RESULTS OF THE ETS-7 MISSION - RENDEZVOUS DOCKING AND SPACE ROBOTICS EXPERIMENTS

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Abstract

On orbit servicing is the indispensable function for future space activities such as building and operation of the international space station, inspection and repair of orbiting satellites, and conducting lunar/planetary explorations. The Rendezvous Docking (RVD) technology to meet and to connect two spacecraft in-orbit is also an essential technology for the future space missions such as logistic support of the international space station. Therefore, National Space Development Agency of Japan developed and launched an engineering test satellite named ETS-VII (Engineering Test Satellite #7) on November 28th, 1997 to conduct the RVD and space robot technology experiments. This paper shows an overview of the ETS-VII project and the results of various experiments on it.

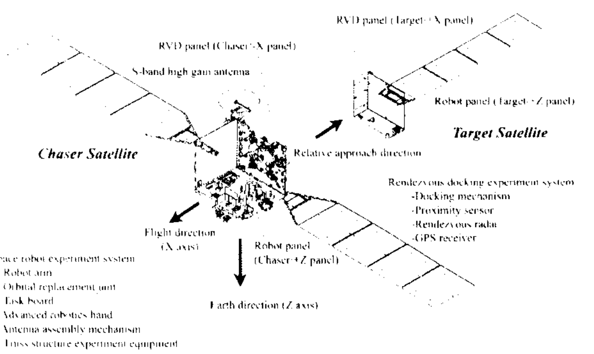

Fig. 1 ETS-VII chaser and target satellite

1. Introduction

1.1 Expectations for the rendezvous docking

In building a large space station in orbit, or providing maintenance services for orbiting satellite such as repair and fuel supply, the RVD technology is necessary. In operating the international space station, NASDA is to deliver Japanese logistic module using NASDA's H-II rocket. Fig.2 shows H-II transfer vehicle named HTV, which deliver the Japanese logistic module to the space station. Even though NASDA has a long history of research on RVD technology, NASDA did not have any experience to conduct the RVD in space. Therefore, NASDA decided to develop the Engineering Test Satellite No.7 (ETS-VII) to conduct the RVD and space robot technology experiments.

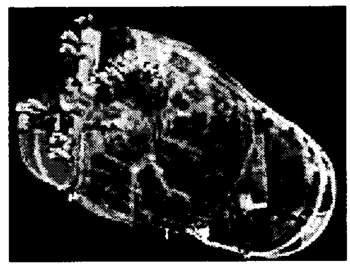

Fig. 2 Artist's image of the H-II transfer vehicle (HTV)

1.2 Expectation for the space robots

There are many tasks to be conducted in space such as building and operation of the international space station, inspection and repair of orbiting satellites, and conducting lunar/planetary explorations. Some of these tasks are currently conducted by astronauts. However most of these tasks are highly risky and expensive. Therefore space robot becomes attractive tool to conduct these tasks. The space shuttle's remote manipulator system (Ref.1) is used many times to deploy and capture satellite to/from space. Similar manipulator systems are to be mounted on the international space station to handle large element of the space station. (Ref.2, Ref.3) These space robot will expand ability of the astronauts. However these space robot are manipulated by astronauts and the limitation of the available manpower of the astronauts limits the capability of the space robots. If the robot can be teleoperated from the ground, the limitation of the astronaut's manpower will disappear. NASDA defined such robots as the second generation space robot. (Ref.4) The first generation space robot what is manipulated by the onboard astronaut(s) such as the shuttle remote manipulator system and the space station's manipulator systems. The third generation space robot is what is highly autonomous one. Planetary exploration robot that does not require frequent assistance from operator would be an example of the third generation space robot and will be realized in near future.

1.3 ETS-VII satellite

Mission of the ETS-VII is to conduct the unmanned automated RVD experiments and the space robot

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technology experiments. Since there was not appropriate satellite in orbit that can be used as target for the RVD experiments, chaser satellite and the target satellite were launched together. They are also called as HIKOBOSHI and ORIHIME respectively which mean a hunter boy and a weaver girl who were separated by the milky way and were allowed to meet each other once a year on 7th of July in an old Japanese love story. Mass of the chaser and the target satellite are 2.5t and 0.4t respectively.

