

TRUSS DEPLOYMENT BY ETS-VII ROBOT ARM USING FORCE CONTROL

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Abstract: Experiment for teleoperation of a truss structure on Engineering test satellite #7 (ETS-VII) is performed as a part of space robotics missions. Truss is effective for a space structure because of its lightness and compactness. Recently, a space robot operated from the ground is expected to construct a space structure. This paper reports the results of space experiment for truss operation tasks by ETS-VII robot arm using force accommodation control. Since the robot arm applies the commanded force and torque against to the object, the force accommodation control has merits in teleoperation with time delay, such that no trajectory information is required, and excessive force and torque cannot be caused. It is especially effective in truss operation of deployment and stowage.

Keywords: Space Robot, Truss Structure, Time Delay, Force Accommodation Control

1 INTRODUCTION

Engineering test satellite #7 (ETS-VII) was launched by National Aerospace Development of JAPAN, for the purpose of rendezvous and robotics missions in space [1]. As a part of the robotics missions, National Aerospace Laboratory (NAL) performs experiments for truss assembly and deployment from the ground teleoperation [2]. Truss is suitable for a large scale structure in space because of its lightness and compactness, and it is also considered to change its configuration easily [3] [4]. On-orbit construction of a truss structure is mainly based on assembling and deploying tasks, and the ground teleoperation of a space robot is expected in order to perform such tasks [5].

In teleoperation with time delay, it is important for a contact task to pay much attention to force and torque, since there is a possibility that larger force or torque are caused on orbit than those monitored on the ground. ETS-VII robot arm has several force control functions, which is based on information from the sensor attached to the end-effector [6]. Compliance control allows position and orientation errors, which cause an excessive force or torque. However, unexpected force and torque are likely to

be caused, since force and torque are monitored a few seconds after commanding position and attitude. ETS-VII robot arm has another force control function, called "force accommodation control." Using this function, the end-effector moves toward the point, where the external force/torque applied to the end-effector becomes the commanded value. Therefore, excessive force and torque over the command cannot be caused. However, the robot arm motion is unexpected when the end-effector is not restricted, since position/orientation cannot be commanded. The force accommodation control is effective for operation of the deployable truss on ETS-VII, because the truss restrict the end-effector trajectory, also because the robot arm does not need to stop except for the deployed or stowed conditions. It is also merit that trajectory information is not essential.

In this paper, the force accommodation control is used for the truss deployment and stowage tasks on ETS-VII. Section 2 shows the devices mounted on ETS-VII for truss experiments. Control functions of the robot arm are explained in section 3. The deployable truss design is explained and its trajectory is examined in section 4. Experimental results of the truss deployment and stowage tasks are described in section 5.

2 TRUSS EXPERIMENT ON ETS-VII

ETS-VII consists of chaser and target satellites. The chaser satellite is cubic, and it has six surfaces. One of these surfaces has rendezvous docking mechanism with the target satellite. Another surface has a highgain antenna in order to communicate with a geostational satellite, and the geostational satellite communicates with ground system. On the reverse surface of the highgain antenna's, experimental devices for robotics mission are mounted as shown in Figure 1. The robot arm operated from the ground with time delay, which is roughly seven seconds, is used for operation of each experimental device. Two CCD video captures of the truss experimental unit are shown in figure 2. The assemble truss is set on the right side of the unit, and the deployable truss is set on the left. Both assembly and deployable trusses are stowed in the right capture, and both are assembled and deployed in the left.

