AIAA Journal
Vol. 40, No. 2, February 2002

Teleoperation of a Truss Structure by Force Command in ETS-VII Robotics Mission

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In space teleoperation under time delay, performance differs significantly for the various control techniques, for example, 1) compliance control by a position/orientation command and 2) force control by a force/torque command. With the latter control technique, the robot arm moves toward the point where the external force/torque applied to the end effector becomes equal to the commanded value. This technique is effective for tracking a restricted trajectory or in peg-in-hole insertion, even though the teleoperation is performed under time delay. The effectiveness of force control is discussed. Experimental results for verification based on an on-orbit experiment for deploying and assembling a truss structure on the Engineering Test Satellite VII (ETS-VII) are presented. To perform the deployable truss operation task within the strongly limited experimental time on ETS-VII, it is necessary to choose the timing of sending commands and the direction of forces in correspondence to the current truss configuration. It is also shown that force control is effective for truss insertion during a truss assembly task, regardless of the time delay.

I. Introduction

WHEN performing contact tasks with a space-based manipulator teleoperated from the ground under the condition of time delay, special attention should be paid to contact forces and torques.[1] The space shuttle remote manipulator system, used mainly to deploy and capture satellites, does not comprise a force/torque sensor.[2] The robot arm 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.[3] In addition, ground-based experimental studies on teleoperation with time delay have been performed as in Refs. 4–6. From those studies it became apparent that to avoid excessive forces and torques during the contact task, either compliance control or force control should be used. Under compliance control, the robot arm attains the desired configuration based on the commanded position and orientation. When contact is established, existing modeling errors may lead to excessive forces and torques. These can be suppressed by the compliance control algorithm, which relies on information obtained from a force sensor attached to the end effector. On the other hand, under force control, the robot arm moves toward the point where the external force/torque applied to the end effector becomes equal to the commanded force/torque. This control technique can be used when the motion of the robot arm is restricted by external constraints, and it is effective from the viewpoint that excessive forces and torques can be suppressed. Force control, however, cannot be used when the robot arm motion is unrestricted, for example, in orbital replacement unit replacement tasks.

The National Aerospace Laboratory performed experiments for teleoperating a truss structure[7] (see Fig. 1) as a part of the robotics mission on the Engineering Test Satellite VII (ETS-VII).[8] The robotic satellite was launched in November 1997 by the National Aerospace Development Agency of Japan. A truss is suitable for constructing large-scale structures in space because of its lightness and compactness and because the truss can easily change its configuration. On-orbit construction of a truss structure is based on a sequence of mainly deploying and assembling tasks to be performed by means of a space robot teleoperated from the ground. The ETS-VII robot arm was equipped with a force-command-based force-control function called force accommodation control. This is quite a specific control law developed especially for the ETS-VII robot arm.[9] Note that force control is considered appropriate during truss operation because the motion of the robot arm is restricted to comply with the prescribed motion of the truss.

Our goal in this paper is, first, to clarify problems related to the effectiveness of teleoperation under time delay and force control based on force command input and, second, to discuss practical aspects of this effectiveness based on the truss teleoperation experiments on ETS-VII, using the force accommodation control method. The structure of the paper is as follows. Section II is devoted to the effectiveness problem. Sections III and IV explain the deployable and assembly trusses on ETS-VII and show experimental results, respectively, especially focusing on the application of the force accommodation control method.

II. Force Command in Teleoperation

A. Suppressing an Excessive Force

When performing a contact task under teleoperation with time delay, attention should be paid to forces and torques. The reason is that the actual forces or torques on the robot arm on orbit may become larger than those monitored on ground. Also, note that accurate trajectory tracking is required when compliance control is used; otherwise, excessive forces or torques will be generated due to the trajectory errors.

We refer now to Fig. 2. The solid line shows the restricted trajectory, and the dotted line describes the trajectory obtained via simulation. The difference between these two trajectories is assumed to be the modeling error. Let us assume that the commanded positioning sequence is (a) → (b) → (c) → (d), that compliance control is used, and that the motion is monitored on the ground. Note first that no force is generated when both the commanded and the current position are located at (a). When the command reaches position (b), the current position remains at (a) due to the time delay. The current position then moves to (B) along the restricted trajectory while the command reaches (c), and the on-ground operator observes the force f_b. Then, the operator will adjust the commanded motion from (d) to

Received 2 June 2000; revision received 7 May 2001; accepted for publication 17 July 2001.

