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Experiences and lessons learned from the ETS-Vil robot satellite

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Abstract

National Space Development Agency of Japan (NASDA) launched ETS-VII (Engineering Test Satellite No.7) on November 28, 1997 to conduct the rendezvous docking and space robot technology experiments. ETS-VII is the world first satellite that used a robot arm on a satellite. The robot arm was 2m long and was tele-operated from the on-ground control station. Mission of ETS-VII lasted for two years and brought may experiences and results. This paper summarizes experiences and results of the ETS-VII robot satellite.

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. Some of these task is currently conducted by astronauts. However most of these tasks are highly risky and expensive. The space shuttle's remote manipulator system [1] is used many times to deploy and capture satellites tolfrom space. Similar manipulator systems are to be mounted on the international space station to handle large element of the space station [2][3]. These space robots will expand ability of the astronauts. However, since astronauts on the space station/ space shuttle manipulate these space robots, limitation of the available manpower of the astronauts limits the capability of the space robots. Therefore a robot system on a spacecraft that can be tele-operated from an on-ground station is an attractive tool for many tasks in space. In realizing a robot satellite which can conduct various tasks in space such as inspection, logistic supply, exchange of equipment and others, a lot of technologies must be developed. Those are, for instance;

(1) Robot related technologies
- Onboard robot system which can work in space
  - Robot arm and end-effector which can handle various payloads whose shape and mass are different
  - Hardware which can survive under the severe environment of space (vibration during the rocket launch, vacuum, thermal cycle, and radiation in orbit.)
  - Control system that can be implemented on the satellite mounted computer whose capability is limited.
- Teleoperation under the time delay and the limited communication bandwidth [4]-[6j

(2) Spacecraft and system related technologies
- Dynamics and control of the satellite that carries a robot
- Automated rendezvous docking technology
- Communication system between the onboard and on-ground systems

2. Mission of ETS-VII

Mission of ETS-VII is to conduct the unmanned automated rendezvous docking and space robot technology experiments. The ETS-VII's planned experiments are as follows [10][11].

(1) Rendezvous docking experiments
- performance evaluation of various newly developed components for the rendezvous docking such as a GPS receiver, a rendezvous radar and a docking mechanism
- autonomous rendezvous docking between the two unmanned satellites
- remote-piloting of the satellite against the target satellite from ground

(2) Space robot experiments
- performance evaluation of the satellite mounted robot system in space
- control of satellite attitude against robot arm's reaction
- tele-operation of a satellite mounted robot system from ground
- demonstration of various on-orbit robotic task such as exchange of equipment and fuel supply using the onboard robot system.

2.1 ETS-VII satellite

ETS-VII is a pair of twin satellites, a larger chaser satellite and a smaller target satellite. Mass of both satellite are 2.5t and 0.4t respectively. These two satellites were launched together by NASDA's H-II rocket on November 2B"', 1997. The orbit of the satellites is 550km altitude and 35degrees inclination. Mission life of ETS-Vil was 1.5 years after the launch. However, since the status of the satellite in orbit was good, the mission was extended to two years. An artist's ima e of the orbitin ETS-VII is shown in Fi 1

Fig.1 Artist's image ETS-VII

2.2 ETS-VII onboard robot system

The ETS-VII's robot arm is mounted on the chaser satellite. It is about 2m stretched length and has 6 rotational joints. Each joints are driven by combination of the DC brush-less motor, the harmonic-drive-gear© and a resolver [12]. A hand eye camera is mounted on the end effecter. Another monitor camera is mounted on the first joint of the robot arm. The first joint acts as a camera 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. ETS-VII's onboard robot system IS shown in Fig.2.