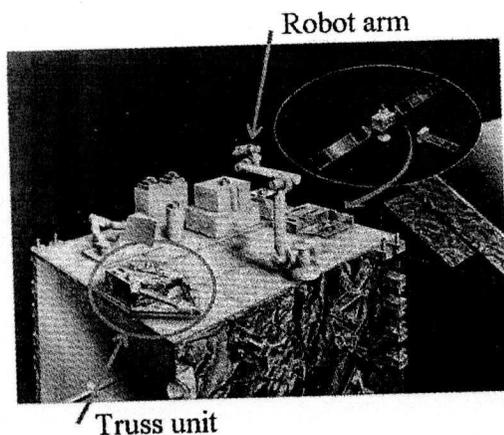


Figure 1 Engineering Satellite #7

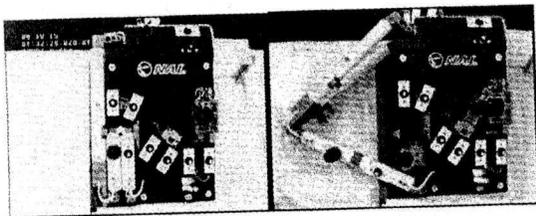


Figure 2 Truss experimental unit

3 CONTROL OF THE ROBOT ARM

3.1 Force feedback control algorithm

ETS-VII robot arm has force control functions based on information from the force sensor attached to the end-effector. Two main functions are "compliance

control" and "force accommodation control." Using the compliance control, robot arm motion is described as:

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

where, m , c and k denote compliance parameters. u_c denotes position/orientation command sent from the ground. f denotes the external force applied to the end-effector and measured by the force sensor. Then, the on-board computer calculates u , which is the end-effector position of the robot arm.

On the other hand, force/torque command f_c is sent from the ground when using the force accommodation control. The on-board computer calculates u_f as:

$$u_f = u + \frac{f_c}{k}. \quad (2)$$

Then, the end-effector motion is described as:

$$m\ddot{u} + c\dot{u} + k(u - u_f) = f. \quad (3)$$

Each control function can be independently set on each axis of the end-effector fixed frame. Control function should be selected, when the robot arm motion stops. At the same time force/torque command should be also determined for the force accommodation control. Control function and force/torque command cannot be changed while the robot arm moves.

3.1 Force accommodation control

The force accommodation control has the following merits, especially in teleoperation with time delay.

- (i) Excessive force and torque over the command cannot be caused.

It takes a few seconds to obtain the on-board condition due to the time delay. Therefore, it is difficult for the compliance control to suppress excessive force and torque after monitoring them, especially when the robot arm is moving. Using the force accommodation control, force and torque over the command cannot be caused regardless of the time delay.

- (ii) Trajectory information is not essential.

Using the force accommodation control, operation is based on force/torque command without position/orientation command. Hence, trajectory information is not essential for operation. Therefore, the end-effector trajectory should be restricted. Otherwise, the robot arm motion is unexpected.

However, the force accommodation control has the following demerits. First, the robot arm cannot stop except for the restricted position/orientation where the robot arm applies the commanded force/torque. Therefore, the robot arm cannot take the desired position and orientation for itself. Second, force/torque command with respect to the object will change when the end-effector orientation/position changes, since the force/torque command is fixed to the end-effector frame.

4 DEPLOYABLE TRUSS

Figure 3 shows deploying and stowing steps for the truss operation tasks. (i), (ii) and (iii) show stowed, deploying/stowing, and deployed conditions, respectively. Base frame Σ_b is fixed to the robotics mission surface of the chaser satellite. Grapple fixture (GPF) is grappled by the end-effector of the robot arm, and Σ_p denotes the end-effector fixed frame. Σ_p is also fixed to GPF when the robot arm grappled it. The deployable truss consists of rigid links connected with five hinges. The number of rotational DOF (degrees of freedom) at each hinge is described in figure 4. Such a composition makes the deploying and the stowing trajectories one DOF.