ETS-VII satellite was launched by H-II rocket on November 28th, 1997. The orbit of the satellites is 550km altitude and 35degrees inclination. Mission life of the ETS-VII satellite was 1.5 years after the launch. However, satellite's status after 1year in orbit was good, mission period was extended to two years after the launch. The ETS-VII satellite on the H-II rocket is shown in Fig.3.

Fig. 3 ETS-VII on board H-II F6

1.4 ETS-VII project

Since ETS-VII is a rare opportunity to conduct the space robot experiments in space, following national agencies were invited to participate the project. These agencies developed their own onboard robot experiment equipment and on-ground control systems to conduct their own space robot experiments. Those are;

- Ministry of International Trade and Industries (MITI) conducts the advanced robotic hand experiments.
- National Aerospace Laboratory (NAL) conducts handling of truss structures by the tele-manipulated robot arm.
- Communication Research Laboratory (CRL) conducts antenna assembling experiments using the onboard robot arm.

Details of experiments by these agencies are shown in Ref.5, 6 and 7.

1.5 ETS-VII experiment system

ETS-VII experiment system consists of the satellite mounted rendezvous docking and robot system, the on-ground control system and the communication network, which connects the both systems. The communication between the onboard system and the ground control system which is located at NASDA's Tsukuba space center is realized using a data relay satellite (NASA's TDRS) in the geo-stationary Earth orbit. This communication network is shown in Fig.4. It is realized by the computer network of large number of computers at various sites. This computer network based communication cause time delay. In the case of ETS-VII, the time delay is about 6 to 7 seconds in return. A similar time lag can be observed on the internet-based communication.

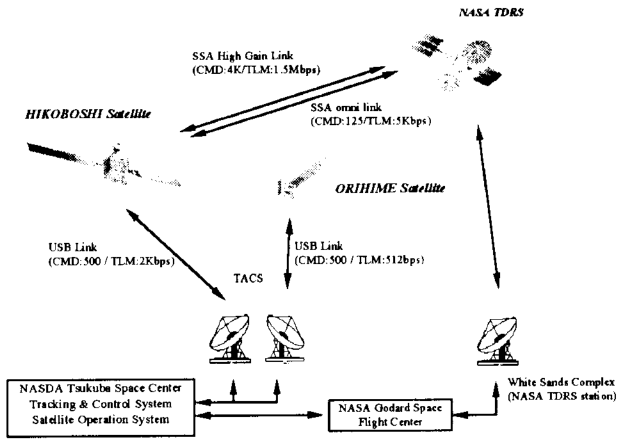


Fig. 4 ETS-VII experiment system

2. Rendezvous docking mission of ETS-VII

2.1 Mission objective

Purpose of the ETS-VII's RVD experiments are to conduct following technology experiments and provide confidence in conducting the following HTV project as mentioned in the section 1.2.

- Unmanned autonomous RVD between the chaser and the target satellites.
- Experiment of the remote piloting of the chaser satellite from the on ground control station.
- Conduct rendezvous flight which simulates the rendezvous against the international space station.

These RVD mission objectives were decided from the following considerations.

2.1.1 Ways of rendezvous

There are several ways of the RVD method. Direction of approaching the target is a matter of consideration. The Russian logistic support vehicle (Soyuz, Progress) approaches the Mir space station from either in front of the station or behind the station. The space shuttle also used similar approach in the past mission that recovered orbiting satellites. However the international space station adopted new way. Spacecraft that approach the space station must approach the station from beneath of it. This is to increase safety (decrease risk of collision of both spacecraft) during the final phase of rendezvous. In this way of approach, it is possible to find a trajectory that does not intersect the orbit of the space station. Approach from in front of or from behind must take a trajectory that intersects orbit of the target.

2.1.2 Way of docking

Way of docking is another point of consideration. The already established way of docking which is used by Russian Soyuz / Progress spacecraft and the space shuttle is "docking" which makes connection of two spacecraft using kinetic energy caused by the relative speed of two spacecraft. The relative speed at docking is in the order a few cm/sec. However this type of docking produces vibration of the flexible appendages such as solar panel. It is not adequate to apply this way of docking to the in-orbit connection of satellite, since satellite are generally built by light weight material and are not rigid enough to conduct the above type of docking. Therefore, a new type of docking mechanism and way of approaching are required.