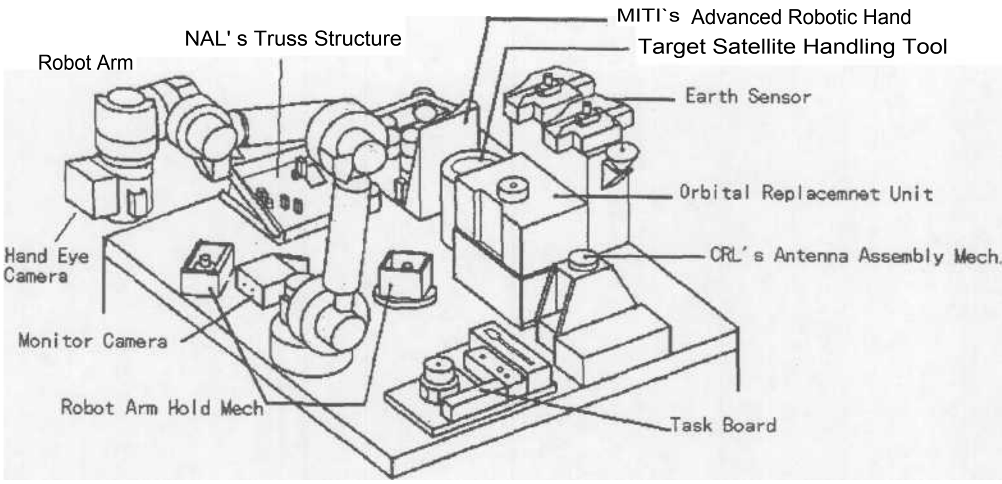

Fig.2 ETS-VII onboard robot system

The 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)

Instructions to the onboard robot arm are given by the on-ground robot control system using robot language commands such as "move A to B". The on-board robot control system generates trajectory to realize the instructed motion and calculates joint angles to realize the required trajectory.

The robot arm's experimental payloads that are mounted on the satellite are an orbital replacement unit (ORU), a task-board, and a target satellite handling tool, an antenna assembly mechanism, truss structures and an advanced robotic hand system. The last three equipment was developed by following national laboratories for their own space robot experiments.

- advanced robotic hand experiment by the Ministry of international trade and industries
- truss structure handling experiment by the National Aerospace Laboratories
- antenna assembling experiment by the Communication Research Laboratories

Details of the equipment and experiment results of these institutions are shown in [121-[141.

2.3 ETS-VII rendezvous docking system

ETS-VII's autonomous rendezvous docking was realized using the newly developed guidance and navigation sensors and the docking mechanism. Within 2m distance, the proximity camera sensor mounted on the chaser satellite measured the relative position and attitude of the two satellites. Between 2m to 500m distances, the laser radar measured the relative distance and the direction of the target satellite. Beyond 500m distance, the relative distance and the relative velocity were measured by the GPS receivers mounted on both satellites. The flight trajectory of the chaser satellite to approach / go away to / from the target satellite was autonomously generated by the onboard computer using these measured data.

2.4 **Communication system**

ETS-VII's rendezvous docking and robot system were monitored and controlled from NASDA Tsukuba Space Center. Communication between the ETS-VII satellite and the on-ground control system wa realized using a data relay satellite (NASA's TDRS) in the geo-stationary Earth orbit. Fig.3 shows ETS-VII's communication network. Since this communication network was realized by the computer network of large number of computers at various sites, it caused a time delay of 6 to 7 seconds in return. A similar time lag can be observed on the Internet based communications.

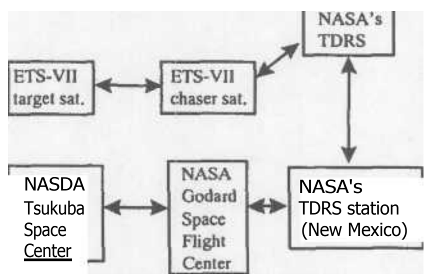

Fig.3 ETS-VII communication system

3. Mission results

Space robot experiments on ETS-VII were conducted for more than 100 days during the ETS-VII' mission, life. NASDA conducted following experiments and gained a lot of experiences.

3.1 Performance of the robot arm

The ETS-VII robot arm was used in space for nearly 2 years and its performance was pretty well. The positioning accuracy and the performance of the compliance control of the robot arm were satisfactory. Fig.4 shows results of the so-called "peg-in-hole" experiment. A peg of 18mm diameter, which was attached to the robot arm, was inserted into holes of 18.4mm and 19mm diameter. The position and attitude errors of the peg were corrected by the compliance control based on the robot arm's force-torque sensor data. Fig.6 shows peg's X and Z (insertion) position when the peg insertion from 5mm offset was conducted into 1 mm clearance hole. The peg was smoothly inserted into the hole. These results give a healthy base for the development and operation of the space station's remote manipulator system.