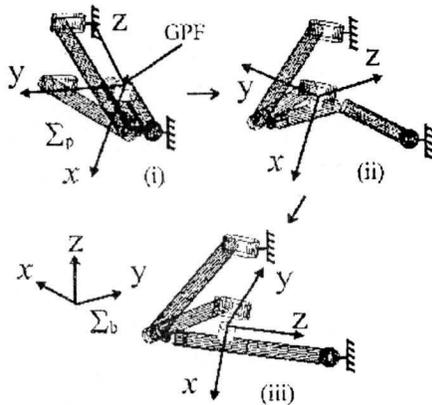


Figure 3 Deployment and stowage steps

The stowed and deployed conditions of the truss are maintained by rock mechanisms. The stowed

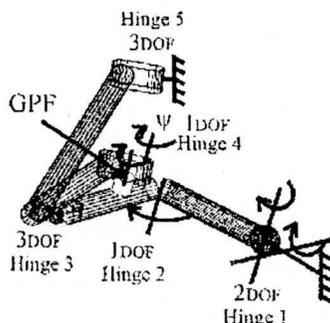


Figure 4 Design of the deployable truss

condition is released by just applying the force/torque in the direction of the deploying trajectory. Unlock motion, which is GPF rotation (GPF can rotate about 30 [deg] around the roll axis of Σ_p), is required in order to release the deployed condition. Condition of the truss can be informed by deployable angle ψ at hinge 4, measured by the potentiometer attached to the hinge. $\psi = 0$ [deg] at stowed condition (i) and $\psi \approx 52$ [deg] at deployed condition (iii), respectively. Rotational springs are attached to Hinge 4 and 5, and hinge 2, respectively. The torque by the springs at hinge 4 and 5 acts toward stowed condition, and the torque by the spring at hinge 2 acts toward deployed condition, respectively. Due to these rotational springs, under the condition that no force and torque are applied to the truss, the truss stops its motion at three conditions: first is the deployed condition, second is the stowed condition, and third is the condition where $\psi \approx 40$ [deg].

Figure 5 shows GPF translational trajectory on 3-dimensional frame Σ_b . Figure 6 shows the end-effector orientation on the Σ_b frame, denoted as roll, pitch and yaw, versus deployable angle ψ . Deployable angle ψ is determined by GPF position as shown in figure 5, hence the end-effector orientation should be determined from figure 6. On the contrary, GPF position is determined by the end-effector orientation. Therefore, GPF position and orientation has one DOF during the deployable truss operation.

In teleoperation with time delay, the accurate trajectory is required for compliance control, because trajectory error will cause excessive force and torque. However, it is difficult to obtain the accurate trajectory of the deployable truss, because GPF translational trajectory is a spline curve, also because position and orientation are coupled. On the other hand, the force accommodation control is effective for the deployable truss operation, since the trajectory is continuous, and the robot arm should stop only at deployed or stowed conditions.

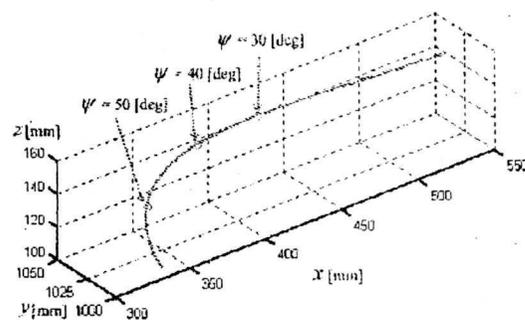


Figure 5 GPF position trajectory

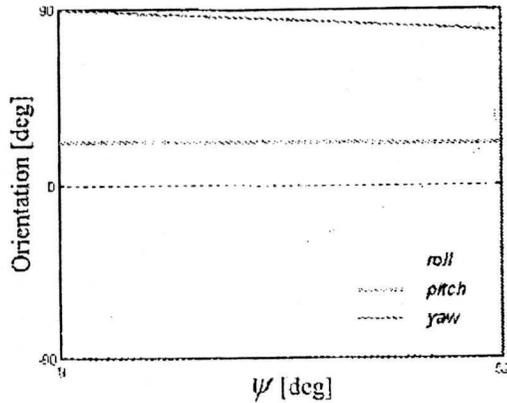


Figure 6 The end-effector orientation

5 EXPERIMENT

5.1 Planning for experiments

Experiments using the force accommodation control were planned. Note here that force and torque applied to GPF will be coupled, because both position and orientation are restricted each other. Therefore, the truss is deployed or stowed by translational force, at the same time, orientation is adjusted in order to suppress the torque.

