

## TELEOPERATION CONTROL OF ETS-7 ROBOT ARM FOR ON-ORBIT TRUSS CONSTRUCTION

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### ABSTRACT

In this paper, we will present an overview and the results of the teleoperation experiments of our truss structure experiment on the Engineering Test Satellite 7, that have been done from last March 1998. The major purpose of our experiment is to establish the basic and advanced teleoperation technology that will be useful for on-orbit truss construction for the future large scale space system.

### 1. INTRODUCTION

At Nov. 28, 1997, NASDA launched the ETS-7 (Engineering Test Satellite 7) (Fig.1). It has been developed to demonstrate two major missions for the Japanese future space activities, these are the rendezvous docking and the space robotics.

For ETS-7, NASDA has developed the baseline teleoperation robot systems on the satellite, such as the arm, vision, communication, controller, and the ground facility<sup>10)</sup>. For this space robotics experiment, other three national institutes, ETL/MITI, CRL<sup>11)</sup> and NAL, have cooperated with each experiment, with own experiment apparatuses on the satellite, and with own ground facility for the ground teleoperation experiment.

We, NAL, have implemented the TSE (Truss Structure Experiment) components on the ETS-7, and the

ground teleoperation facility at Tsukuba Space Center. Until the last May 1999, we have finished almost all TSE planned experiments, and are preparing the phase 2 advanced experiments in the rest of this year.

### 2. GROUND TELE-OPERATION OF DEXTEROUS TASKS BY SPACE ROBOT

From the viewpoint of the expectation for the space robots<sup>1)</sup>, current space robots have two problems, those are the lack of the ground teleoperation, and the lack of the dexterity of their works.

Even in the space station era, the astronauts' on orbit manipulation are the primary operation for the station robots. The main reason is the lack of the technological maturity of the teleoperation, although the main tasks of the station robots will be the handling of the modules, that are designed for the robot works.

Most of the EVA tasks, such as the repair or assembling, will still remain for the human tasks, since those tasks require the dexterous human operation. For the Hubble telescope repair mission, the space robot possibility was also considered instead of the human repair, and was not implemented because of the lack of maturity of the dexterous tasks.

We have selected the truss structure tele-handling tasks as the model tasks on the ETS-7 for the future space robots, since the truss structure and its joints,

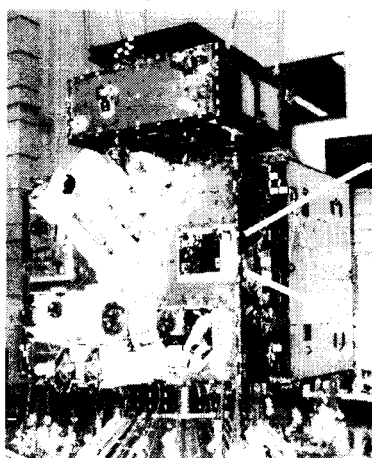


Fig.1 ETS-7 before Launch

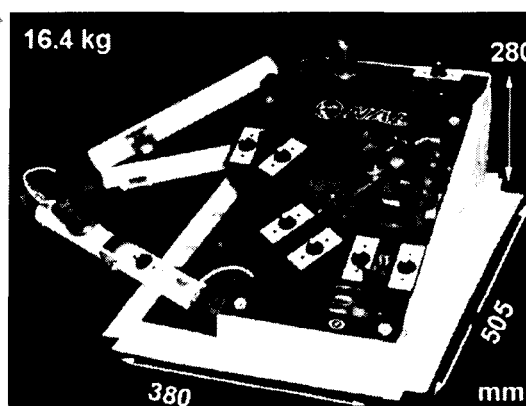


Fig.2 TSE (Truss Structure Experiment)

require the dexterous handling capability of a small target in its teleoperation<sup>5)</sup>. The next generation space station, the solar power satellite, and the space hotel in the far future, will essentially require the space robot as its constructors to solve the large scale assembling work requirement.