2.1.3 Unmanned rendezvous docking

Way of control of the RVD is also matter of consideration. Rendezvous docking of NASA's space shuttle or Russian Mir station is controlled or monitored by astronauts onboard the space craft. However in the case of ETS-VII, it is unmanned satellite and continuous monitoring / control can not be realized without using two or more data relay satellite in geostationary orbit. At the time of planning the ETS-VII satellite, only one experimental data relay satellite was foreseen to be used by ETS-VII. Therefore ETS-VII's RVD system was decided to be autonomous one.

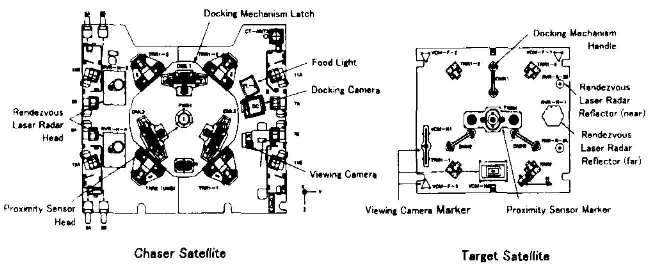


Fig. 5 RVD equipment on docking panel

2.2 GNC function of ETS-VII RVD

To perform autonomous RVD, the navigation function to measure and estimate relative position and velocity are needed. ETS-VII has three navigation sensors which are GPS receiver (GPSR), Rendezvous laser Radar (RVR) and Proximity sensor (PXS), and selects main navigation sensor according to relative range. ETS-VII GNC function is divided into three phase. One is the docking phase using the PXS. Another is the final approach phase using the RVR. The other is relative approach phase using the GPSR. The overview of these function as follows. (Ref. 8,9) Table-1 shows GNC performance required in each phase.

Within 2m distance, the relative position and relative attitude of the target satellite are measured by the PXS mounted on the chaser satellite. The chaser satellite approaches or goes away to/from the front of target satellite using this data. In the separation phase, The

Table-1 GNC performance required in each phase.

	requirement
TF Injection Accuracy	
Relative position $((X\text{-}TF)^2+Z^2)^{1/2}$ (m)	less than 80
Y(m)	less than 60
Relative velocity Vx,y,z (m/sec)	0±0.2
VP Injection Accuracy	
Relative Position X(m)	VP±0.3
Y(m)	0±0.3
Z(m)	0±0.3
Relative Velocity X,Y,Z (m/sec)	0±0.01
DM Capture Condition	
Relative Position X(m)	0.532±0043
Y,Z(m)	0.0±0025
Relative Velocity Vx(m/sec)	0.01±0005
Vy(m/sec)	0.0±0002
Vz(m/sec)	0.0±0005
Relative Attitude roll(deg)	0.0±1.9
pitch, yaw(deg)	0.0±1.6
Relative Attitude Rate roll, pitch, yaw (deg/sec)	0.0±0.1

chaser satellite drifts out of capture area of Docking Mechanism Latch (DML), the chaser satellite automatically starts 6 DOF control based on PXS navigation. In the approach phase, the chaser approaches for the target at the velocity of 1cm/sec with 6 DOF control. On injection capture area, the DML automatically closes and captures the Docking Mechanism Handle (DMH) mounted on the target satellite. On the capture area of DML, both satellite's Reaction Control System (RCS) are disabled.

Between 2m to 520m distance, the relative distance and the direction of the target satellite are measured by the RVR. In this phase, reference trajectory guidance and Line Of Sight (LOS) control by the RVR navigation are adopted. The RVR measures the relative range and LOS angle. The Guidance Control Computer (GCC) estimates the relative position and velocity by processing the RVR measurement and earth sensor (ESA) data. The GCC issues the position and velocity command along the fixed reference trajectory along the V-bar. The chaser approaches/departures at the velocity of 5-10cm/sec along the V-bar. During V-bar approach/departure, the chaser executes LOS control against the target. At the end of the approach phase, the chaser is injected to Vicinity Point (VP:2m) to hand over the docking phase.