As described in the previous section, the end-effector orientation changes during the deployable truss operation. Then, GPF translational trajectory on the end-effector fixed frame Σ_p is examined. Figure 7 shows the unit vector components in the direction of GPF translational trajectory on Σ_p . It can be said from the result that force command should be set mainly along the y and z axes, since change of the x axis is small. It is also noted that force command must be changed during deploying and stowing tasks, since both signs of y and z components changes between the stowed and deployed condition.

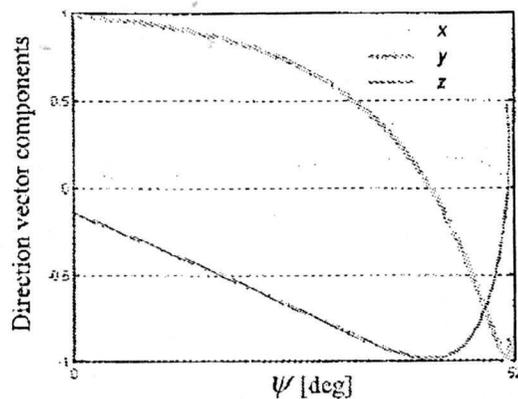


Figure 7 GPF trajectory direction on the end-effector fixed frame

Force command in x, y, and z axes during a task is changed by the following process.

- (i) Confirm that force telemetry reached to the force command.
- (ii) Confirm that the end-effector velocity is small.
- (iii) Determine the next force command, referring to telemetry of the position trajectory and the orientation of the end-effector.
- (iv) Send the next force command.

Orientation should be operated in order to suppress a torque. From figure 6, the roll axis orientation changes large compared to the pitch and yaw axes. Also, it is noted that the torque caused around the roll axis much influence on truss deployment and stowage tasks. Note that GPF can rotate around the roll axis because of the rock mechanism. Then, in order to suppress the torque caused around the roll axis, GPF keeps its rotation in the middle point by joystick operation from the ground. On the other hand, the pitch and yaw axes orientations are commanded from the ground joystick operation when deploying, and controlled by the force accommodation control function of the zero force command when stowing.

Figure 8 shows CCD video capture during the truss deployment task. The following characteristics of the deployable truss operation have been found in the past experiments. Larger force is needed to deploy than that to stow because of the composition design of the truss (the rotational springs attached to the hinges). On the other hand, it is difficult to judge the robot arm motion from the deployable angle ψ , since its change near the deployed condition is small. Then, the robot arm motion is judged from the end-effector velocity.

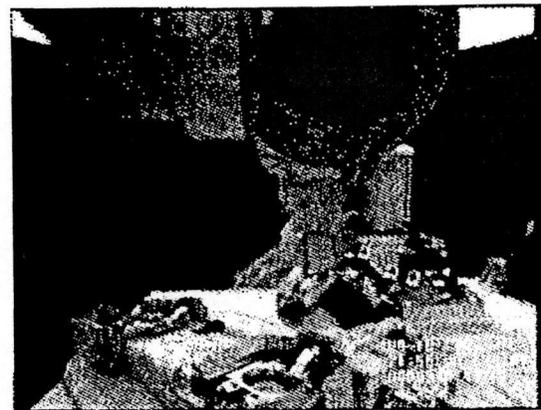


Figure 8 Deployable truss operation

5.2 Result of the truss deployment task

Figure 8 shows the result of truss deployment using the force accommodation control. Where F_x , F_y , F_z

in x , y , z axes and T_x , T_y , T_z in roll, pitch, yaw axes denote force and torque telemetry from the sensor. ψ is the deployable angle telemetry from the potentiometer, and v denotes the end-effector velocity calculated from time history of the joint angle telemetry of the robot arm, respectively. The force accommodation control is used in translational axes, and force command value is set as:

