Truss Structure Teleoperation using ETS-7 Space Robot

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1. Introduction

ETS-7 (Fig. 1), was launched Nov. 28, 1997 by NASDA, to demonstrate two major on-orbit service missions, the rendezvous docking and the space telerobotics.

Four agencies, those are NASDA, MITI/ETL, CRL, and NAL, have cooperated in the ETS-7 telerobotics experiments. The basic robot systems of the satellite and the ground facilities were developed by NASDA. The other three national institutes, including NAL, developed their own experimental apparatus for the satellite and their own ground facilities related to tele-robotic research. Until May 1999, ETS-7 maintained its planned mission life, and from June to December post mission utilization experiments were done.

2. Space Robot and its Ground Tele-Operation

The ground teleoperation of the space robot on the manned space facility has not been implemented or demonstrated, with few exceptions such as ROTEX and MFD, mainly due to the high level requirements of operational safety and the lack of technological maturity. These current space robots' status seems to be far from the initial recommended benefits and expectations for space Automation and Robotics[1]. For future space robots, more dexterous tasks and small work objects shall be teleoperated effectively from the ground, to release humans from unsuitable and/or hazardous work.

For this purpose, the ground teleoperation system shall show the solutions for the two major communication problems; time delay and lack of capacity, by verifying the safety level of ground teleoperations using the real space systems.

NAL has selected the truss structure handling tasks as the model tasks for future space robots. Due to the diameter of the truss strut and the complexity of the truss joints, dexterous handling capability of the small target is essential for truss manipulation. In future space development, the truss structure will be used in the next generation space station, the solar power satellite, and/or the space hotel. (Fig.2)

3. ETS-7 Robot Arm

The ETS-7 robot arm's basic design was introduced from the JEM small fine arm. Its tip position accuracy is quite a bit worse than usual ground robots, because of vacuum lubrication. For the work monitoring, the arm has a pair of hand eye, and a pair monitor camera on its shoulder. The TV images are compressed into monochrome JPEG at 5 Hz. The end-effector tool has two modes of capturing the grapple fixtures. The finger open operation captures the standard GPF-S/M. The finger close operation captures the GPF-N (Grapple Fixture-N) that is designed for our TSE (Truss Structure Experiment apparatus). (Fig. 5)

The ETS-7 teleoperation has two modes; program control and direct teleoperation control. In the direct tele-operation control, the arm tip motion will be controlled at 4 Hz directly from NAL's ground teleoperation facility. On-line verification against the collision, singular attitude, speed, and acceleration is done within NAL.

For force control, the ETS-7 arm has three modes; compliance control, active limp control, and force accommodation control.

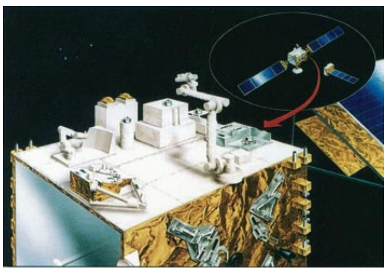


Fig.1 ETS-7
(Engineering Test Satellite)

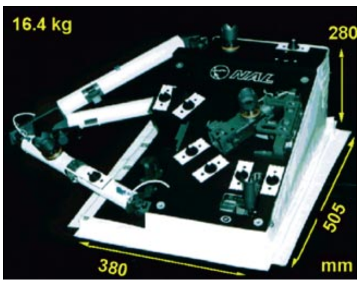
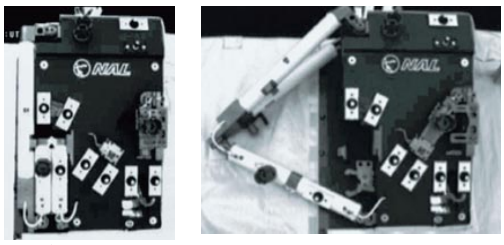


Fig.2 Truss Structure Experiment



Stowed Deployed

Fig.3 Truss Deployment and Stow

4. TSE: Truss Structure Experiment Tasks[3)]

The TSE experiments are composed of the following three tasks. Every task requires GPF-N capturing and release processes.