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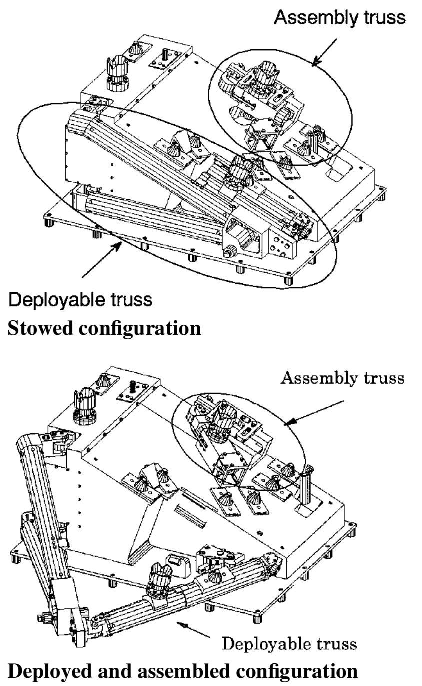

Fig. 1 Truss experimental unit on ETS-VII.

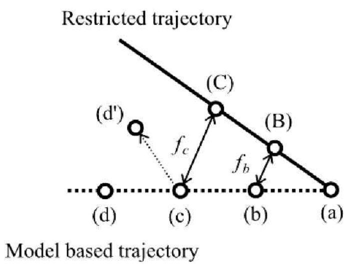

Fig. 2 Excessive force occurred when using compliance control.

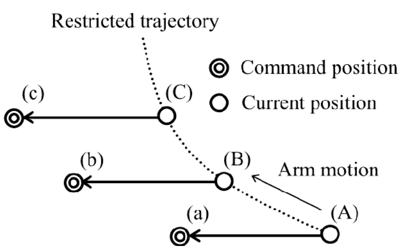

Fig. 3 Tracking a restricted trajectory using force command operation.

(d′), but, nevertheless, the force f_c cannot be avoided. On the other hand, note that when using a force command, the aforementioned excessive motion can be avoided because the maximum force is determined by the commanded value.

B. Restricted Trajectory Tracking

Under force command control, continuous motion of the robot arm is possible when tracking the restricted trajectory. As shown in Fig. 3, the current position u moves from (A) along the restricted trajectory, when the command position u_c is set at (a). With compliance control, the current position u stops around (B) because the commanded position u_c remains at (a) due to the time delay, until the next command is sent from the ground. When using force command control, however, the commanded position u_c will be at (b) when the current position u is at (B), and u_c will be at (c) when u is at (C). It becomes apparent that the robot arm motion continues regardless of the time delay.

C. Peg-in-Hole Insertion

Force control by a force command is useful in such a restricted-motion task as peg-in-hole insertion. Note that a large friction force will occur during the truss insertion task. Consequently, the robot

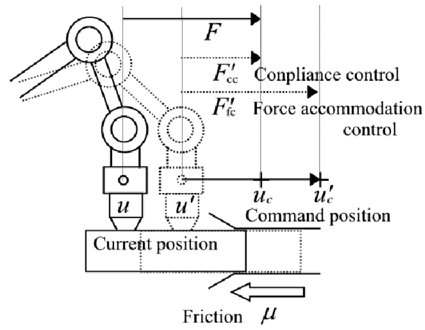

Fig. 4 Peg-in-hole by force command operation with time delay.

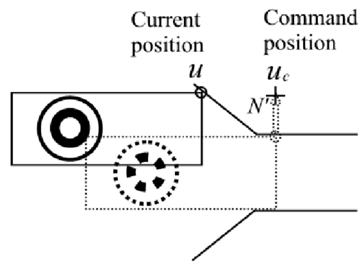

Fig. 5 Side force by force command operation.

arm has to apply a force exceeding the friction force. At the same time, however, any excessive force should be suppressed. Now we refer to Fig. 4. The truss begins to move when $F > \mu$, and the current position moves from u to u'. Under compliance control, the commanded position u_c is maintained until the next command is sent from the ground. As a result, F decreases to F'_{cc}, and the motion stops because $F'_{cc} < \mu$. On the other hand, under force control, when the current position moves from u to u', the commanded position u_c will move to u'_c (using onboard computer calculation), and, consequently, the motion will continue because $F'_{fc} > \mu$. It becomes apparent that under force control the insertion process will continue regardless of the time delay.

