Proceeding of the 6th International Symposium on Artificial Intelligence and Robotics & Automation in Space: i-SAIRAS 2001, Canadian Space Agency, St-Hubert, Quebec, Canada, June 18-22, 2001.

ETS-VII: Achievements, Troubles and Future

Oda, Mitsushige
National Space Development Agency of Japan (NASDA)
Sengen, Tukuba-shi, Ibaraki-ken, 305-8505 Japan
E-mail: oda.mitsushige@nasda.go.jp

Keywords: ETS-VII, space robot, tele-operation, rendezvous docking, satellite attitude control, satellite service

Abstract

ETS-VII (Engineering Test Satellite No.7) was launched on Nov.1997 to conduct automated rendezvous docking and space robot technology experiments. A 6dof robot arm which is mounted on the ETS-VII chaser satellite were tele-operated from ground and were used to in various experiments such as ORU exchange, equipment handling and satellite capture. These results came by overcoming various troubles in orbit.

1. Introduction

The rendezvous docking and space robot are "must technologies" for future space missions. NASDA is now developing the H-II transfer vehicle (HTV) to carry logistics to the international space station (ISS). It will be launched by NASDA's H-IIA rocket and carries a logistic module of the Japanese Experiment Module (JEM) of ISS. JEM has a manipulator system to handle the logistic module and experiment equipments. In building these systems, rendezvous and space robot technologies must be verified in advance. The automated rendezvous docking and the space robot technologies are also to be developed to conduct future space missions such as satellite servicing.

ETS-VII (Engineering Test Satellite No.7) is a satellite to develop and verify these technologies. ETS-VII is a twin satellite consisting a chaser satellite and a target satellite. Masses of both satellites are 2.5 ton and 0.4 ton respectively. These two satellites were launched together in a connected configuration. The target satellite was released from the chaser satellite during the rendezvous docking experiments and re-captured during the experiment. The ETS-VII chaser satellite has a 2m-long robot arm that is tele-operated from ground. The robot arm has 6 rotational joints, an end-effecter, and cameras on the end-effecter and the 1st joint. Fig.-1 shows an artist image of ETS-VII satellite.

Fig.1 An artist image of ETS-VII (chaser & target)

Mission operation of ETS-VII continued for 2years after its launch in Nov. 1999. During this mission operation period, various rendezvous docking and space robot technology experiments were conducted. The rendezvous docking experiments were conducted three times between the ETS-VII chaser satellite and the ETS-VII target satellite. The robot experiments conducted were such as various type of tele-operation experiments, satellite-servicing experiments (ORU exchange, fuel supply, visual inspection, etc), and satellite attitude control experiments against robot arm motions. Many other institutions besides NASDA also conducted various robot experiments. Institutions those conducted robot experiments on ETS-VII are NASDA, MITI (Ministry of International Trade and Industry), NAL (National Aerospace Laboratory), CRL (Communication Research Laboratory), ESA, DLR and many universities.

However these successful results were achieved by overcoming various troubles encountered during the ETS-VII mission operations. The troubles include such as loss of satellite attitude, disruption of communication link, disruption of rendezvous, sudden stop of onboard computer, and others. These troubles were overcome by extensive effort of onground satellite operation crews and support engineers.

This paper introduces achievement of ETS-VII project, lessons learned from the project, and some ideas for future missions based on the ETS-VII's experiences.

2. ETS-VII satellite

ETS-VII that was launched in November 1997 aiming to demonstrate the automated rendezvous docking and space tele-robot technologies. The ETS-VII satellite consists with two satellites, the chaser satellite and the target satellite. Both satellite were launched together and were separated during the rendezvous docking experiments.

The ETS-VII chaser satellite is about 2.5t in mass and has two solar paddles, a data relay antenna to communicate with a data relay satellite in the geo-stationary orbit, a 2m-long robot arm, and a docking mechanism that capture the target satellite. Size of the satellite platform is about 2.4m in each side. Three reaction wheels and the hydrazine thrusters maintain attitude of the chaser satellite.