### 3. ETS-7 ROBOT ARM AND ITS TELEOPERATION

The ETS-7 robot arm was introduced from the JEM small fine arm with a little modification in its length, the tool, and controller. Its tip position accuracy is quite worse than the ground robot in a factory, because of the vacuum lubrication. For the work monitoring, a pair of hand eye and a pair of shoulder camera were implemented, with compressed monochrome JPEG at 4 Hz. The endeffector tool has two modes of capturing the grapple fixtures. The finger open operation captures the standard GPF-S and GPF-M. The finger close operation captures the GPF-N that is designed for TSE. (Fig. 6)

The ETS-7 teleoperation has two modes; those are the program control and the direct teleoperation control. Before sending the program control command to the ETS-7, NASDA's ground facility checks its safety verification using the simulator. In the direct teleoperation control, the arm tip motion will be controlled at 4 Hz directly from NAL's ground teleoperation facility. On-line verification against collision, singular attitude, speeds, acceleration, and so on is done within NAL's facility.

For the force control, the ETS-7 arm has four modes; those are position control, compliance control, active limp control, and force command control.

### 4. TSE: TRUSS STRUCTURE EXPERIMENT

Our TSE (Truss Structure Experiment apparatus) on the ETS-7 is designed and developed to implement the two basic truss teleoperation works; those are the deployment of the truss structure and assemble of the truss joint. In addition to these tasks, TSE launch lock is also designed to be teleoperated by the ETS-7 robot. TSE is composed by three major parts. (Fig. 2)

(1) **Launch Lock (LL):** TSE LL, which locked the

deployable truss element and the truss assembly joint, was released by the 90 degrees ETS-7 arm tip rotation. The major difficulty of this task was the GPF-N capture itself, since the capture task was the first operation for NAL, without any trial or experience at the ground.

(2) **Deployable Truss structure (DT):** The latch component of DT is same as the DTB (Deployable Test Bed)<sup>2)</sup> for JEM. The DT is one section of a triangle truss structure that can be deployed and folded. (Fig. 4)

The arm deploys DT along a 3 dimensional spline curve under closed link movement (Fig. 3). The operational difficulty is to move the arm along the 3D trajectory within limited tip force and torque. The closed link movement along a strictly constrained trajectory is the first operation for ETS-7.

(3) **Truss assembly Joint (TJ):** TJ was originally designed for STAR\*Bay-2 truss<sup>3)</sup> to be operated by human. Its mechanism was modified for one hand robot operation without any hand-over.

TJ assembly task is similar to the "peg-in-hole", but harder because of its mechanical obstacles. During TJ assembly, even if it is positioned at the center of the inserting hole, TJ assembly task requires about 10-20N force to surmount the mechanical obstacles of the joint. A mechanical guide was also attached to the joint receiver (JR) to compensate the insufficient accuracy specification of ETS-7 arm tip control.<sup>5)</sup> (Fig.5)

(4) **Grapple Fixture for NAL (GPF-N):** GPF-N is designed as the smallest grapple fixture only for TSE truss strut. The GPF-N diameter is only 38mm,