Also note that the lateral force (which causes the friction force) will be canceled using a zero force command. As shown in Fig. 5, such a lateral force occurs under compliance control when the truss moves along the tapered guide part.

III. Force Accommodation Control of the ETS-VII Robot Arm

The ETS-VII robot arm comprises force control functions, based on information from the force sensor attached to the end effector. The force-feedback algorithm of the ETS-VII robot arm is described as

$$m\ddot{u} + c(\dot{u} - \dot{u}_c) + k(u - u_c) = f \tag{1}$$

where m, c, and k denote compliance parameters; u_c denotes a position/orientation command; and f denotes the external force applied to the end effector and measured by the force sensor. The onboard computer calculates u, which is the end-effector position and orientation of the robot arm.

Two main force control functions are compliance control and force accommodation control. The respective commands sent from the ground are u_c for compliance control and f_c (a force/torque command) for force accommodation control. The onboard computer calculates u_f as

$$u_f = u + f_c/k \tag{2}$$

u_c moves forward to u_f at a speed v_f, and the motion of the robot arm follows Eq. (1). Each control function can be independently set on each of the axes of the end-effector fixed frame. At the same time, a force/torque command should be determined for the force accommodation control. The control function and the force/torque command cannot be changed while the robot arm moves.

IV. Deployable Truss Operation

A. Trajectory of Deployable Truss

Figure 6 depicts the steps for deploying the deployable truss on ETS-VII. The satellite base fixed frame and the end-effector fixed

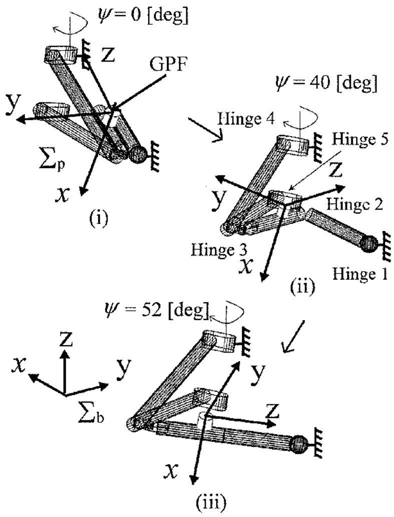

Fig. 6 Deploying steps of the truss operation task.

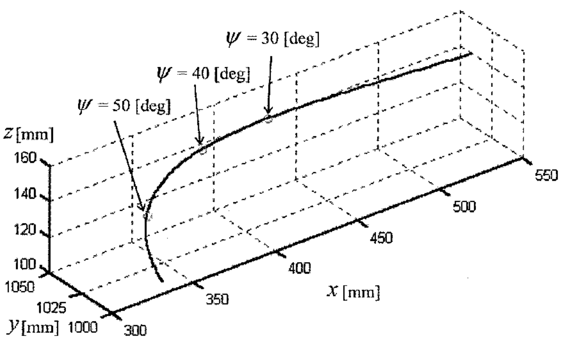

Fig. 7 GPF translational trajectory.

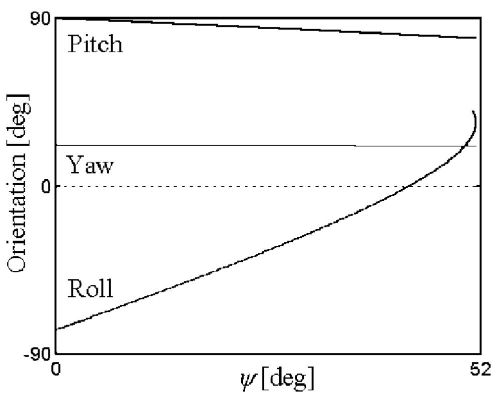

Fig. 8 GPF orientation trajectory.

frame are denoted as Σ_b and Σ_p, respectively. During truss operation, the robot arm grasps the grapple fixture (GPF), which means that the Σ_p frame will be affixed to the GPF. The GPF has one degree of freedom (DOF) due to its hinge composition. The current configuration of the truss can be verified by angle ψ at hinge 4, measured by a potentiometer attached to the hinge, $\psi = 0$, 40, and 52 deg at configurations a, b, and c, respectively.