The target satellite is about 0.4t in mass and has one fixed solar paddle. Nitrogen thrusters are used to maintain attitude of the target satellite. Since volume of the nitrogen gas tank is limited, the target satellite can maintain its attitude only for a few weeks. Therefore, the target satellite is normally attached to the chaser satellite by the docking mechanism.

The relative navigation of the chaser satellite against the target satellite is realized using four type of sensors, a proximity camera sensor in short distance (within 10m distances), a laser radar in middle distance (between 2 to 500m distances), GPS receivers on both chaser and target satellites to measure relative distance in long distance (beyond 500m distances). An accelerometer is used to control thruster firings.

Control system of the chaser satellite is complicated since it must support the normal satellite attitude control including control of the solar paddles, but also the rendezvous docking maneuvers, control of the inter-satellite communication antenna's direction and the satellite attitude control while the robot arm moves on the satellite. Fig.2 shows the attitude and orbit control system of the ETS-VII chaser satellite.

Since control system of the ETS-VII satellite and its operation are complicated, we adopted the failure detection, isolation and re-configuration (FDIR) system to cope with various types of anomalies on the satellite. The FDIR system works as follows.

- Monitors the attitude control status (attitude error, error rate, equipment status, etc.). If some equipment shows problem, switches to redundant equipment.
- If the attitude control status is not proper, change the attitude control mode into a safer mode.
- Checks rendezvous guidance, navigation control status and its equipments. If they are not in a proper condition, then switches to redundant equipment or to a safer mode (Disabled Abort, Collision Avoidance Maneuver).
- Checks robot arm motion (angular momentum, velocity of the arm, etc.). If the robot will generate excess reaction to the satellite platform, then such a motion will be inhibited.
- Checks satellite attitude control status. If the satellite motion is not stable enough, then inhibits robot arm motions.
- Checks status of the inter-satellite communication link. If the communication link is disrupted, then inhibits robot arm motions.

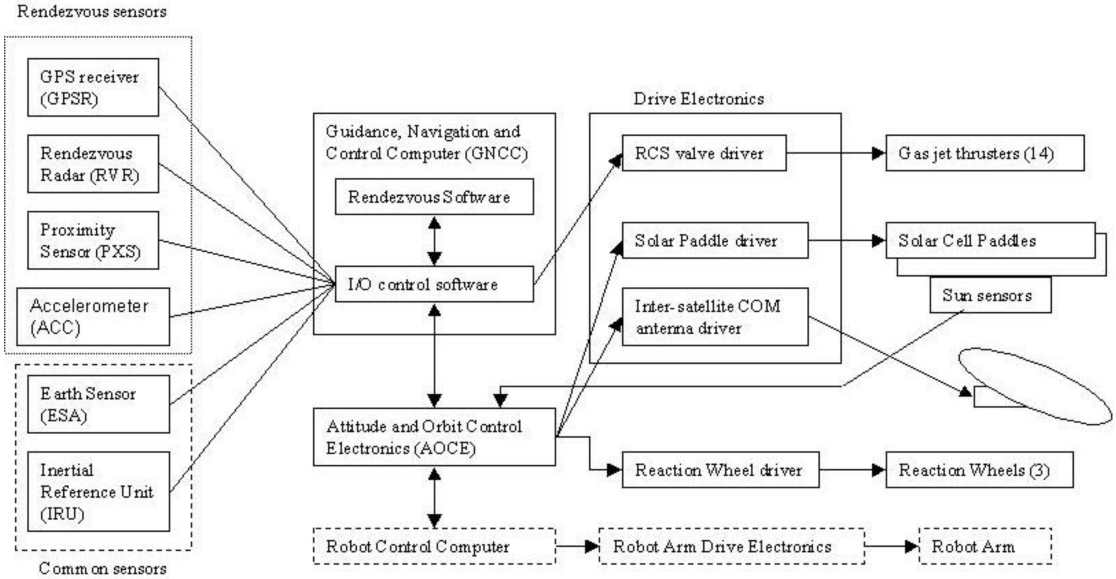

Figure 2. Attitude and orbit control system of the ETS-VII chaser satellite

3. Achievement of ETS-VII

ETS-VII brought many successful results. These results are reported in many papers. This section will briefly summarize them.