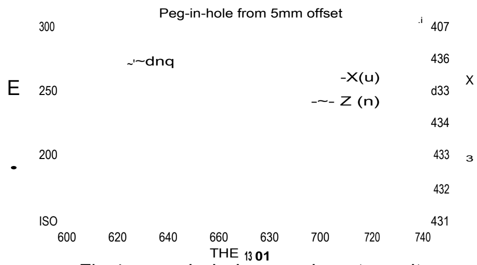

Fig.4 peg-in-hole experiment result

3.2 Tele-operation of the onboard robot arm

The ETS-VII on-ground robot operation facility was designed considering following requirements. [16]

- To be easy in learning and operating the system even under the time-delayed and limited communications environments. The time delay in the robot control loop is 6 to 7 seconds in return. The data rate to send commands to the satellite including onboard robot system and satellite platform is 4kbps. This data rate was decided from the existing communication system for the satellite operations. The down-link data rate is 2Mbps including video and telemetry data. The reduced data rate was preferred since it did not require to use higher frequency for the inter-satellite communication with the data relay satellite. Use of the higher frequency requires finer tracking control of the inter-satellite-communication antenna. Fine antenna pointing against the robot-arm's reaction is not easy.
- Number of operators necessary to operate the system should be minimum and the hours to be required to learn and to prepare operations should also be minimum. These is to lower the satellite operation cost.
- 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 such action

Fig.5 shows NASDA's ETS-VII on-ground robot tele-operation facility.

Tele-operation of the onboard robot arm from this operation system is realized in two modes, the supervised control mode [7] and the telemanipulation mode. In the supervised control mode, instruction to the onboard robot system are 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 and generates robot arm's tip trajectory. Then it calculates joint angles using the inverse kinematics, and controls individual joints. In this operation mode, all or most of the necessary instructions can be prepared and verified in advance before the actual task execution. In the actual operations, operator can call necessary operation procedures and can instruct to start the process. This way of task execution is simple and safe and is recommended to most of tasks on the satellite.

Fig.5 ETS-VII robot teleoperation facility

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 input 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's 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 do not arrive constantly, the onboard computer's FIFO (first-in-first-out) buffer adjusts the time interval.

Telemanipulation under the time delay of 6 seconds is not easy [6]. 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 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 workload during the contact operations.

3.3 Tele-manipulation 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 January 1996. His skill to operate the shuttle manipulator is highly recognized within NASA and is appointed as a crew member who assembles the international space station using the shuttle manipulator. His given task in the telemanipulation experiments on ETS-VII was to trace surface of the experimental equipment, the taskboard, on ETS-VII by the onboard robot arm keeping the push down force around 20N 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 hand-on training on the robot teleoperation system. This shows ETS-VII robot system is a user-friendly system that is easy to learn and to operate. Fig.6 shows Mr.Wakata tele-manipulates the ETS-VII robot arm.

Fig.6 Shuttle astronaut (Mr. Wakata, left) operated ETS-VII robot arm

3.4. Coordinated satellite and 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 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. There are some studies in the dynamics and control of robot satellite [8][9]. However those are not practical when the state-of-the-art satellite attitude control system and requirements for the safety are considered. ETS-VII adopted the coordinated control of the satellite attitude and the robot arm through the coordination of the onboard satellite attitude control system, 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 that 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.

Fig.7 shows the attitude motion of the chaser satellite while the robot arm manipulated the target satellite. The robot arm on the chaser satellite moved the target satellite forward and upward to generate the large reaction to the chaser satellite. Then the target satellite was moved back to the original position. Fig.7 shows the angular momentum of the robot arm motion and the attitude of the chaser satellite. Fig.8 show images from the satellite and CG images during this experiment. Attitude control of the chaser was by the feedback control during the first half period of the experiment and then the coordinated satellite attitude control. The gas jet thrusters were used as the attitude control actuators throughout this experiment. It is clear that the coordinated control worked well. Details of the coordinated satellite attitude and robot arm control are shown in [17][18].

