Space robot experiments on NASA's ETS-VII satellite  
—An overview of the project and experiment results—

Dr. Mitsushige Oda  
National Space Development Agency of Japan (NASA)  
2-1-1 Sengen, Tsukuba-shi, Ibaraki-ken, Japan  
e-mail: Oda.Mitsushige@nasda.go.jp

1. Introduction  
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. Astronauts currently conduct some of these tasks. However most of these tasks are highly risky and expensive. Therefore space robot becomes attractive tool to conduct these tasks. However, if an astronaut onboard spacecraft such as the shuttle or the space station operates the robot, utilization of the robot is limited by the limitation of the available hours of the astronauts. Therefore, NASA started development of the second-generation space robot[1], which is controlled from the ground. NASA launched an engineering test satellite named ETS-VII on November 28, 1997 to conduct the rendezvous docking and the second-generation space robot technology experiments [2]-[4]. This paper shows an overview of the ETS-VII project and the space robot experiment results gained by ETS-VII.

2. ETS-VII satellite  
ETS-VII is the latest in NASA's series of engineering test satellites. ETS-VII is in fact a pair of satellites, a larger chaser and a smaller target satellite, which can be released for the rendezvous and docking experiments (Ref.4). The larger satellite carries a robot arm with a stretched length of about 2 m, and a set of experimentation equipment to test the robot's capabilities: a task board on which typical robot manipulation activities can be performed and measured, an Orbital Replacement Unit (ORU) to be removed and reinstalled, a truss structure to be erected, an antenna assembly mechanism to be actuated and an advanced robot hand.

ETS-VII satellite was launched by the H-II rocket on November 28th, 1997. The orbit of the satellites is 550km altitude and 35degrees inclination. Mass of the chaser and the target satellite are 2.5t and 0.4t respectively. The ETS-VII satellite on the H-II rocket is shown in Fig.1. Since ETS-VII is a rare opportunity to conduct the space robot experiments in space, Ministry of International Trade and Industries, National Aerospace Laboratory, Communication Research Laboratory, European Space Agency, German Aerospace Center were invited to participate the experiments. Details of experiments by these agencies are shown in Ref.5 to 8.

2.1 Mission objectives of the ETS-VII robot experiments  
Mission of the ETS-VII robot experiments are to conduct following technology demonstration experiments and to shows taxpayers that the teleoperated space robot system is a useful tool for future space missions.

- Performance evaluation of the onboard robot system: ETS-VII robot arm works in space more than one year without maintenance while the space shuttle's remote manipulator system receives thorough maintenance each after its flight of one to two weeks.

- Experiment of the coordinated control of the satellite attitude and onboard robot arm: ETS-VII robot arm is mounted on a small satellite (2.5t / chaser) and therefore, the reaction from the robot arm will disturb stability of the satellite attitude. However instability of the satellite attitude makes it difficult to direct a communication antenna to a data relay satellite. Therefore, satellite attitude and the antenna direction must be controlled against robot arm's reaction.

- Teleoperation of the onboard robot arm from ground. Since the communication between the onboard robot system and the on-ground control system are realized by a complicated computer network and a data relay satellite, a time delay to communicate with ETS-VII from an on-ground control station becomes 6 to 7 seconds in return. The pure telemanipulation which manipulates the onboard robot arm seeing only video image(s) from the satellite under this time delay is not easy and is not preferred from the stand point of safety and operator's work load. Therefore, improvement of the teleoperation technology is required.
• Demonstration of the in-orbit satellite servicing such as visual inspection, equipment exchange, fuel supply, target satellite handling and others: These are to show the taxpayers and potential space robot users that the space robots are applicable for future space missions.

• Support space robot technology experiments by other agencies that participated the ETS-VII project. Agencies which participated the ETS-VII project are:[6]-[9]
  * Ministry of International Trade and Industries (MITI) which conducted the advanced robotic hand experiments.
  * Communication Research Laboratories (CRL) which conducted the antenna assembling experiments.
  * National Aerospace Laboratories (NAL) which conducted the truss structure handling experiments.

These agencies developed their own experimental equipment that was mounted on the ETS-VII satellite. Some other agencies and universities conducted space robot experiments borrowing NASA’s onboard and on-ground equipment under the agreements with NASA to conduct joint research using the ETS-VII satellite.