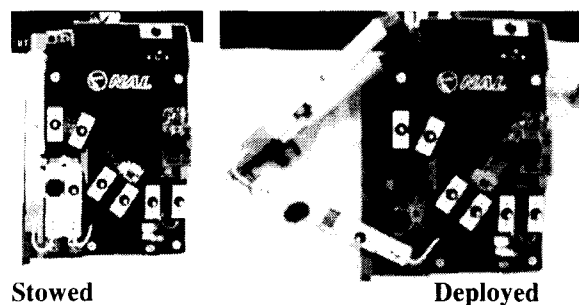


Fig.4 Truss Deployment and Stow

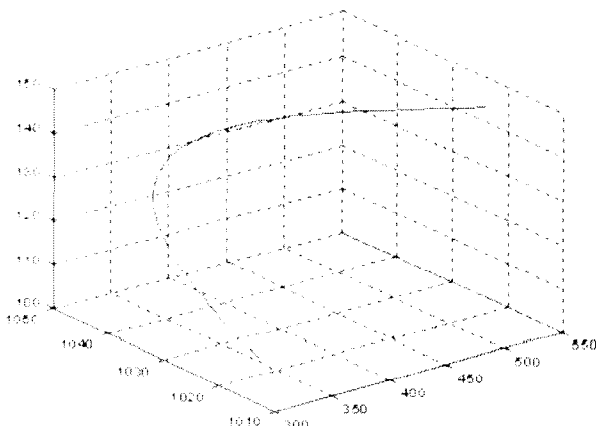


Fig. 3 3D Spline Trajectory of DT Deployment

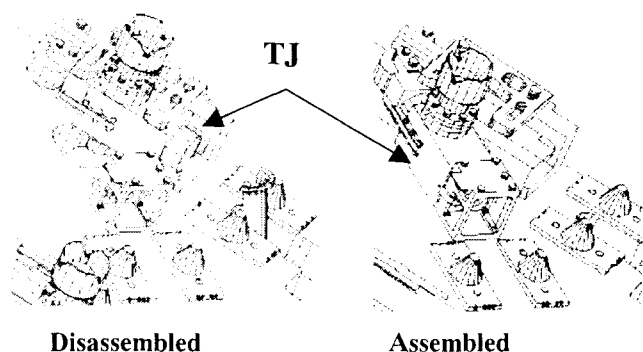
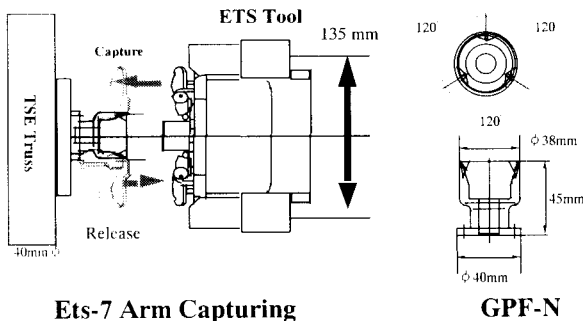


Fig.5 Truss Assembly Joint

although the diameter of other GPF-S&M is 138mm. The finger close capturing method is also different for GPF-N, as described before. (Fig. 6)



Ets-7 Arm Capturing

Fig.6 GPF-N and its Capture

## 5. NAL GROUND TELEOPERATION FACILITY

We have implemented our tele-operation facility using NASDA's ETS-7 robot facility as a transparent monitor. The major functions of our teleoperation facility are the followings; (Fig.9)

- (1) Generation of the program mode teleoperation command for the ETS-7 robot arm.
- (2) Generation of the direct teleoperation command at 4Hz with online safety verification.
- (3) Graphic simulation for the predictive display, and safety checking of collision and singular attitude.
- (4) Joystick for the direct teleoperation by human operator from NAL facility.
- (5) The precise measurement of the arm tip position and attitude by target marker image processing.
- (6) Hardware simulator of the ETS-7 robot arm with the TSE-EM (engineering model).
- (7) Advanced research software I/F.

The **hardware simulator** is used to verify every teleoperation procedure and algorithms, to train the operator before the real teleoperation, and to improve the programs, procedure, and/or operation skill under more realistic teleoperation environment than software

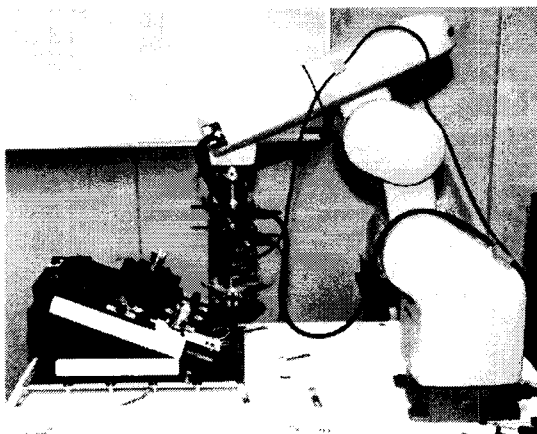


Fig.7 NAL-TSE Hardware Simulator

simulator. This simulator is composed of the industrial robot and the TSE-EM, and can partially simulate the motion and control of the ETS-7 arm. (Fig.7)