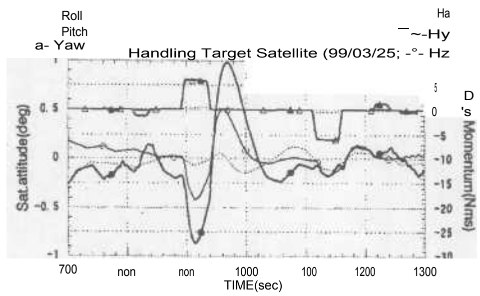

Fig.7 Satellite attitude and robot arm's momentum during the target satellite handling experiment

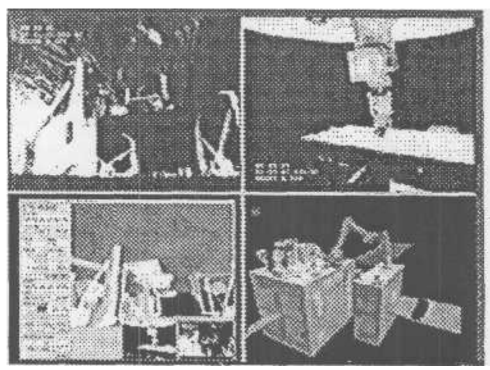

Fig.8 Target satellite handling experiment

3.5 Handling various payload by a robot arm

The ETS-VII robot arm can attach additional tools to the robot arm to handle small and large payloads beside the ordinary payload such as ORU [15]. Fig.9 shows the robot arm handles ORU. Fig.10 shows the robot arm with the task-board-handling tool handles a small metal cube on the task-board. A peg is also fixed with this tool and was used in the peg-in-hole experiments, whose results were shown in Fig.4.

Another tool, the target-satellite-handling tool was used when the robot arm handled the target satellite. The tool is always stored in a cylinder-like container on the chaser satellite (see Fig.2). This tool was attached when the robot arm handled the target satellite (see Fig.8). Power to drive mechanism of these tools is provided by a socket wrench in the end-effecter of the robot arm. The advanced robotic hand, which is usually attached to another small robot arm was also attached to the robot arm and was used to manipulate payload on the target satellite [12].

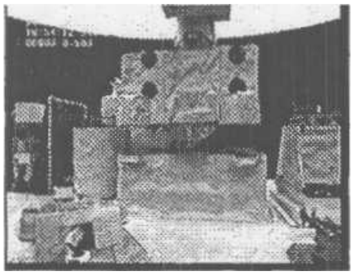

Fig.9 ORU handling by the ETS-VII robot arm

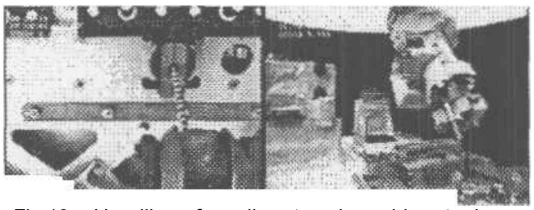

Fig.10 Handling of small parts using add-on tool

3.6 Capture and berthing of the target satellite by the onboard robot arm

ETS-VII onboard robot system has a capability to track a moving object using the onboard video data processing. A target satellite tracking and capturing experiment was successfully conducted as one of the additional experiments during the extended mission period. Details are shown in other paper to be presented at ICRA2000 (19).

3.7 Rendezvous docking experiments

ETS-VII's rendezvous docking were conducted three times. In the first rendezvous docking experiment, the chaser and the target satellite were separated up to 2m distance and then united each other after 24 minutes [11]. Fig.11 shows the image taken just before the docking by the onboard camera on the chaser satellite. The second and the third rendezvous docking experiments showed the autonomous rendezvous docking capability from 12km distance usin_ GPS.