Figure 7 shows the GPF translational trajectory in the three-dimensional frame Σ_b. Note that the trajectory represents a spline. Figure 8 shows the GPF orientation in the Σ_b frame, denoted as roll, pitch, and yaw vs ψ. Here, ψ is determined from the GPF position as shown in Fig. 7, hence, the GPF orientation should be determined from Fig. 8. Conversely, the GPF position is determined by the GPF orientation. Therefore, the GPF position and orientation have always only one DOF during the deployable truss operation. Because the GPF translational trajectory is a spline and also because position and orientation are coupled, it will be difficult to obtain an accurate trajectory of the deployable truss.

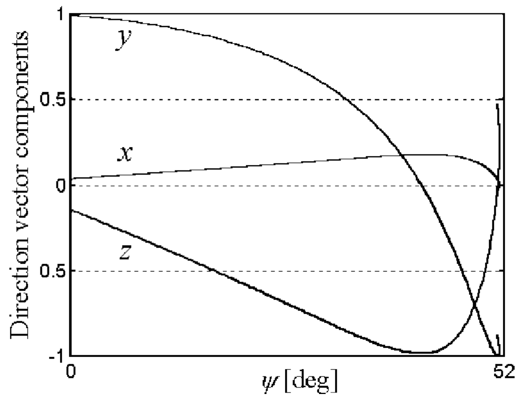

Fig. 9 Direction of the GPF translational trajectory on end-effector fixed frame.

B. Deployable Truss Operation Using Force Accommodation Control

1. Characteristics of Deployable Truss Trajectory

Note here that force and torque applied to the GPF will be coupled during the truss deployment operation task because both position and orientation are restricted. Therefore, the strategy used is as follows: The truss is operated applying a translational force, and at the same time, the orientation is adjusted to suppress the torque coupled with the translational force.

Depending on the deployable truss configuration, the direction of the translational trajectory will change. Likewise, Σ_p changes with changes in the orientational trajectory, as shown in Fig. 8. The desirable force command should be set along the tangential direction of the translational trajectory. Figure 9 shows the unit vector components in the direction of the translational trajectory in the Σ_p frame. Note that the force command should be set mainly along the y and z axes because variations along the x axis are relatively small. Note also that the translational trajectory directions are different for the stowed and deployed configurations. This can be easily understood from Fig. 6, when the orientation of the Σ_p frame in configurations a and b are compared.

2. Teleoperation Aid for Sending a Force Command

To achieve the deployable truss operation task in the limited experiment time for ETS-VII because of its communication, the desirable force command, whose direction is along the deployable truss trajectory, should be sent when the robot arm motion becomes slow. The following two visual aids are used for assistance when sending a force command. First, the end-effector velocity of the robot arm is displayed to monitor the robot arm motion. When this velocity becomes one-quarter of v_f, then the next force command is sent. Second, trajectory history and current orientation of the end effector are displayed. The operator selects a force command with about $\pi/4$ accuracy. This accuracy is sufficient because force control by force command does not require high-accuracy trajectory information.

C. Experimental Result of the Deployable Truss Operation and Deployable Truss Deployment

Figures 10 and 11 show the results of the truss deployment and stowage operation tasks, respectively. In both tasks, force accommodation control has been used. Force telemetry data from the force sensor are denoted as F_x, F_y, and F_z along the x, y, and z axes, respectively. Angular telemetry data of the deployment obtained from the potentiometer are denoted as ψ. Here, v denotes the end-effector velocity calculated from the time history of the joint angles of the robot arm. Force accommodation control has been applied along the three translational axes x, y, and z. The speed of approach of u_c toward u_f is set as $v_f = 1$ mm/s. The orientation is controlled via a joystick to suppress unnecessary torques.

For the deployment operation task in Fig. 10, the following force commands were sent: step 1, $x = 0$, $y = -10$, and $z = 10$ N; step 2, $x = 0$, $y = 0$, and $z = 15$ N; and step 3, $x = 0$, $y = 10$, and $z = 10$ N. Note that due to the time delay, it takes a few seconds in each step to start the robot arm motion after the ground command is sent. Note