Beyond 500m distance, the relative distance and the relative velocity are measured by the GPSR mounted on both satellites and a flight trajectory of the chaser satellite is automatically generated by the GCC. In this phase (relative approach or departure phase), the C-W guidance based on the relative GPS navigation is adopted. The chaser satellite GPSR receives absolutely navigation data of the target that is transmitted from the target GPSR via the inter-satellite communication link between the chaser and the target satellite. The chaser GPSR computes relative position and velocity. The GCC computes delta-V command to inject the aimed position based on the GPS relative navigation data. To minimize the injection error, mid course maneuvers are also executed. Each the thruster firing automatically cut off based on the velocity increment measured by the accelerometer (VIC: Velocity Increment Cut off guidance). The injection accuracy by the GPS relative navigation is about 80m. On the other hand, the measurement range of RVR is 600m and the FOV of RVR is 3deg for the relative range. Accordingly, in the worst case, the LOS angle is over 4deg. Therefore we fixed the acquisition point by RVR (Terminal phase Finalization point :TF point) at 520m on the V bar, and the Chaser control LOS pointing based on the GPS relative position to pick up the Target by RVR.

Beside the above autonomous RVD, remote piloting of the chaser satellite is planned to supplement the autonomous functions.

2.3 ETS-VII Flight Management Function

The flight management function is very important function for autonomous RVD. ETS-VII flight management system (FMS) is realized by RendezVous docking Flight Software (RVFS) installed on Guidance Control Computer (GCC). The transition among these modes are executed by FMS or command from ground support facility. The ground support crews monitors both satellite conditions before transition to the next phase and sends "GO" command. During the RVD experiment flight, the FMS ensures the safety of the Chaser and the Target i.e. prevent from collision. In the ETS-VII, two fail safe criteria is adopted within 30m from the Target. To ensure this criteria, not only FMS is installed the fault tolerant computer but also safe approach trajectory and closing velocity are selected.

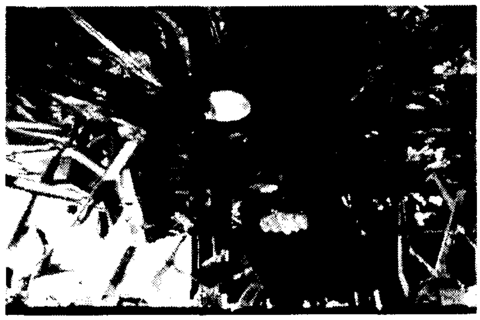
The FMS has the five functions, mode control, time control, fault detection, fault isolation/recovery and safety control. The mode control function change the mode/sub-mode according to fixed condition about relative position, relative velocity, sensor/actuator status and system status. The time control function calculates the elapsed time from beginning of each experiment and relative time based on GPS time. The fault detection function detects the failure of sensors (PXS, RVR, GPSR earth sensor and inertial reference unit) and actuators (reaction control system, docking mechanism). The failures are detected by monitoring change of sensor data and status. The fault isolation/recovery function discriminates the fail sensor or actuator and switches it to redundant component. If redundant sensor or actuator is fail (two failure), the mode transition to Safety Ensuring Mode (SEM) is required. The safety control function detects the failure of satellite system and changes it to SEM if necessary. The system failures are as follows. 1)navigation failure, 2)guidance failure, 3)Chaser/Target, Chaser/TDRS inter satellite communication link failure 4) Guidance Control Computer (GCC)failure, 5) power supply system failure.

If mode transition to SEM is required, a Disable Abort (DA) or a Collision Avoidance Maneuver (CAM) is executed automatically according to relative position. The DA is adopted beyond 30m range from the Target. In this region, non-collision trajectory, witch both satellites never collide if the Chaser orbit maneuver disable (DA) is selected. CAM is adopted within 30m range from the Target because non-collision trajectory can not be selected within the area . In this region, the approach velocity along the V-bar is limited (<=5cm/sec) under the safe velocity witch the CAM can be executed.