(1) **Launch Lock (LL):** TSE LL, which locked TSE, was released by the 90 degree arm tip rotation of the ETS-7 arm. The major difficulty of this task was the GPF-N capture itself, as the first NAL operation without any trial or experiment on the ground.

(2) **Deployable Truss structure (DT):** The DT is one section of a triangle truss structure for the JEM-DTB (Deployable Test Bed), that can be deployed and folded. (Fig. 3)

The arm deploys the DT along a 3 dimensional spline curve under closed link movement. The operation difficulty is to move the arm along the 3D trajectory within suitable tip force and torque levels.

(3) **Truss assembly Joint (TJ):** TJ was originally designed for human operation, and modified for one hand robot operation without any hand-over. The mechanical guide was used to compensate the insufficient accuracy of ETS-7 arm tip control.

The TJ insertion into the Joint Receiver (JR), that is similar to a peg-in-hole, originally assumes human operation; thus it requires the most precise, difficult, and strong arm tip motion control for the ETS-7 robot tasks.

(4) **Grapple Fixture for NAL (GPF-N):** The unique characteristics of GPF-N are its size and its arm capture method. Although the diameter of other GPF-S&M is 138mm, GPF-N's diameter is only 38mm, as the smallest one designed for NAL-TSE. The finger close capturing method is also unique only to NAL GPF-N. (Fig. 5)

5. Ground Teleoperation Facility (GTF)

On the ground, we have developed our teleoperation facility just behind the NASDA's ETS-7 facility. The major characteristics of our ground teleoperation facility are the following:

(1) Graphic simulation for the predictive display.
(2) Image processing for arm tip position and attitude precise measurement.
(3) Hardware simulator with TSE-EM.
(4) Software I/F for advanced research programs.

The hardware simulator is composed of the industrial robot and the engineering model (EM) of the TSE. The arm tip motion and the compliance control characteristic are simulated within the restricted region and tasks, where the hardware simulation is significant. Using this simulator, every procedure and algorithm has been tested and trained before real teleoperation. (Fig.6)

6. Overall Experiment Plan

NAL was assigned 28 mission days (56 paths) during the ETS-7 official mission period. In each mission path, the robot experiment could consume 20 (baseline) to 30 minutes (maximum).

NAL's 28 mission days are classified as follows;

(1) Initial (2 days): Release LL in May 1998.
(2) Basic (8 days): DT and TJ experiments using the program mode control from May to July 1998, and the direct teleoperation control include joysticks from Sep. to Oct. 1998.
(3) Nominal (11 days): Various teleoperation aid systems from Nov. 1998.
(4) Advanced (7 days): Advanced teleoperation aid, such as virtual reality, long communication delay (> 10sec), force feedback, from Mar 1999.
(5) Post Mission (2 days): NASDA's task board teleoperation and arm distortion evaluation from Sep. to Nov. 1999.

7. TSE Teleoperation Experiments

The following are the major results of our experiments:

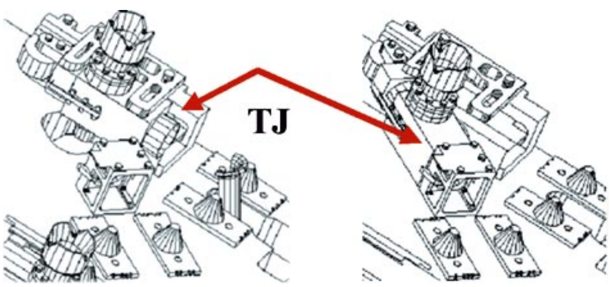
(1) Predictive Force Teleoperation Aid [4)]

For the direct teleoperation of the unknown closed link tasks, we have developed a new aid system, using predictive force.

The predictive force method (PFM) was developed to estimate the most reliable / optimal current force value using the past arm tip position that was transmitted from the orbit with 6-sec time delay.