**The advanced research software I/F:** We prepared this I/F to enable the innovative telerobotics algorithm from the laboratory into the real space robot experiments with minimum and earliest preparation.

For the additional, but essential tasks, such as on-line safety check, arm setting, and human operator's override, the standard NAL facility's function is utilized to keep NAL facility's safety reliability.

**The command and telemetry I/F:** Two RS-232C lines with 9600 bps are used. One RS232C is used for teleoperation command at 4Hz, and others for the telemetry data distribution at 10Hz. On board TV images are delivered at 4Hz by NTSC. (Fig.8)

## 6. BASIC TELEOPERATION FOR TSE

For TSE teleoperation, we have implemented and tried the following methods as basic experiments.

- (1) **Program Mode Teleoperation:** Using the ETS-7's program control, every teleoperation command is programmed just like a "robot control language". Every arm tip motion is specified by a straight line movement controlled by the on-board arm controller.

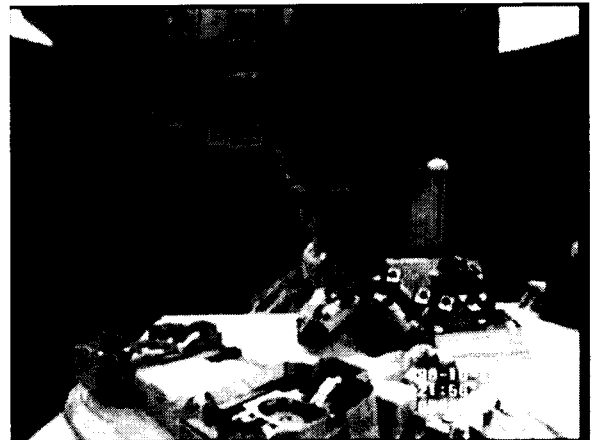


Fig.8 TSE from Shoulder Camera during Deployment



Fig.9 NAL Ground Teleoperation Facility

This control mode is the basic mode of ETS-7. However, since our TSE's tasks are basically closed link operations, this control mode has the following inconvenience for TSE teleoperation.

1. **Discontinuous tip force control:** After every tip movement, the arm controller will keep the final tip position based on the arm joint encoder. Thus, for the compliance force control tasks with relatively large working force, this discontinuity of tip force could not be ignored.
2. **Safety check for the command trajectory:** The verification time is linear to the length of the trajectory, and might increase the additional time delay for teleoperation.

The initial experiments were done only by this control mode. The initial LL release, DT deployment and stow, and TJ assemble and disassemble were done successfully. However, for TJ assembling we needed a slight change of assemble sequence to avoid the effect of the tip force discontinuity.

## (2) Programmed direct teleoperation control:

We developed the program control language over the direct teleoperation control.

In this control mode, the continuous transfer between programmed control and Joystick (JS) direct teleoperation can be achieved. JS is used for the human operators to override to the programmed control. This mode could prevent the inconveniences of the program mode teleoperation, mentioned above.

The major problem of this control is;

1. **Low control frequency:** Because of the low command frequency, at 4Hz, and low telemetry data rate, at 10Hz, the tip motion is limited with relatively slow speed except when free tip motion.
2. **Over safety for the time delay:** Because of the long time delay between the ground and ETS-7, up to 5.5 sec, we have to use the over-safety criteria, that can assure the safety under the worst motion.