2.4 Experiment Result

2.4.1 First RVD Experiment Flight

On July. 7 1998, the first autonomous RVD experiment flight (Flight Path 1 (FP-1)) are successfully completed. The FP-1 is executed during one event of the TDRS (1 event is approximately 40min.). The ground support crews sent the "separation command" at 7:09(JST) and the Chaser separated the Target at the speed of 1.8cm/sec. When the Chaser drifted out the capture area of Docking Mechanism Latch (DML) , the chaser started to control automatically and the Target started earth pointing control. Then the Chaser kept the relative position at Vicinity Point (VP:2m) for 15 minutes. After position keeping at VP, the ground crews sent the "Target control off" "approach command" and the Chaser approached the Target at the speed of 1cm/sec. On entering DML capture area, the Chaser automatically cut off its thruster and the DML captured the docking mechanism handle on the Target and mated it at 7:33 . Photo- 1 shows docking camera on the Chaser



Upper : The Target, Lower : The Chaser, Left bright sphere : The earth

Photo- 1 Capturing Target satellite before contact

2.4.2 Second RVD Experiment Flight

On Aug. 7 1998, the second autonomous RVD experiment flight (Flight Path 2 :FP-2)) was performed. In the original plan, the Chaser would make a flight over range of 0 to 500m using the RVR. It would take four hour from separation to docking.

In the first sight of TDRS, separation operation, which had been already demonstrated in FP-1, was executed and the Chaser kept the position at VP for 10 minutes. During the position keeping, the Chaser switched its navigation system from PXS to RVR. After checking performance of the Line Of Sight control using RVR, ground support crews sent "VP departure command" at 3:13 (JST) . The Chaser departed along the V-bar at the speed of 10cm/sec.

In the second event of TDRS, the Chaser was departing at the range of 450m. Then the Chaser reached at 525m point. After monitoring FMS's mode change and status of both satellites, ground support crews sent "TF departure command" at 4:57(JST). The Chaser approached along the V-bar at the speed of 10cm/sec.

In the third event of TDRS, the Chaser would be approaching at the range of 30m from the Target. But in the acquisition of sight from TDRS, the Chaser change its flight mode to Safety Ensuring Mode (SEM), and made flight at the range of 1.6km from the Target to retreat point. During invisible time after second event, the Chaser's thruster miss firing was happened. Then the Chaser caused attitude anomaly. As a result, the Chaser automatically change its mode to SEM and executed the Disable Abort (DA).

After this anomaly, five times attitude anomalies were happened during V-bar approaches and position keeping maneuvers. During the experiment, the Chaser made a flight over range of 0 to 12km using not only RVR but also GPS relative navigation. Thruster miss firing, witch caused attitude anomalies, always happened on the Z direction thrusters. The Chaser assigned three thrusters for three degree of freedom such as +roll, +pitch and +Z. If the Z thruster is miss firing, the control of 3 degree of freedom must be performed by two thruster. Therefore, attitude anomaly was happened.

Many approaches were tried to make re-docking with the Target. To avoid the Z thruster miss firing, it was necessary to limit to use the Z thruster. Therefore, only X thruster were used to inject into the TF point as possible, and V-bar approach range was made short. In the original plan, the Chaser would switched its navigation from relative GPS navigation to RVR navigation at TF(520m) point. But, fortunately, the relative GPS navigation was much more accurate than our expectation. Then the Chaser could be injected to TF'(150m) point by C-W guidance or manual delta X maneuver using relative GPS navigation. Additionally, RVFS was modified to minimize possibility of attitude anomaly by the Z thruster miss firing. As a result, on Aug. 27th, the Chaser successfully mated with the Target. Fig. 6 shows trajectory in the FP-2 experiment.

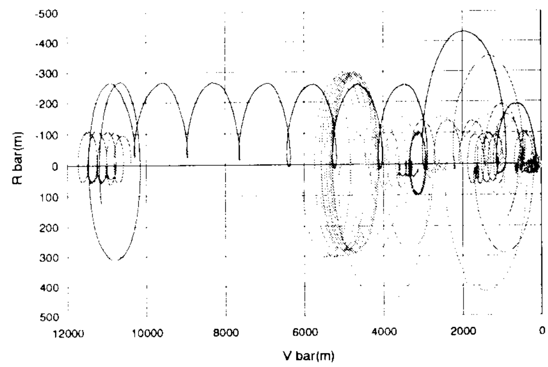


Fig. 6 trajectory in the FP-2 experiment.

