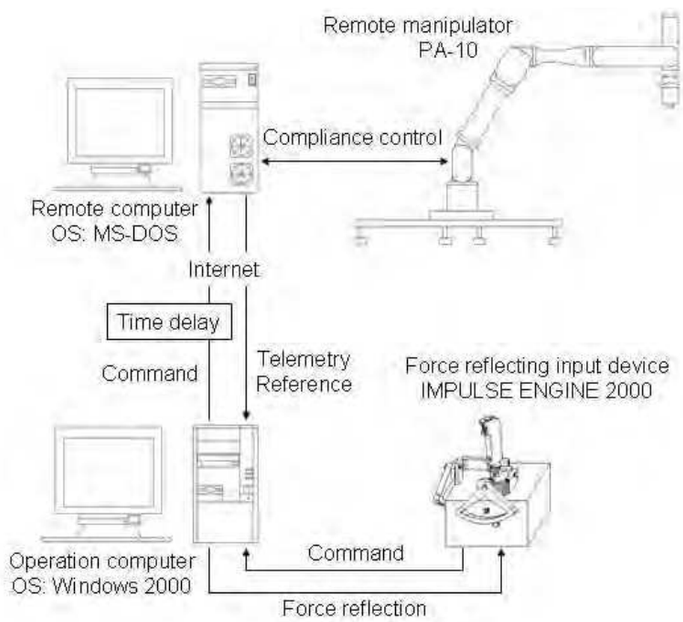


Figure 4. Experimental system for teleoperation

Figure 5. Experimental hardware

4. Force Telemetry

4.1 Experimental settings

The first experiment was performed to examine effectiveness of force reflection calculated as following cases:

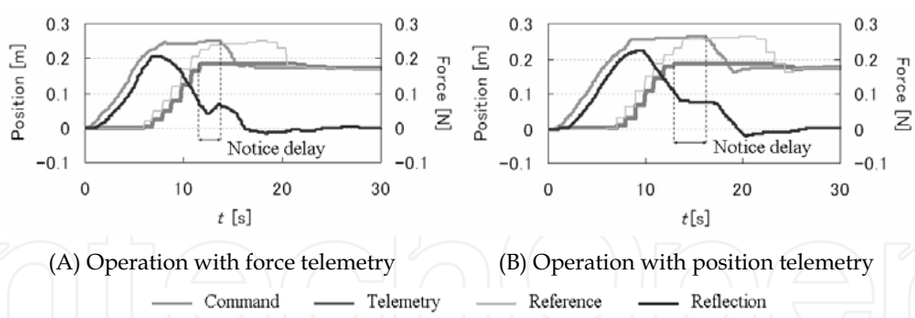
(A) $\boldsymbol{f_a} = \boldsymbol{f}$;

(B) $\boldsymbol{f}_a = k_c(\boldsymbol{x}_c - \boldsymbol{x}_t)$,

where k_c is control gain, and set as $k_c = k_t$. Force sensor value is used in case (A), and compliance calculation is employed in case (B). Experiment is vertical contact to target. Here, operation was performed based on "sequential manipulation," explained as follows. An operator terminates the first command which overshoots the target surface, before the manipulator begins to move. Then, the operator begins to send the second command to reduce contact force, after the manipulator stops its motion by the first command. Also it is terminated before the manipulator begins to move.

4.2 Experimental result

Figure 6 shows time history of an example data in the experiment. Here, command input by joystick was position. Reference $\boldsymbol{x}_r$ followed command $\boldsymbol{x}_c$ after the 5 seconds time delay. Telemetry $\boldsymbol{x}_t$ followed reference $\boldsymbol{x}_r$ with errors due to the compliance motion, and then it stopped at the contact point. The operator sends command to reduce contact force as soon as he notices contact. Then, "notice delay" shows that time delay for recognition of contact by the operator.



(A) Operation with force telemetry (B) Operation with position telemetry

Figure 6. Time history of experimental result in cases (A) and (B)

Figure 7 shows averages and standard deviations of "notice delay" for three times trial by three operators. From the result in figures 8 and 9, it is noted that an operator notices contact more accurately in case of (A) f_a = telemetry force sensor. The reason is explained in figure 7 that change of the force reflection is sharper in case of (A) than that in case of (B) when the manipulator makes contact.