By this programmed direct teleoperation control, the DT deployment and stow, and the modified TJ assemble and disassemble were tried successfully with

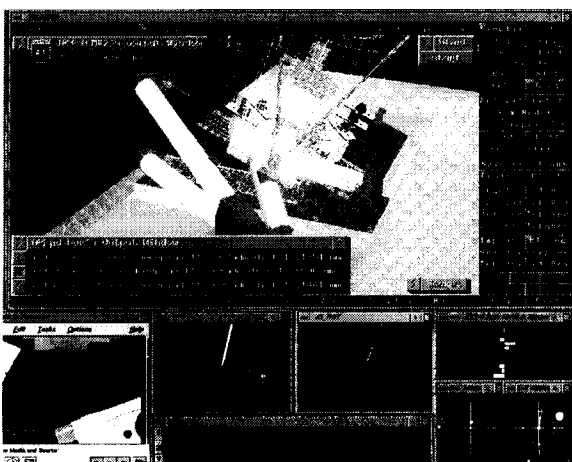


Fig.10 Visual Aid using Predictive Force Method

better performance in its working force.

## 7. HUMAN DIRECT TELEOPERATION BY JOYSTICK FOR UNKNOWN ENVIRONMENT

In the programmed direct teleoperation control, the human operator overrides the operation by using JS and tries to adjust slight miss-match between the ground model and the on-orbit situation.

In addition to such override function, the major expectation of the human operator is its adaptive and flexible control capability under a situation of malfunction or unknown trajectory. However, if a working target has some closed link characteristics, such as our truss structure, its ground teleoperation becomes drastically complex for human teleoperation without a suitable operation aid system.

Thus in addition to the basic JS operation, we have developed the several advanced aid systems for the human direct teleoperation from the viewpoint of the "tip force", described in the followings.

### (1) Visual Aid using Predictive Force Method<sup>10)</sup>

For the direct teleoperation of the unknown closed link trajectory, we have developed a new visual aid system that assists the human operator based on the "tangential direction" of the past trajectory and "predictive force". For the smooth closed link operation, we assume that the best/optimal direction of the operational force should be the tangential direction of the trajectory. (Fig.10)

The "tangential direction" can be defined from the past trajectory telemetry data, using various estimation method such as the least square approximation or the moving average. The "predictive force" is defined as the theoretical compliance force using the subtraction of the arm tip positions from the current command and the latest telemetry data.

In our aid method, only the past arm tip trajectory history and the last teleoperation command are used, and the design database is never used, although it is the essential parameter in a usual predictive aid system.

The appropriate joystick inputs have two components. One is in parallel with the tangential direction of the current point to apply the deployment force (tangential input). The other is in the vertical direction of the tan-

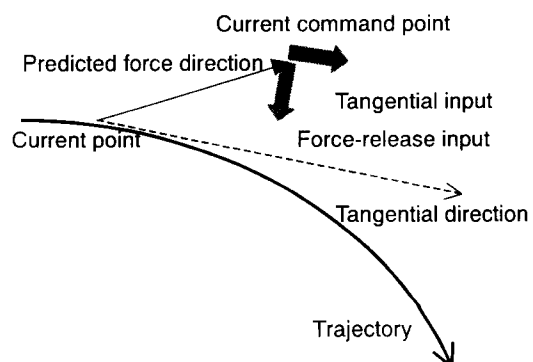


Fig. 11 Joystick Assists by Predictive Force

gential input to release the excessive force (force-release input). These diagonal input directions are converted into the joystick coordinate. By this aid system, the operator can easily handle the complex 3D spline closed link trajectory without move-and-wait, and within allowable force. (Fig.11)

## (2) Ground Loop Tele-Control based on Predictive Force Method<sup>10)</sup>

We have extended this predictive force method to the ground loop control. When the operational force is specified, the target command point can be determined uniquely on the tangential line. The suitable next command is decided toward the target point within the arm tip speed limitation and control gain.