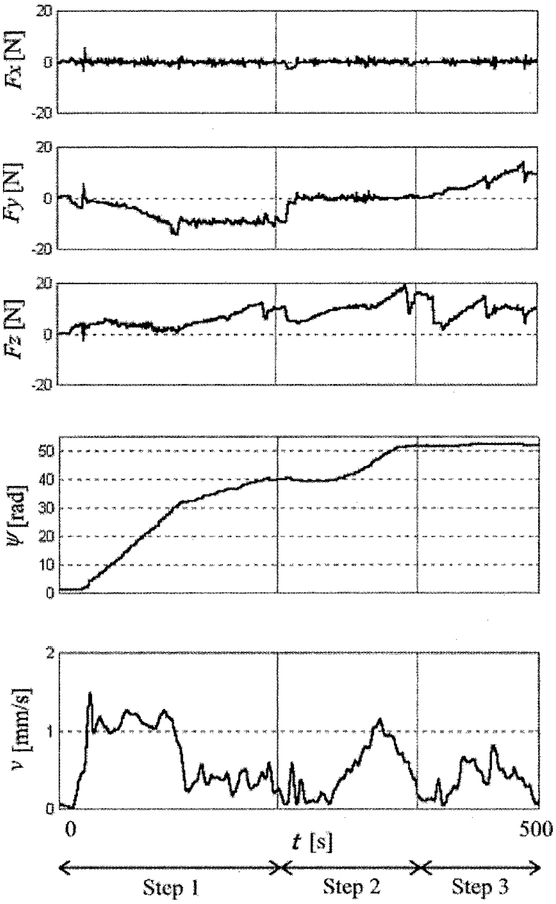

Fig. 10 Telemetry data of the truss deployment operation task using force accommodation control.

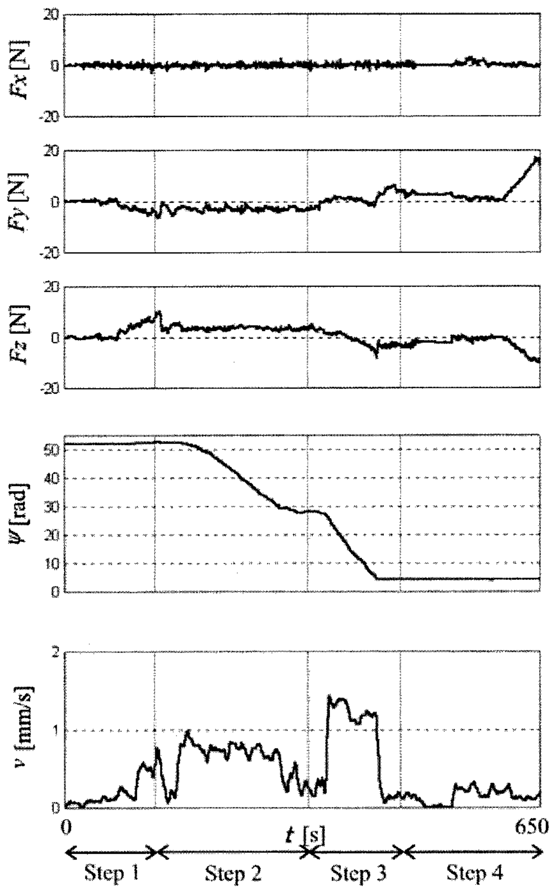

Fig. 11 Telemetry data of the truss stowage operation task using force accommodation control.

also from the force telemetry data that the force increases gradually to reach the commanded values. This is because force command direction deviates from the GPF translational trajectory. The end-effector velocity is about 1 mm/s when no external force is applied; it becomes small when an external force is applied and finally becomes zero when the force telemetry data reach the commanded value. Therefore, we can conclude that monitoring the end-effector velocity was useful for evaluation of the robot arm motion. During step 1, the end-effector velocity becomes small when the force F_y from the telemetry data reaches the force command, although

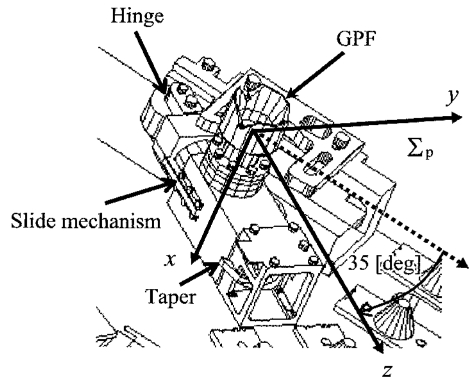

Fig. 12 Design of assembly truss.