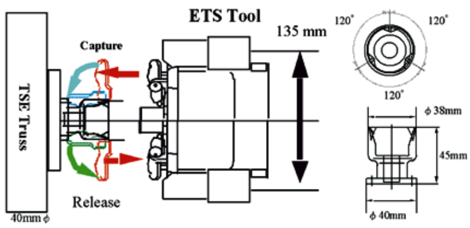
Assumption:

(a) The arm is controlled with some force feedback control, such as compliance control.
(b) Closed link task trajectory is relatively smooth.



Disassembled Assembled

Fig.4 Truss Assembly Joint



ETS-7 Arm Capturing GPF-N

Fig.5 GPF-N and its Capture

The required arm tip work frequency is slower than the communication time delay.

In the PFM, the estimated force $\mathbf{f}_e$ is defined by the function of past/current position $\mathbf{P}_t$, that is estimated from the telemetry data, and next arm tip position command $\mathbf{P}_c$. For the compliance control;

$\mathbf{f}_e = k^*(\mathbf{P}_c - \mathbf{P}_t)$ k: compliance coefficient

For $\mathbf{P}_t$, we can use various estimation methods, such as the Karman filter. In our experiments, the position telemetry value, as the simplest one, is used as $\mathbf{P}_t$.

In the PFM, we also estimate the most suitable/optimal direction, where the arm tip force shall be loaded. Under the assumption (b), it shall be around the tangential direction of the trajectory. In our experiments, the least square approximation was used for this estimation.

By visual displays of the PFM guidances, the teleoperator can easily estimate and recognize the magnitude and direction of the force, that will appear as the telemetry data 6-sec after, and also easily identify the most suitable/optimal direction to go. Thus, in the teleoperation assisted by this method, the "move & wait" operation could be minimized from the direct joystick teleoperation, without any design data.

The PFM performance was tested by the Japanese astronaut Mr. K. Wakata, and highly evaluated in March 1999. (Fig. 8)

PFM Programmed Control

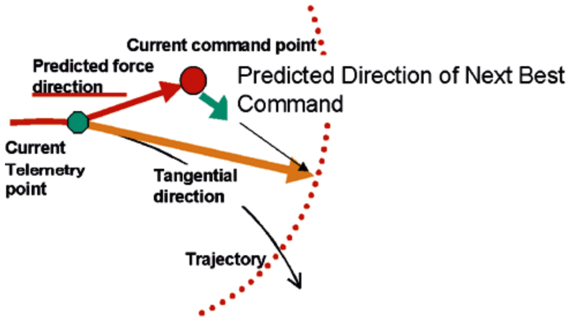


Fig.6 Predictive Force and Tangential Direction

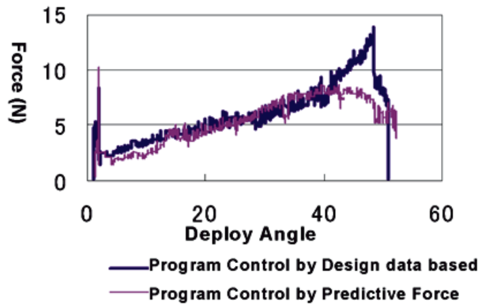


Fig.7 Predictive Force Method vs Designed Trajectory

We have extended this PFM to the autonomous programmed ground control. When the maximum working force is specified, the target command point can be determined uniquely on the tangential line. (Fig.6) Thus, the suitable next command is decided toward the target point within the arm tip speed limitation. The predictive force and the real working force can be controlled within the specified force. Furthermore, although the PFM needs no design data at all, it might show better performance than the basic program control, that moves the arm tip along the design data trajectory. (Fig. 7)

(2) Force Accommodation Control

The "force accommodation control. (FAC)" can be described as some implementation of the supervisory /shared control. By this FAC, the robot arm will continue to move, until the external force/torque at the arm tip reaches the specified force value.

This FAC has the following merits, especially in teleoperation with time delay, since it works in on-orbit controller.

(a) Excessive force and torque over the command can be suppressed.

(b) Trajectory information is not essential.