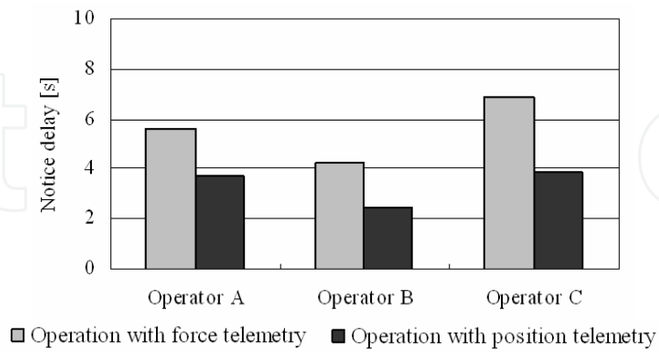


Figure 7. Average of notice delay in cases of (A) and (B)

5. Command Input

5.1 Experimental settings

The second experiment was performed to examine difference of hand controller input:

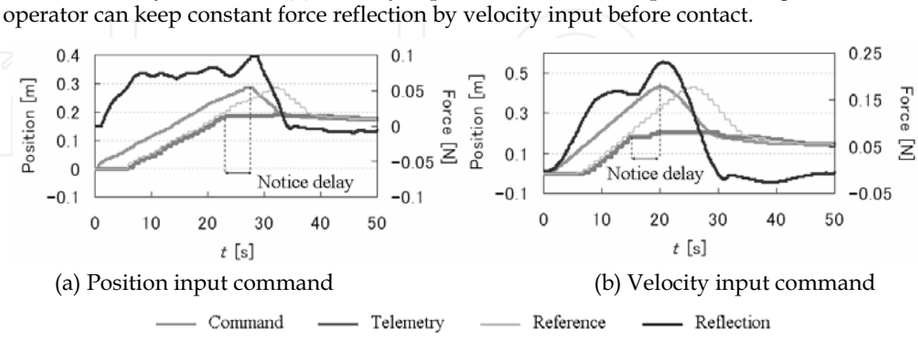
(a) position command;
(b) velocity command.

Experiment is vertical contact to target. Here, operation was performed based on "continuous manipulation," explained as follows. The manipulator begins to move during sending the first command. An operator sends the second command to reduce contact force as soon as the contact is noticed.

5.2 Experimental result

Figure 8 shows time history of an example data in the experiment. Here, force reflection was based on position telemetry (B). In this experiment, the operator sends opposite command to reduce contact force during sending progressing command, as soon as he notices contact. Then, "notice delay" also shows that time delay for recognition of contact by the operator.

Figure 9 shows averages and standard deviations of "notice delay" for three times trial by each operator. From the result in figures 8 and 9, it is noted that an operator notices contact more accurately in case of (b) velocity input. The reason is explained in figure 8 that an operator can keep constant force reflection by velocity input before contact.



(a) Position input command (b) Velocity input command

Figure 8. Time history of experimental results in cases of (a) and (b)

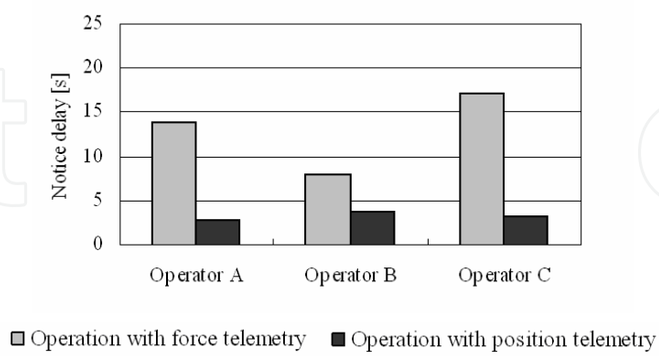


Figure 9. Average of notice delay in cases of (a) and (b)

6. Tracking Task

6.1 Experimental settings

The final experiment was performed to examine tracking task by the proposed teleoperation approach. Figure 10 shows image of the experimental task. Operation is tried as follows. First, the manipulator begins to move downward along the z axis (in figure 5). After the manipulator makes contact with slope, it is operated to track the slope. The tracking task was performed under the following condition:

(i) without force feedback by position command;
(ii) force telemetry feedback by position command;
(iii) position telemetry feedback by position command;
(iv) force telemetry by velocity command;
(v) position telemetry by velocity command.