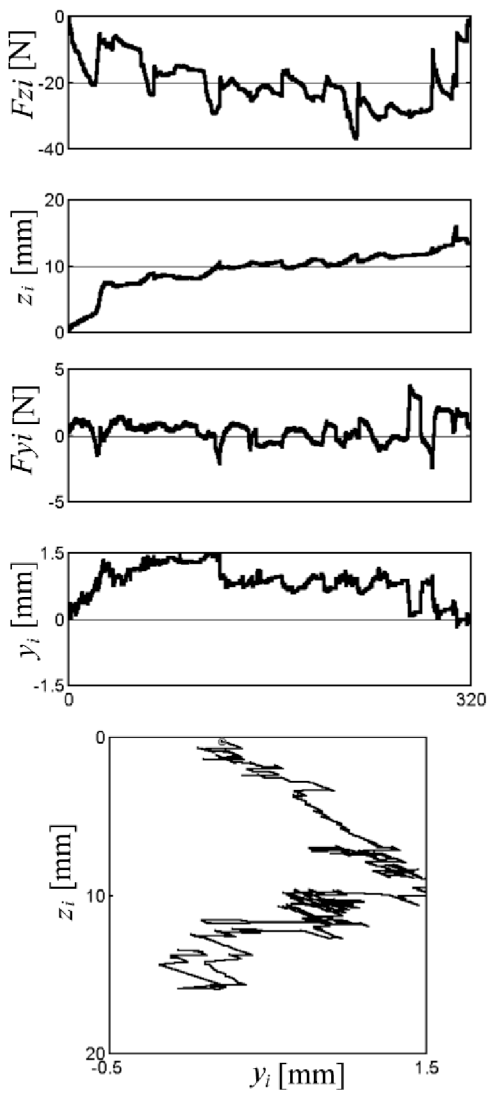

Fig. 13 Telemetry data of the truss insertion with compliance control in experiment 1.

the force F_z from the telemetry data does not reach its commanded value. The reason is that each axis is controlled independently.

For the stowage operation task in Fig. 11, the unlock operation of the GPF was required during step 1 in Fig. 11, and the operation to overcome the stowed lock mechanism was also required during step 4 in Fig. 11. Force accommodation control was used for operation in steps 2 and 3, and the force command values sent were step 2, $x = 0$, $y = -3.5$, and $z = 3.5$ N and step 3, $x = 0$, $y = 3.5$, and $z = -3.5$ N. From the result during step 2, it becomes apparent that the end effector kept its velocity after the force from the telemetry data reached the commanded value. Also note that in the stowage task a force smaller than that in the deployment task is needed. The reason is that the torque due to the rotational springs attached to hinges 4 and 5 acts toward the stowed configuration.

V. Assembly Truss Operation

A. Design of the Assembly Truss

Figure 12 shows the design of the assembly truss. When the robot arm grapples the GPF, the Σ_p frame will be fixed to the GPF, as shown in Fig. 12. Note that the rotation around the hinge and the translation along the slide mechanism restrict the GPF motion in the direction of the y and z axis, respectively. The assembly truss has two DOF in the yz plane within the Σ_p frame. The sequence of the truss assembly is as follows:

1) The truss is rotated around the hinge about 35 deg.

2) The truss is inserted into the hole along the z axis about 15 mm.

During sequence 1, the robot arm has to apply the force to the truss because of the rotational spring attached to the hinge. Because of the spring torque, the truss will be stowed by itself, if the robot arm releases the GPF just after sequence 1. The hole has a tapered guide part. The truss moves along this guide, as in sequence 2.

B. Experimental Result of Truss Insertion

The following three experiments were performed: 1) compliance control at $u_c = 2$ mm/s, 2) force accommodation control with the maximum speed $v_f = 1$ mm/s, and 3) force accommodation control with the maximum speed $v_f = 0.3$ mm/s.

Experiment 1 was performed to compare the performance under force accommodation control and compliance control. A translational force is required in the yz plane to insert the truss into the hole. The force command value for force accommodation control is $y = 0$ and $z = -20$ N in the Σ_p frame. Telemetry data for force and position along the direction of truss insertion (denoted by the z_i axis), along the vertical direction (denoted by the y_i axis), and the GPF trajectory in the $y_i z_i$ plane are shown in Figs. 13–15 for experiments 1–3, respectively.