3. Space robot mission of ETS-VII

3.1 Mission objectives

ETS-VII robot experiments are to conduct following experiments and to show taxpayers that the teleoperated space robot or the second generation space robot is a useful tool for future space mission.

- Performance evaluation of the onboard robot system: ETS-VII robot arm works in space more than one year without maintenance.
- Experiment of the coordinated control of the satellite attitude and onboard robot arm.
- Teleoperation of the onboard robot arm from ground.
- Demonstration of the in-orbit satellite servicing such as visual inspection, equipment exchange, fuel supply, target satellite handling and others:
- Provide space robot experiment opportunity to national laboratories outside NASDA since opportunity to conduct space robot experiments in space is quite rare. (Ref.5-7)

3.2 ETS-VII robot experiment system

3.2.1 Onboard robot system

ETS-VII onboard robot system consists of 6 DOF robot arm and a set of robot arm's payloads which are shown in Fig.7. These equipment are mounted on an Earth looking surface of the chaser satellite. This is to use the reflected sun light from the Earth atmosphere as the light source for the cameras. The reflected sunlight from the earth atmosphere is preferable since it is scattered light and makes little shade. (Ref.10)

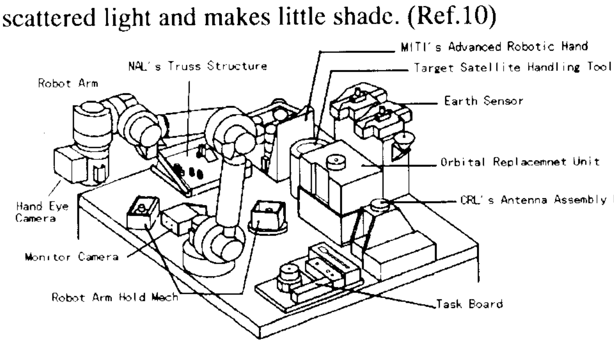


Fig. 7 ETS-VII onboard robot system

(1) Robot arm

The ETS-VII robot arm is about 2m stretched length and its joints are driven by combination of the DC brush-less motor, the harmonic-drive-gear© and a resolver.

ETS-VII robot arm has following control modes;

- Arm tip position control mode
- Joint angle control mode
- Compliance control mode (incl. force control, active limp and impedance control)

The compliance control is realized by the onboard robot control system using data from the force-torque sensor on the robot arm. Instructions to the onboard system are given by the on-ground robot control system using robot language command such as "move A to B". On-board robot control system generates trajectory to realize the instructed robot arm's tasks and calculates joint angle to realize the required robot arm's motion. Joint velocity or arm tip velocity commands are sent in forms of joint position or arm tip position commands. This is to assure safety against sudden disruption of the communication link during the robot arm's motion. These control modes were tested in orbit and showed good performance. The positioning accuracy (repeatability) of robot arm was better than 1.5mm.

(2) Video cameras on the robot arm

A hand eye camera is mounted on the end effector. Another monitor camera is mounted on the first joint of the robot arm. The first joint acts as camera's pan unit. Up to five video images out of two cameras per a second (5 frame/second) can be sent to ground using the JPEG compression format.

(3) Add-on tools

ETS-VII robot arm's end-effector is most suitable to handle medium size/weight equipment, which is attached on the same platform with the robot arm. It is not suitable to handle small equipment or to grasp a floating object. Therefore, ETS-VII robot arm uses additional tools to handle these payloads. A taskboard handling tool, which has two fingers and a fixed peg, is used to handle various equipment on the taskboard such as slider, switch, and hole for peg-in and others. A target satellite handling tool, which has large two fingers, is used to grasp the target satellite. Photo-2 shows the robot arm with the taskboard handling tool is handling a metal ball with a metal chain on the taskboard. (Ref.11)

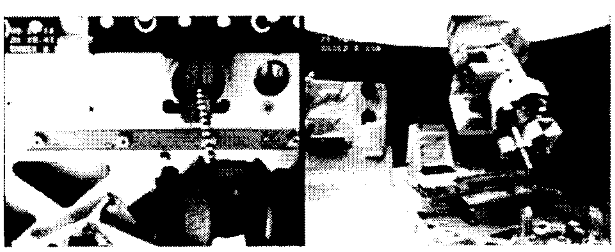


Photo- 2 Handling of small parts using add-on tool

(4) Orbital Replacement Unit (ORU)

The orbital replacement units (ORU) are widely used on the internal space station to exchange equipment in orbit. ETS-VII carries one ORU as an experimental payload of the robot arm. Size and mass of the ORU are similar with those of a microwave oven. It housed fuel tanks, valves, liquid connector and electrical connectors which were used by the fuel supply experiments. Photo-3 shows ORU handling by the onboard robot arm.