3.1 Rendezvous docking experiments

The rendezvous docking experiments were conducted three times. They were all successful even though there were some critical problems that are introduced in later section.

(1) 1st rendezvous docking experiment

The 1st rendezvous docking experiment was conducted on July 7th, 1998. The day is the day in an old Japanese love story (see Ref.1) that the two star separated by the Milky way can meet one a year. Name of the star is "Hikoboshi (Puller Star or the Altair)" and "Orihime (Weaving Princess Star or the Vega)". ETS-VII chaser's nick name is Hikoboshi, and the target is Orihime. The two star (satellites) were separated up to 2m distances and re-united automatically in 20 minutes. The onboard proximity sensor that is based on a CCD camera measured relative position and attitude of both satellites..

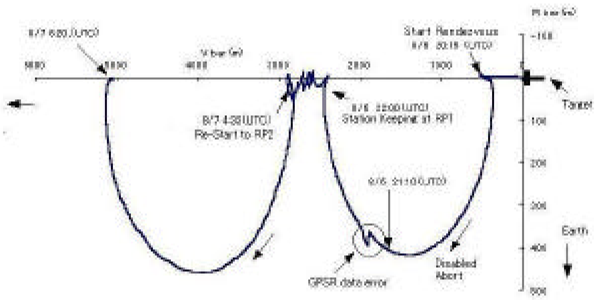

Fig.-1. ETS-VII chaser's trajectory against the target. (During the disabled abort in the 2nd RBD exp.)

(2) 2nd rendezvous docking experiment

The 2nd rendezvous docking experiment was originally planned to demonstrate the autonomous rendezvous capability within 500m distances using a rendezvous-radar. Separation to 500m distances was conducted without problems. However, during the rendezvous maneuver to the target satellite, gas jet thrusters of the chaser satellite stopped proper operations. This caused the built-in safety maneuver, which is named the Disabled Abort. This caused abort of approach as planned. Several trials to approach the target satellite were conducted without any good results.

Since the volume of nitrogen gas to be used for the attitude control of the target satellite was limited, the onboard guidance, navigation and control software of the chaser satellite was modified in a week to modify the rendezvous maneuvers in order not to use the failed thrusters. This brought successful re-docking of both satellite 3 weeks after their separation. Fig.-4 shows the flight trajectory of the ETS-VII chaser satellite against the target satellite. Details of the 1st and 2nd rendezvous docking experiment results are shown in Ref-2.

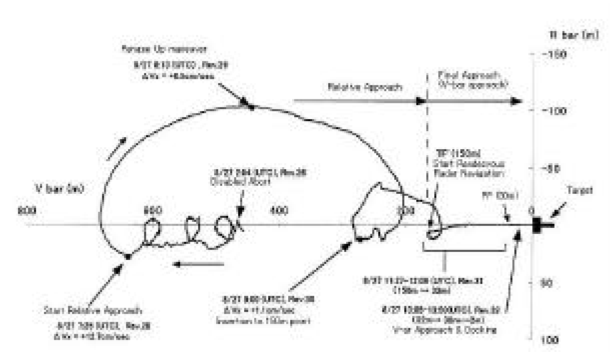

Fig.-2. ETS-VII chaser's trajectory before the docking (The 2nd rendezvous docking experiment)

(3) 3rd rendezvous docking experiment

The third rendezvous docking experiment was successfully conducted in October 1999 using the renewed onboard guidance, navigation and control software. The so-called "R-bar Approach" was tested to simulate HTV's rendezvous to the international space station. The remote-piloting experiment that an on-ground operator navigates the chaser satellite using telemetry data and video images from the chaser satellite was also conducted in this flight experiment.