Step 1: $x = 0$ [N], $y = -10$ [N], $z = 10$ [N],

Step 2: $x = 0$ [N], $y = 0$ [N], $z = 15$ [N],

Step 3: $x = 0$ [N], $y = 10$ [N], $z = 10$ [N],

in each step divided by vertical lines. The compliance control commanded by joystick operation is used in orientation.

It is noted that the force telemetry increases gradually to the commanded values, since the force command direction deviates from the deployable trajectory due to the robot arm motion. It is also noted that it takes a few seconds to start the robot arm motion after the commanding due to the time delay. During step 1, the end-effector velocity became small when the force telemetry in the y axis reaches to the force command, although the force telemetry in the z axis does not reach to the command. The reason is that each axis is controlled independently. It is also noted that the end-effector velocity becomes small, when the force telemetry reaches to the command. On the other hand, truss condition can be initially judged from the deployable angle, however, it is difficult to judge finally near the deployed condition. Then, the end-effector velocity was useful in order to judge the robot arm motion.

Referring to the torque telemetry, the torque caused around the roll axis is small due to GPF rotational freedom. The torque caused around the pitch and yaw axes is rather large, because of human joystick operation with time delay.

5.3 Result of the truss stowage task

Figure 9 shows the result of truss stowage using the force accommodation control. In order to stow the truss, unlock operation of GPF was required during step 1, and the operation to overcome the stowed lock mechanism was also required during step 4. The force accommodation control was used for operation in step 2 and step 3, and force command is set as:

Step 2: $x = 0$ [N], $y = -3.5$ [N], $z = 3.5$ [N].

Step 3: $x = 0$ [N], $y = 3.5$ [N], $z = -3.5$ [N].

The force accommodation control is also used in the pitch and yaw axes, where torque command is set as 0 [Nm]. For the roll axis orientation, the same joystick operation for the deployment task is used.

From the result during step 2, it is noted that the end-effector keeps its velocity after the telemetry

force reaches to the force command. The reason is that the torque due to the rotational springs attached to hinge 4 and 5 acts toward the stowed condition. Also, it is noted that the stowage task needs smaller force than the deployment task. On the other hand, the torque caused around the roll axis is small like the result of the deployment task. However, the torque caused around the pitch and yaw axes vibrates. Then it can be said that the force accommodation control of the end-effector orientation of ETS-VII robot arm does not work well.

5 CONCLUSION

This paper discussed about the truss deployment and stowage tasks by ETS-VII robot arm, using the force accommodation control. This control strategy is effective in teleoperation with time delay, because excessive force and torque cannot be caused, also because no trajectory information is required.

For preparation of experiments, the trajectory of the deployable truss was examined. Then, it is noted that the force accommodation control is effective for the deployable truss operation, since the continuous trajectory is restricted, and the robot arm should stop only at deployed or stowed conditions. It is also noted that the force command on the end-effector fixed frame should be changed during the task, since the end-effector orientation changes.

Experiments were planned that the deployable truss is deployed and stowed by translational force using the force accommodation control, at the same time, orientation is adjusted in order to suppress the torque which will be coupled with the translational force. As a result, the experiments for truss deployment and stowage were succeeded using the force accommodation control. In the experiment, the force applied to the end-effector is suppressed in the commanded value, and the tasks were achieved without trajectory information.