It becomes apparent that the truss repeats the inserting motion twice in experiment 2. First, the force F_{zi} increases gradually. Then the truss begins to move along the z_i axis when F_{zi} becomes large enough to overcome the friction force. At the same time, force F_{zi} begins to decrease. Soon, the truss motion slows down. When force accommodation control is used, as soon as F_{zi} decreases, the motion speeds up again. Hence, the truss begins to move again, which constitutes the second motion of truss insertion. Note, however, that when using the compliance control, the force F_z does not increase because the commanded position does not change. Therefore,

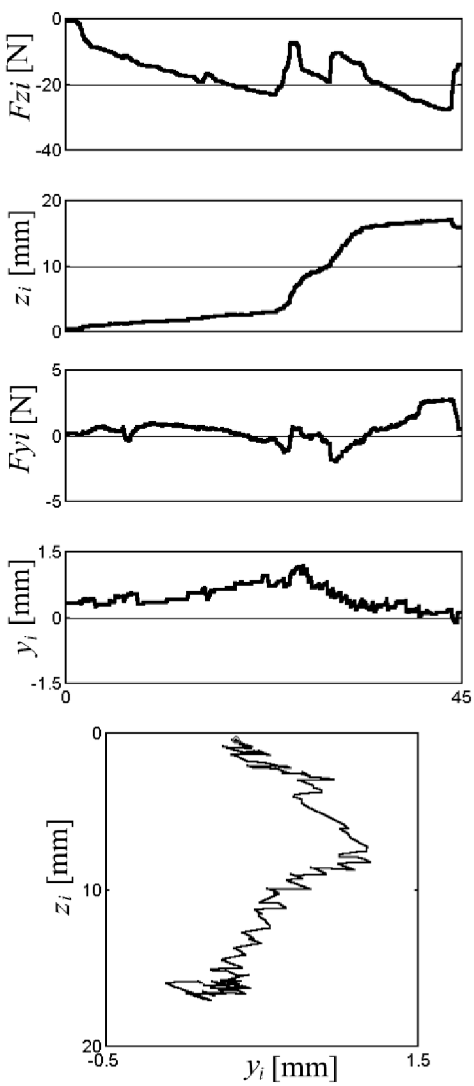

Fig. 14 Telemetry data of the truss insertion with force accommodation control in experiment 2.

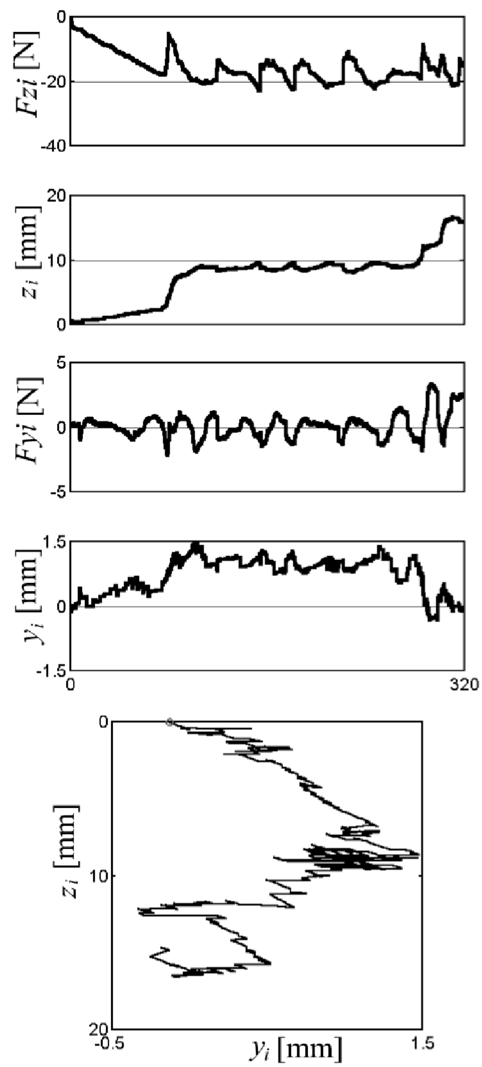

Fig. 15 Telemetry data of the truss insertion with force accommodation control in experiment 3.

we can conclude that the force command operation is useful in teleoperation with time delay, from the viewpoint of time efficiency. Also note that the GPF initially moves toward the stowed configuration, $+y_i$. The reason is that the rotational spring acts toward $+y_i$, and the force command is set to zero. After the tip of the truss hits the tapered guide part of the hole, the GPF moves toward the deployed configuration, $-y_i$, along the tapered guide. Such a motion is easily observed in the $y_i z_i$ trajectory.