The predictive force is controlled within the specified force. The time delay might be the major disturbance for this control, but its effect is not so severe when the control gain is set as small enough. Furthermore, this control method might decrease the excessive operational force of the usual pre-programmed control based on the design data, because it essentially does not rely on any design model.

In Fig.12, the direct human teleoperation shows that our visual aid successfully assists the operator to trace the correct trajectory. And the result by the ground looped programmed predictive force control shows the successfully generation of the appropriate arm tip movement without any design data.

## (3) Teleoperation through Virtual Force Reflection

It is well known that the direct force reflection (FR) (bilateral control scheme or force feedback) might be effective only with delays of less than 1 second and so with heavy degradation and is not suitable for the space robot teleoperation. However, the use of FR to the operator is expected to improve the human hand task performance. We have used a FR system to display virtual forces for the continuous teleoperation guide of on-orbit manipulators, with long communication time delay up to 7 seconds. A two DOF force reflecting joystick have been used as the FR hand controller (FR-HC).

The FR-HC guides the operator hand movement based

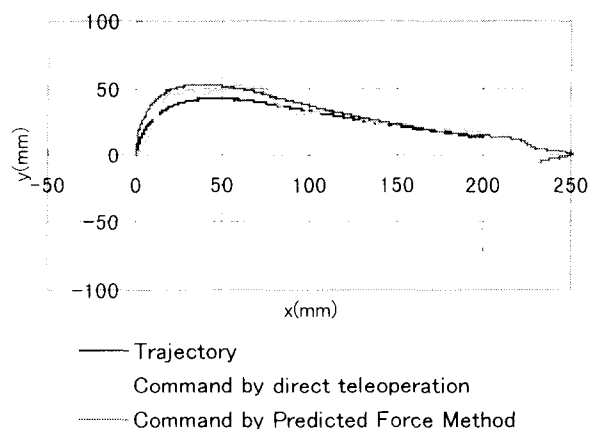


Fig. 12 Result of the Predicted Force Method Human JS Operation vs Programmed PFM

on the following virtual forces, instead of the real/telemetry force data. Using this FR guide, capturing the GPF-N and the TJ assembling were successfully completed.

### a) Potential virtual force fields

In this FR, the CAD data is only used as the potential field to decrease the effect of inaccuracy and time delay, and to increase the human operator's judgement based on other data. The operator keeps the control during the movement, can stop it, reverse it or overrun the guiding force reflection. Using the tip position measurement, by the ground image processing, the operator will update the force potential field. (Fig.13)

### b) Virtual force as physical constraints

The potential virtual force field is also generated from the closed link trajectory, that constraints the arm tip movement physically.

For these virtual physical constraints, FR robot model and "snapshot" procedure are developed to reflect the virtual force field to the operator, according to the real robot position in the work environment. (Fig.14)

### c) Adaptive Virtual force by probing environment

Finally, since the TJ assembling looks like a too severe "peg-in-hole", the TJ insertion task requires more precise positioning than a known design database. Thus in this virtual force approach, we implement the probing the environment task before the insertion task itself.