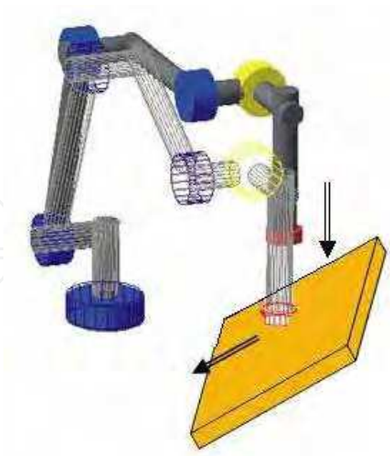


Figure 10. Tracking task

6.2 Experimental result

Figure 11 shows example data of tracking task in experiments (i) – (v). It is noted that smooth operation is possible by force feedback. Command input was adjusted many times, and then command line became discontinuous. Because force feedback based on force sensor is noisy and sensitivity, operation is smoother in cases (ii) and (iv) than that in cases (iii) and (v), respectively. On the other hand, contact point was recognized more accurately in case (ii) and (iv) when force sensor value is used for force feedback. It is also noted that delicate operation is possible by position command in cases (ii) and (iii), compared to operation by velocity command in cases (iv) and (v).

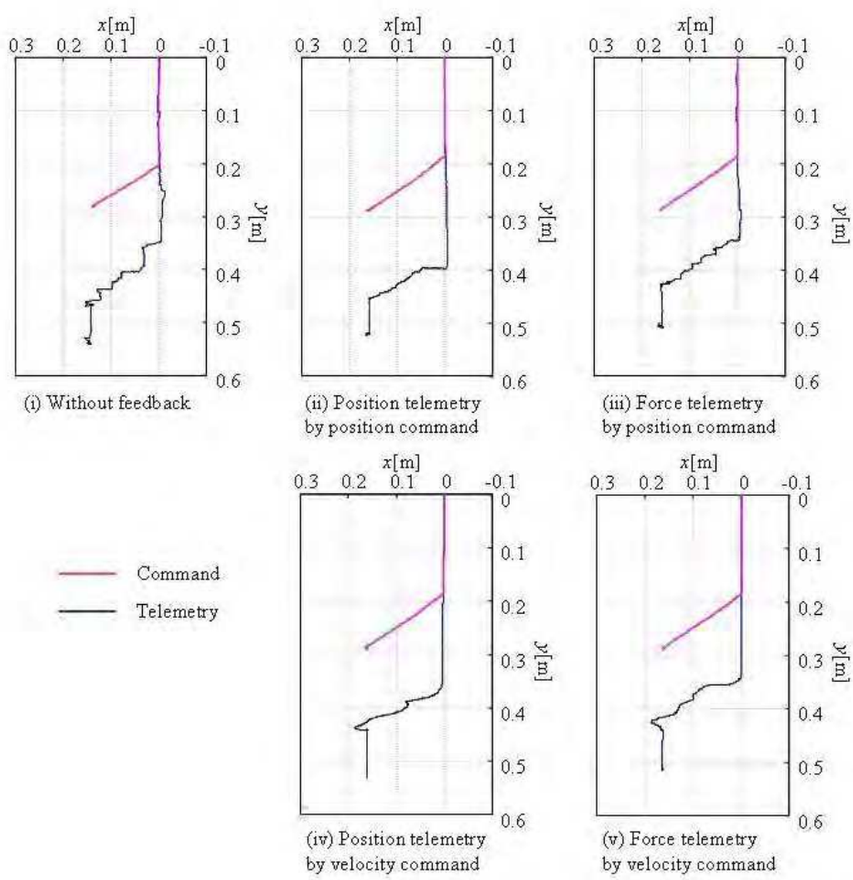


Figure 11. Experimental result of tracking task

7. Conclusion

This paper discusses our proposed strategy for space teleoperation under communication time delay, which makes it possible to know conditions of a remote manipulator through force reflection. In the proposed approach, the communication time delay and a contact force are displayed to the operator by the force reflection, and the remote manipulator can be operated as if the operator moves it through a virtual spring.

By experimenting example tasks, characteristics and effectiveness of the proposed approach have been clarified. From experiment of vertical contact with target, it is noted that an operator notices contact more accurately when;

(i) force reflection is calculated based on telemetry of force sensor;

(ii) command input by velocity.

Also, it is noted from tracking task that smooth operation is possible by force feedback. Also, operation based on position telemetry feedback is smoother than that based on force telemetry feedback, and delicate operation is possible by position command

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