In Fig. 15, experiment 3, it takes 350 s to insert the truss at $v_f = 0.3$ mm/s. On the other hand, in experiment 2, the time required is 45 s at speed $v_f = 1$ mm/s. Note that the elapsed time is in proportion to the commanded velocity. The reason for this is that at low speeds the static friction force influences significantly the robot arm motion. The truss has been inserted about 10 mm in the first motion for around $t = 80$ s. After the first motion, the lateral force F_{yi} starts oscillating around zero whereas the truss keeps its position. F_{yi} is positive when the spring force toward the stowed configuration is applied to the truss. It becomes negative when the truss contacts with the tapered guide. As a result, the truss has been inserted about 15 mm, and, hence, the assembly of the truss has been completed. Also note from the $y_i z_i$ trajectory that the truss motion in the lateral direction is large because of the lateral force.

VI. Conclusions

We discussed problems related to the effectiveness of teleoperation under time delay and force control, based on force/torque command input. The method is effective for tracking a restricted trajectory without the need for accurate trajectory information. Particularly, it has been shown that the method is useful for peg-in-hole insertion regardless of the time delay. The effectiveness was confirmed through an experiment of space truss teleoperation, as a part of the space robotics missions on the ETS-VII.

In truss deployment and stowage operation tasks, the timing of sending commands and the direction of the force corresponding to the truss condition are important. We displayed and used the end-effector velocity and the trajectory history and current orientation of the end effector to evaluate the timing of sending commands and to set the direction of the force command, respectively. As a result, truss deployment and stowage tasks were performed well within the limited experimental time. Also, we could conclude favorably about the usefulness of force commands for truss insertion in a truss assembly task because we could obtain a continuous motion regardless of the time delay, regardless of the frictional force, and because a null force command was effective for suppressing the lateral force.

Then, we can summarize the characteristics of force control by a force/torque command as follows:

1) Excessive forces and torques can be avoided by the onboard control algorithm.

2) Trajectory information is not essential when the trajectory is continuous.

3) Continuous motion is possible even if a large friction force is generated, regardless of the time delay.

References

[1] Sheridan, T. B., "Space Teleoperation Through Time Delay: Review and Prognosis," *IEEE Transactions on Robotics and Automation*, Vol. 9, No. 5, 1993, pp. 592–606.

[2] Ravindran, R., and Doetsch, K. H., "Design Aspects of the Shuttle Remote Manipulator Control," AIAA Paper 82-1581, 1982.

[3] Hirzinger, G., Brunner, B., Dietrich, J., and Heindl, J., "Sensor-Based Space Robotics—ROTEX and Its Telerobotics Features," *IEEE Transactions on Robotics and Automation*, Vol. 9, No. 5, 1993, pp. 649–663.

[4] Hannaford, B., "Ground Experiments Toward Space Teleoperation with Time Delay," *Teleoperation and Robotics in Space*, edited by S. B. Skaar and C. F. Ruoff, AIAA, Washington, DC, 1994, pp. 87–106.

[5] Funda, J., Lindsay, T. S., and Paul, R. P., "Teleprogramming: Toward Delay Invariant Remote Manipulation," *Presence*, Vol. 1, No. 1, 1992, pp. 29–44.

[6] Hirata, M., Sato, Y., Nagashima, F., and Marayama, T., "Design of Teleoperation System with a Force-Reflecting Real-Time Simulator," *JPL 3rd International Symposium on Artificial Intelligence, Robotics and Automation*, Jet Propulsion Lab., California Inst. of Technology, Pasadena, CA, 1994, pp. 305–308.

[7] Matsumoto, K., Wakabayashi, S., Penin, L. F., Nohmi, N., Ueno, H., Yoshida, T., and Fukase, Y., "Teleoperation Control of ETS-VII Robot Arm for On-Orbit Truss Construction," ESTEC, Paper WEA21-3, June 1999.

[8] Oda, M., Kibe, K., and Yamagata, F., "ETS-VII (Engineering Test Satellite #7)—a Rendezvous Docking and Space Robot Technology Experiment Satellite," International Astronautical Federation Paper IAF-95-U.2.01, Oct. 1998.

[9] Uchibori, Y., and Oda, M., "Force/Torque Control of Engineering Test Satellite VII Robot Mission," JSME Paper 22A2, May 1999.

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