3. ETS-VII robot experiment system

ETS-VII robot system consists of the satellite mounted robot system, the on-ground robot control system and the communication network, which connects the onboard and on-ground systems. This communication is realized using a data relay satellite (NASA’s TDRS) in the geo-stationary Earth orbit (36,000km altitude orbit).

3.1 Onboard robot system

ETS-VII’s onboard robot system consists of 6 dof(degrees-of-freedom) robot arm and a set of robot-arm’s payloads which are shown in Fig.1 and Fig.2.

![Fig.2 ETS-VII onboard robot system](image)

(1) Robot arm

The ETS-VII’s 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 robot control system are given by the on-ground robot control system using the robot language commands such as “move A to B”. The on-board robot control system generates trajectory to realize the instructed robot arm’s tasks and calculates joint angles 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.

(2) Video cameras on the robot arm

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

(3) Experimental payloads of the robot arm

A lot of experimental payloads that are handled by the onboard robot arm are mounted on the satellite. Most of them are mounted on the chaser satellite as shown in Fig.2. Some of them are mounted on the target satellite. Experimental payloads of the robot arm are as follows.

• Orbital Replacement Unit (ORU)

The orbital replacement units (ORU) are widely used on the international 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 houses fuel tanks, valves, liquid connector and electrical connector s which were used by the fuel supply experiments. Fig.7 shows ORU handling by the onboard robot arm.

• Taskboard

The taskboard is an equipment which simulates various robotic tasks such as peg-in-hole, slider handle, surface for tracing, spring mechanism for force-torque sensor calibration and others.

• Target Satellite Handling Tool

The target-satellite-handling tool is a hand with two large fingers to grasp a handle bar on the target satellite during the target satellite handling and capturing experiments. This hand is normally stored in a cylindrical storage container and is attached to the robot arm when it is necessary

• Advanced Robotic Hand system

This is the equipment developed by MITI for its
own experiments. The hand is normally attached to MITT's small robot arm. During the ETS-VII's mission operation, the hand was re-attached to NASA's robot arm.

• Truss Structure Equipment
  This is the equipment built by CRL for its own experiments and was handled by NASA's robot arm.

• Antenna Assembling Mechanism
  This is the equipment built by NAL for its own experiments and was handled by NASA's robot arm.

3.2 On-ground robot control system
Design requirements for the robot teleoperation system of ETS-VII are:

• To be easy in learning and operating the system even under the time-delayed and limited communications environments. 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.

• To be safe and reliable in conducting tasks. Any dangerous action such as collision against other object or too fast motion which disturbs satellite attitude stability should automatically be prohibited even if the operator try the action without knowing the influence of the planned action.

ETS-VII's teleoperation system is designed as follows to realize the above mentioned requirements. (Ref.9,10)

3.2.1 Teleoperation mode
ETS-VII robot system has two teleoperation modes, the “supervised control mode” which uses non-interval commands and the “telemanipulation mode” which uses the 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 that 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 are instructed to start when they are required. Then the on-ground robot control system automatically sends commands each after the previous command is successfully transmitted and executed. This operation method is simple and safe, and is recommended for most of space robot's tasks, which are well defined. Fig.3 shows ETS-VII robot teleoperation facility.

Fig.3 ETS-VII robot teleoperation facility

3.2.2 Telemanipulation mode
In the telemanipulation mode, instructions to the onboard robot system are sent in the form of the robot arm's tip position and pose at each 250msec. These instructions are generated from the inputs by two 3-dof joysticks, which are similar with those of the space shuttle's manipulator system. The onboard robot control system will generate robot arm trajectory by interpolating these data. Telemanipulation under the time delay of 6 seconds is not easy. Therefore, the ETS-VII's on-ground robot control system uses following operator aids to assist telemanipulation.

• Predictive computer graphics which shows how the robot arm will move if a command will be executed. The graphics also shows pose of the current robot arm using telemetry data from the satellite.

• Shared control between the telemanipulation and the automatic control. Control of each control coordinate can be selected between the automatic control and the telemanipulation

• Imaginary guide plane to guide the robot arm motion to a desired position and to inhibit other motions.

Other functions such as the real-time health check of the onboard robot system which are used in the supervised control mode are also used in this telemanipulation mode to ease operator's workload. The compliance control, which is realized by the onboard robot control system also reduces operator's work load during the contact operations.