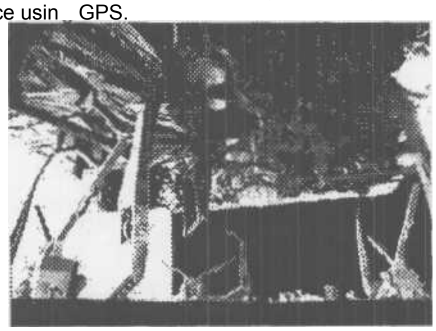

Fig.1 1 docking of the ETS-VII chaser (lower) and the target (upper) satellites

4. Lessons learned from the ETS-VII project

4.1 Development of the experiment system

ETS-VII satellite project was proposed in 1990 and its budget to develop the system was funded from 1992. Since cost of a rocket is not small, ETS-VII shared the capability of the H-II rocket with another satellite named TRMM (Tropical Rainfall Measurement Mission) that must be launched in 1997. Therefore, development of the ETS-VII satellite and its on-ground operation system must be finished by mid of 1997. The budgets to develop the satellite and the on-ground systems were also limited since there were many on-going projects at that time. This forced the ETS-VII project as the so-called faster, better and cheaper one. The strict control of the schedule and the cost avoided slip of the schedule and the cost-over-run that can be seen in many space projects.

Development of the ETS-VII satellite and its onboard robot system was conducted based on experiences of NASDA and its contractors to develop satellites. The most difficult work was development of various mechanisms that fasten various experimental payloads to the satellite platform. Since these payloads must be easily removed by the robot arm, while they must be tightly fastened during the launch of the satellite. Otherwise, the severe vibration during the rocket launch will destroy the payloads.

Development of the force-torque sensor was also a difficult task. An accurate force-torque sensor was required to realize the compliance control of the robot arm. However this requirement was inconsistent with the requirement that equipment on the satellite must survive through the severe environment during the rocket launch. This inconsistent was overcome by using a mechanism to suppress excess distortion of the force-torque-sensor caused by the vibration during the rocket launch.

4.2 Satellite operation

Satellite operation of ETS-VII went well, even though it suffered some critical problems after its launch. Most critical one was loss of the satellite-attitude stability, which occurred on its 3rd day in orbit. This was due to noises in its attitude sensors and was overcome by modifying the onboard attitude control software. ETS-VII's second rendezvous docking experiment was disrupted several times by problems with the gas jet thrusters. This was also overcome by modifying the onboard software. ETS-VII's robot operation was smooth on the whole. However it should be mentioned that its operations were sometime disrupted by the malfunction of the onboard computer, whose cause is thought to be radiation in space. This kind of malfunction should be avoided by the redundant system in the operational system. However, since ETS-VII is an experimental system, it has very limited redundancy for these malfunctions.

The number of operators and the cost of the space network that includes a data relay satellite mainly decide the cost of satellite operation. ETS-VII robot operation facility was designed so that the least number of operators can operate it. Just 5 operators as shown in Fig.5 operated it and helped to reduce the operation cost. ETS-VII was the first experience that used a data relay satellite. Using the space network that includes a data relay satellite is expensive. Use of a constellation of communication satellites in a low earth orbit would be an another solution to reduce the mission operation cost.

4.3 Satellite attitude control of a robot satellite

Many pat studies about robot satellites considered that the satellite is in a free motion without the attitude control. However, experience of ETS-VII showed that the satellite attitude control is necessary in most cases and the satellite attitude can be maintained using the reaction wheels.[18] Use of the gas jet thrusters that uses hydrazine may provide contamination to the video equipment such as the hand-eye-camera. Therefore, the gas jet thrusters were used in limited cases such as handling large/heavy payload (target satellite) and discharging the angular momentum that were stored in the reaction wheels.

It should also be mentioned that if the product of inertia in the inertia tensor is large, then the gravity gradient torque becomes dominant on a spacecraft in near earth orbit. If the satellite is in free motion, this gravity gradient torque changes the satellite attitude even if the robot arm is not moving. This fact is forgotten or neglected in many studies and textbooks,

5. Conclusions

This paper introduced mission results of ETS-VII, which demonstrated the unmanned-automated rendezvous docking and space robot technologies. The projects after ETS-VII such as the logistic support vehicle (HTV) for the international space station (ISS) and the manipulator system on it (JEMRMS [3]) are using these technologies. Development of the on-orbit satellite servicing system is also under consideration.

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