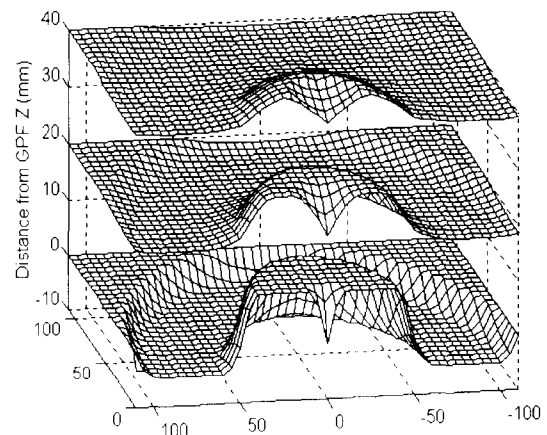


Fig. 13 Force field for GPF grasping

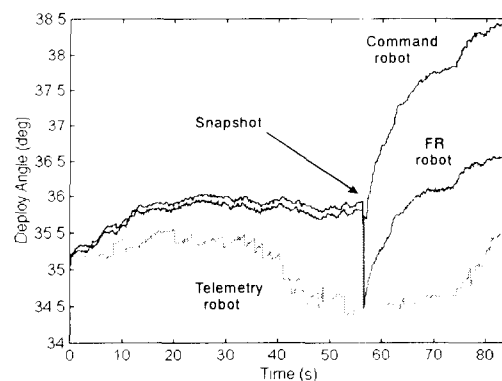


Fig.14 Snapshot during disassembly of the TJ

From the force and position telemetry data by the probing, an on-line map of the TJ peg-in-hole environment is built as a virtual force map to guide the operator through the task.

#### (4) Force Accommodation Control

In addition to the compliance control, ETS-VII robot arm can be controlled by the force/torque command, called "force accommodation control". In this control algorithm, the robot arm will continue to move until the external force/torque at the arm tip will reach the specified force/torque value.

Since the force accommodation control is implemented in the on-orbit controller, the following merits will be expected in teleoperation with time delay.

1. Excessive force and torque over the command can be suppressed.
2. Trajectory information is not essential.

Since the force accommodation control is fixed to the arm tip frame, the force direction deviates gradually from the correct trajectory during the truss deployment. Because of this trajectory deviation, the external force at the arm tip reaches the specified control force, and stops the robot movement. At this point the force accommodation control parameter shall be changed to the next one.

Fig.15 shows the result of deploying DT using the force accommodation control. When the telemetry force reaches the commanded force, the tip velocity becomes slow.

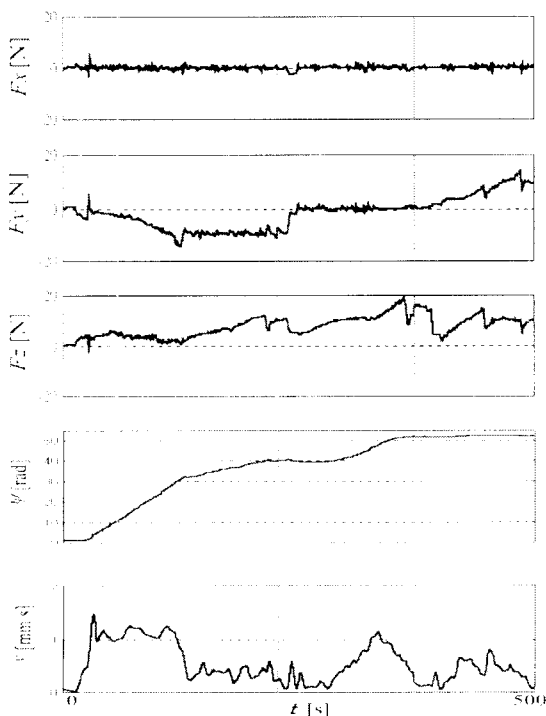


Fig.15 Experimental result of truss deployment

## 8. CONCLUDING REMARKS

Through the Truss Structure Experiments (TSE), the complex and dexterous space robot teleoperation for a small work object has been demonstrated on ETS-7. In the TSE experiments, two conventional teleoperation systems and three advanced aid systems have been tested and shown their better performance for the truss handling. Through the TSE experiment, the space robot capability and problems have been examined and demonstrated for the future truss structure construction.

The ground facility for the TSE experiments has been used and has shown its reliability for the space robot teleoperation. Through the TSE experiments, the advantage and the importance of the hardware simulator at the teleoperation facility are affirmed. The advanced research software I/F has also been utilized in the advanced teleoperation aid experiments.

For the phase 2 advanced experiments of ETS-7, we will continue to develop advanced teleoperation support technology, using the force feedback joysticks and other innovative aid systems until next November 1999.

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