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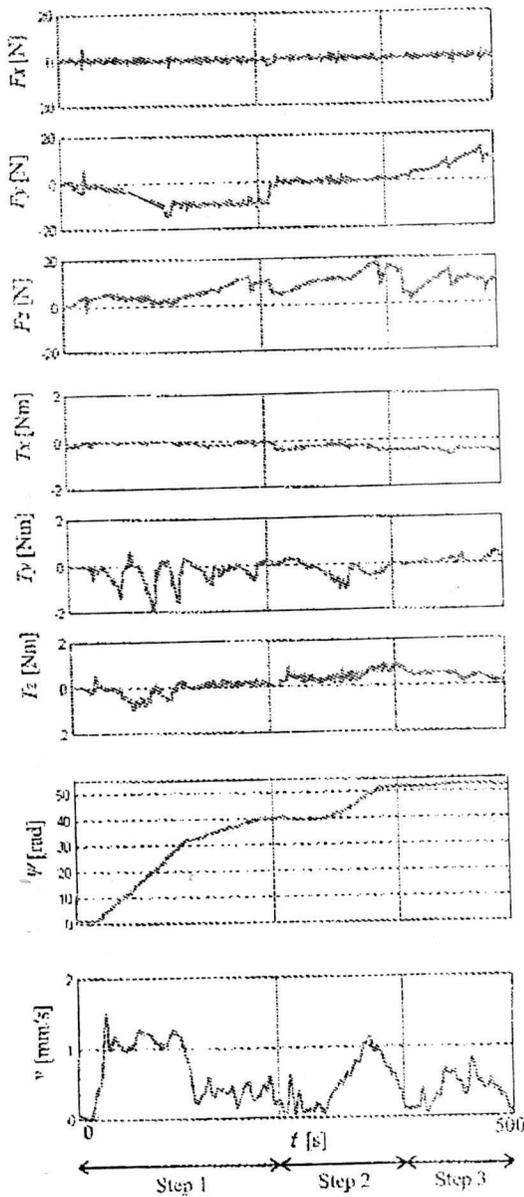


Figure 8 Result of truss deployment

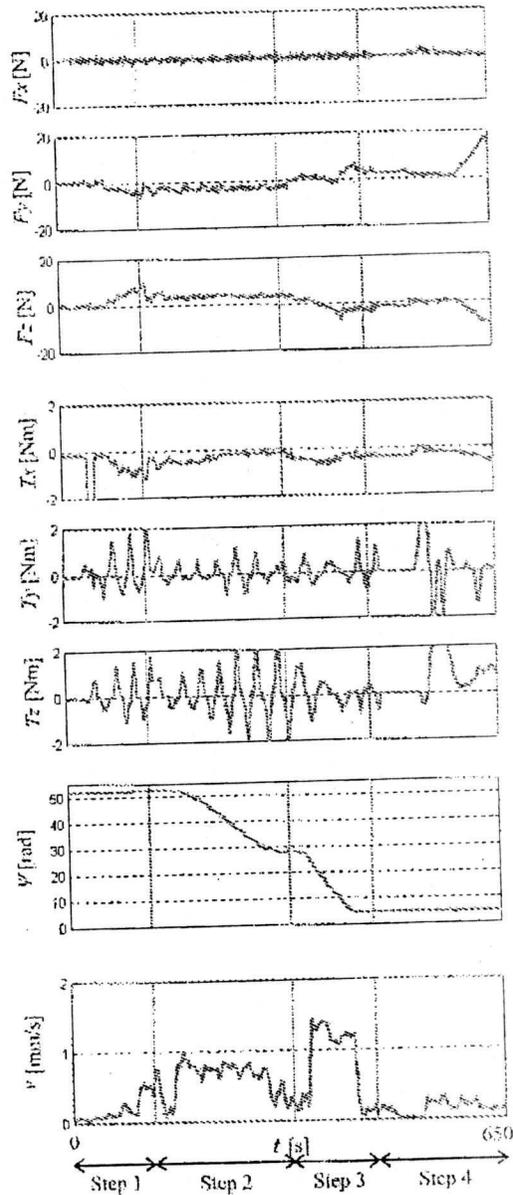


Figure 9 Result of truss stowage