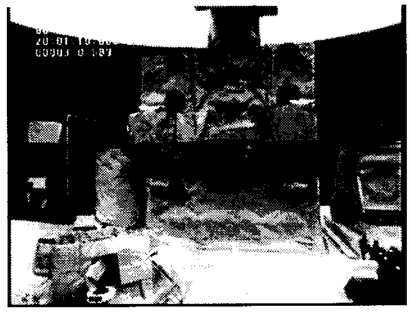


Photo- 3 ORU handling by the ETS-VII robot arm.

3.3 On-ground robot control system

Design requirement for the robot teleoperation system of ETS-VII is;

- Number of operators necessary to operate the system should be minimum and the hours to be required to learn and to prepare operations should be minimum.
- Any dangerous action such as collision against other object or too fast motion which distributes satellite attitude stability should automatically be prohibited even if the operator try the action without knowing the influence of the planned action.

Since ETS-VII's data communication is realized by the packet data transmission through a lot of computers at various sites which are shown in Fig.4, the overall time delay in the robot control loop is 6 to 7 seconds.

Command data to the onboard robot system can be sent in two modes, the non-interval command mode and the interval command mode. In the time interval command mode, command data can be sent at each 250msec. However to maintain a data rate within the allocated data rate, limited volume of data can be sent in this mode. In the non-interval command mode, larger command data can be sent at lager time interval. ETS-VII's teleoperation system is designed as follow to realize the above mentioned requirements and these constraints. (Ref. 12-16)

3.3.1 Teleoperation Mode

According to the two command data transmission modes, ETS-VII robot arm system has two teleoperation modes, the "supervised control mode", which uses non-interval commands and the "telemanipulation mode", which uses time interval commands. In the supervised control mode, instruction to the onboard robot system can be sent in codes which mean like "Move from A to B at a speed of C, acceleration D, compliance parameters of E and, etc......" The onboard robot control system decodes this instruction to generate robot arm's tip trajectory, to calculate joint angles using the inverse kinematics, and controls individual joints.

If the robot arm's working environment and the tasks to be conducted are well defined, the automatic task execution is realized using this control mode. In this mode, the command sequences can be written using GUI (graphical user interface) into a flowchart. This commands sequence is verified using the on-ground robot simulator, which simulates the actions of the onboard robot system. The verified command sequences are stored in the robot operation facility. In the actual operations, necessary command sequences are selected by an operator and instructed to start when they are required. Then each command is sent out automatically each after the previous command is successfully conducted. This operation method is simple and safe, and is recommended for most of space robot's tasks, which are well defined.

3.3.2 Telemanipulation mode

In the telemanipulation mode, instruction to the onboard robot system are sent in the from of the robot arm's tip position and pose at each 250msec. These instruction are generated from input by two 3-dof joysticks, which are similar with those of the space shuttle's remote-manipulator system. The onboard robot control system will generate robot arm trajectory by interpolating these data. If one data is missing by a communication error or other reasons, the onboard robot system will interpolate the missing command. If more than two commands are missing, the onboard system will stop robot arm's motion assuming that the commands from the on-ground station were stopped by the operator or by the communication error. If commands from the on-ground station does not arrive constantly, the onboard computer's FIFO (first-in-first-out) buffer adjusts the time interval.

Teleoperation under the time delay of 6 seconds is not easy. ETS-VII's on-ground robot control system uses following operator aids to assist telemanipulation.

- Predictive computer graphics, which show how the robot arm will move if a command will be executed.
- Shared control between the telemanipulation and the automatic control.
- Imaginary guide plane to guide the robot arm motion to a desired position and to inhibit other motions.