Using this FAC for the truss joint assembling, the required force for joint insertion is expected to be smaller than the compliance control. Since the vertical direction force can be specified as to zero, the friction force from the joint receiver cylinder wall is expected to be small during the insertion. Telemetry of force in the direction of truss insertion (the z-axis) is shown in Fig. 9. The solid line shows the

Fig.8 Astronaut Mr. Wakata Teleoperates The Deployable Truss from the ground

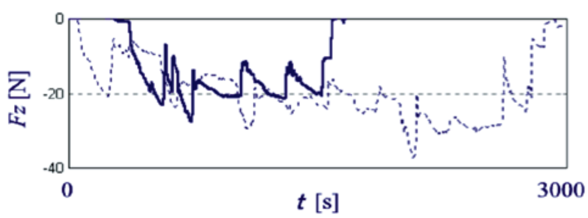


Fig.9 Force Accommodation Control during Truss Joint Assembly

result of the force accommodation control, the dotted line shows the result of the compliance control.

(3) Teleoperation by Virtual Force Reflection [5]

The force reflection (FR) to the operator is expected to improve the hand task execution performance dramatically, although direct FR (bilateral control scheme or force feedback) can be used only with delays of less than 1 second because of the PIO (Pilot Induced Oscillation)[2]. Thus we have used the FR system to display virtual forces for the continuous teleoperation of on-orbit manipulators, with long communication time delay up to 7 seconds. A 2 DOF force reflecting joystick has been used as the FR hand controller.

In our FR system, the following virtual forces were implemented to guide the operator's hand movement.

a)Potential virtual force fields
b)Virtual force as physical constraints
c)Adaptive virtual force by probing environment

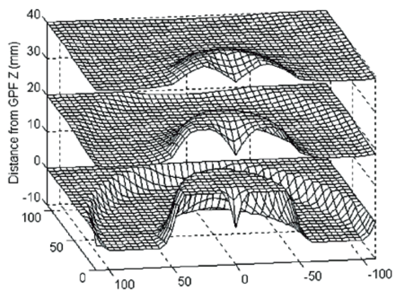
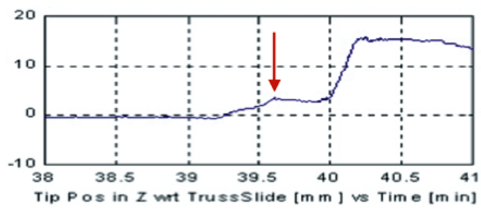
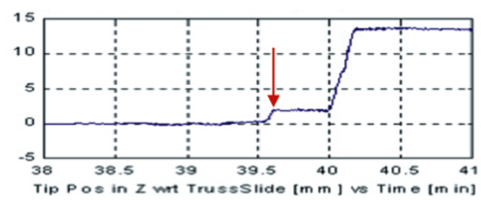


Fig.10 Potential Virtual Force for GPF-N Capture



Arm Tip Position (without compensation)



Arm Tip Position (compensated)

Fig.11 Truss Joint Assembly by Arm Distortion Compensation

(4) Arm Distortion Estimation

Though the ETS-7 arm is designed as a rigid body arm, a slight distortion was foreseen, because of the harmonic joint gear and mechanical backlash. This distortion might not be negligible when a large arm working force is required.

In the TJ assembling experiment, it requires a relatively large insertion force, 20 - 40 N, and also requires very precise arm tip position, 0.7mm, and attitude control.

Fig. 11 shows the experiment results. Without the distortion estimation, it is too hard for the teleoperator to identify whether the joint begins to move for insertion, or just stay at the entrance position with the arm distortion.

8. Concluding Remarks

The Truss Structure Experiments (TSE) by the ETS-7 robot arm has been done to demonstrate the space robot capability for the truss structure construction work, which requires rather complex dexterity and small work objects. The TSE ground teleoperation facility has shown its reliability and capability for the space robot's dexterous ground teleoperation, even for the case of lack of precise trajectory data.

We will continue our study to realize the more sophisticated and diversified teleoperation, for the ground teleoperation of the Space Station JEM's robot, the on-orbit servicing system to capture and repair the troubled satellite, the teleoperation of the moon and planetary rover, and/or the future space robot.

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