4. Experiment results
4.1 Performance evaluation of the onboard robot system
Operation of the ETS-VII onboard robot system started in March 1998 after the initial checkout of the satellite platform. Since then, various robot experiments were conducted on ETS-VII. The ETS-VII's originally planned mission life was 1.5 years after the launch. However, since status of the satellite
was healthy and some experimental tasks remained at the time to finish the originally planned mission period, operation of the ETS-VII satellite was extended another 6 months and further robot and rendezvous docking experiments were conducted.

The onboard robot system worked properly without critical problems until the end of the extended mission. Fig.4 shows result of the so-called “peg-in-hole” experiment. A peg of 18mm diameter, which was attached to the tip of the robot arm was inserted in a hole of 19mm diameter. The robot arm was controlled in the compliance control mode by the onboard robot control computer. The initial misalignment of 5mm (X: horizontal) was removed while the peg was inserted into the hole (Z: depth). The robot arm’s positioning accuracy (repeatability) was better than 1.5mm.

Fig.4 result of the “peg-in-hole” experiment

4.2 Teleoperation experiments
Most of the ETS-VII’s robot experiments were conducted in the supervised mode, since robot’s working environment is well defined and most of the robot’s tasks were also well defined. From the experience of various experimental operations, it was found that the supervised mode operation, which uses the electronic operation procedure, was quite easy and reduced workload of operators. Every electronic operation procedures, which were used, were saved and re-used in the later experiments to save the experiment preparation hours.

Some tasks such as the visual inspection of onboard equipment were conducted by the telemanipulation. Even though there was a time-delay of 6 to 8 seconds, the telemanipulation was not difficult, since operator can try (rehearsal) the operation using the actual operation console. The built-in onboard robot simulator, which included the electrical identical onboard robot control computer responded as if the data comes from the satellite. The predictive computer graphics image of the onboard robot also reduced operator’s workload.

4.3 Telemanipulation by a shuttle astronaut
NASDA astronaut, Mr. Wakata was invited to conduct telemanipulation of the ETS-VII onboard robot arm. He operated the shuttle manipulator to recover a free flyer from orbit in 1996. His skill to operate the shuttle manipulator is highly recognized within NASA and is appointed as a crew who assembles the international space station using the shuttle manipulator. His given task in the telemanipulation experiments was to trace surface of the experimental equipment on ETS-VII by the onboard robot arm keeping the push down force at the required force under 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 lectures 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. Fig.4 shows Mr. Wakata, a shuttle astronaut, telemanipulates the ETS-VII robot arm (March 16, 1999).

Fig.5 Shuttle astronaut (Mr. Wakata, left) operated ETS-VII robot arm

4.4 Coordinated control experiment of the satellite attitude and onboard robot arm
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 400 kg (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, the onboard robot control system, and the on-ground 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 the 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.11,12. Fig.6 shows satellite attitude and angular momentum of the robot arm while the robot arm grasped the target satellite and moved around the chaser satellite. The traditional feedback control was used till 1100 sec. The coordinated satellite attitude control that uses the feed-forward angular momentum cancellation, was used after 1100sec. It is apparent that the satellite attitude error became smaller by the coordinated control.

![Fig.6 Satellite attitude and robot arm's momentum during the target satellite handling experiment](image)

**4.5 Handling of various payload by the onboard robot arm**

ETS-VII onboard robot arm has an end-effector, which has three sets of fingers and latching mechanism. The combination of the fingers and the grapple fixture that has curved surface guide the robot arm to a position that the fingers and the latching mechanism can firmly grasp and lock the payload. This capability is useful to handle orbital replacement units (see Fig.7) and similar payloads. However it is not suitable to handle small payload and large floating payload. Therefore, ETS-VII uses additional tools that are attached to the end-effector. A taskboard-handling-tool is used to handle various small payloads on the taskboard. The target-satellite-handling-tool is used to handle the target satellite by the robot arm.

![Fig.7 ORU handling by the ETS-VII robot arm](image)

**5. Conclusions**

NASA's ETS-VII satellite which was launched on November 28, 1997 have conducted various space robot technology experiments and showed taxpayers that the teleoperated and satellite mounted robot can conduct various tasks which are needed in near future space activities. Further information on ETS-VII can be reached on the world-wide-web. (14)

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