3.3.3 Telemanipulation by a shuttle astronaut

In March 1999, NASDA astronaut, Mr. Wakata was invited to conduct telemanipulation of the ETS-VII robot arm. He operated the shuttle manipulator to recover a free flyer from orbit in 199 and his skill to operate the shuttle manipulator is highly recognized within NASA. His given task in the telemanipulation on ETS-VII was to trace surface of the experimental equipment on ETS-VII by the onboard robot arm keeping the push down force around 20 Newton in the telemanipulation mode. With help of the compliance control of the onboard robot arm, he conducted the task very smoothly, even though he could spent only two days for training including lecture and training on the robot teleoperation system. This shows ETS-VII robot system is a user-friendly system, which is easy to learn and to operate.

4. Coordinated satellite attitude & robot arm control

The mass of the ETS-VII chaser satellite is about 2.5t. The ETS-VII's robot arm handles payloads of a few kg to 400kg (target satellite). Attitude of the satellite platform must be maintained within a few tenth degrees by the reaction wheels and the gas jet thrusters even against the robot arm's reaction. This is to maintain the communication link through the data relay satellite and to generate electrical power from its solar arrays. However, if the reaction of the robot arm motion is too large, the satellite attitude control system can not maintain the proper satellite attitude. Therefore, the coordinated control of the satellite attitude and the robot arm is realized through the coordination of the onboard satellite attitude control system, onboard robot control system, and the on-ground robot control system. Fig.8 shows this coordinated control system.

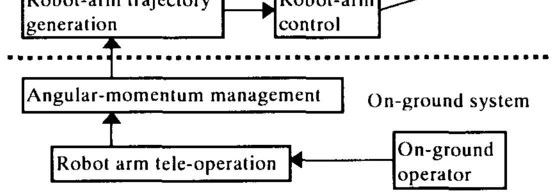


Fig. 8 Coordinated satellite and robot control system

The onboard robot control system estimates the angular momentum that the planned or commanded robot arm motion will produce. This estimated angular momentum is provided to the onboard satellite attitude control system to conduct the feed-forward angular momentum compensation. The on-ground robot control system also estimates the angular momentum which the planned robot arm motion will produce. If the estimated angular momentum is too large for the satellite attitude control, then the planned or instructed robot arm motion will be canceled or modified to prevent the excess satellite motion beyond the capability of the satellite attitude control system. This assures satellite attitude stability even if the robot arm motion is instructed by telemanipulation which the robot control system can not predict its motion. Detail of the coordinated satellite attitude and robot arm control is shown in Ref.17-19.

4.1 Handling target satellite by the robot arm

An experiment to handle the target satellite by the onboard robot arm was conducted. One of the aims of the experiment was to test the coordinate satellite attitude and robot arm control capability. Since mass of the chaser satellite is about 2.5t and that of the target is 0.4t. Therefore the reaction from the robot arm when it manipulate the target satellite is large enough to disturb stability of the chaser satellite's attitude. Photo-4 shows the experiment. Images are from onboard cameras and the computer graphics, which animates the robot arm and satellite motions. The robot arm moved the target satellite to disconnect from the chaser satellite and then moved back to the docking position. The first move was under the traditional satellite attitude control and the latter was under the coordinated satellite attitude and robot control. It is clear that the coordinated control worked well.

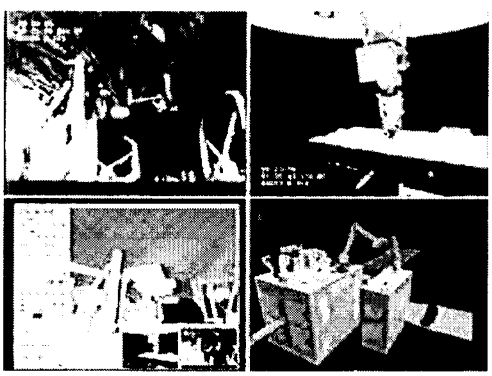


Photo- 4 Target satellite handling experiment

5. Conclusion

In this paper, we introduced an over view of the project and experiment results of the ETS-VII which is conducted the unmanned automated rendezvous docking experiments and the second generation space robot experiments. The most up-to-date information on ETS-VII experiment will be got on the Internet at "http://oss1.tksc.nasda.go.jp/ets-7/".

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