3.2 Results of the Robot Experiments

Institutions those conducted robot experiments on ETS-VII are NASDA, MITI (Ministry of International Trade and Industry), NAL (National Aerospace Laboratory), CRL (Communication Research Laboratory), ESA, DLR and many universities.

NASDA conducted following robot experiments.

- Coordinated satellite attitude and onboard robot arm control experiments to stabilize the satellite attitude motion against robot arm motion.
- Tele-operation of onboard robot arm under a time delay of more than 6 seconds.
- Demonstration of satellite servicing such as the visual inspection of onboard equipment using cameras on the robot arm, exchange of equipment (ORU, tools for the robot arm) using the onboard robot arm, simulated fuel supply experiment that connects liquid connector of ORU by the onboard robot arm and transfers gas and

liquid from one tank to other tank, handling of the target satellite by the onboard robot arm.

- Autonomous satellite capturing by the onboard robot arm
- Joint robot experiments with ESA, DLR, and universities.

Details of these experiment results are shown in Ref.-3.

Other institutions those brought onboard equipment on ETS-VII conducted following robot experiments.

- Truss assembling experiments (NAL)
- Antenna assembling experiments (CRL)
- Advanced robotic hand experiments (MITI)

Peoples in these institutions present details of these experiments and their results. (e.g., Ref.4-6)

4. Troubles during the mission

Beside various fruitful results mentioned above, ETS-VII suffered various troubles in orbit. Some of them were quite critical that might have terminated mission operation of ETS-VII.

4.1 Loss of satellite attitude stability and recovery from it

ETS-VII was launched on November 28th, 1997. An initial orbit of ETS-VII was an eclipse orbit whose perigee was 350km and the apogee was 550km. This initial orbit was selected since the rocket carried another rocket that must be released in 350km altitude circular orbit before separating ETS-VII. After separation from the rocket, ETS-VII automatically gained its three-axis attitude stabilization. Initial checkouts and transfer to an operation orbit (550km altitude circular orbit) were then to be conducted using the direct communication link from NASDA's tracking control stations. Since NASDA's tracking control stations were located around the mainland of Japan, communications with ETS-VII satellite can be realized in very limited timings. Communications with the ETS-VII satellite is only possible for 5 to 10 minutes in 6 orbital passes over Japan out of 16 orbital revolutions of the satellite around the Earth. On the 3rd day after the launch of the satellite, on-ground operators successfully conducted the planned checkout tasks using the 5 communication windows. Then at the beginning of the 6th communication windows, on-ground engineers found that the telemetry data from the satellite is quite disordered. They imagined that some problems occurred on the satellite. However, the telemetry data from the satellite attitude control system showed inconsistencies and it was not easy to understand the situation. This critical problem occurred in early Sunday morning. There were not many engineers there. Engineers were called up soon. After reviewing the telemetry data, following phenomena were identified.

- Solar cell paddles drive was switched off. Electrical power generation level was changing periodically. From change of the power generation level, it was determined that the satellite was spinning around the satellite pitch axis at about a few rotations in a minute.
- FDIR (Failure Detection, Isolation and Re-configuration) system detected some problem in the reaction wheels (RW) and selected gas jet thrusters (RCS) as the attitude control actuators.
- Primary and backup Earth sensors were both switched off. However the FDIR system did not detect this critical problem.
- Satellite attitude control mode remained in the normal control mode even though the three-axis attitude stabilization was lost. The design philosophy of the FDIR system was to change the satellite attitude control mode to the safe hold mode or the attitude acquisition mode in such a critical situation.

(1) Recovery from trouble

Unhappily, there was not another communication link for more than a half day after this accident. NASDA asked other space agencies to track ETS-VII satellite and to relay telemetry data and commands to/from NASDA. A communication link with the satellite was re-established in 3 hours. Commands to power-on the earth sensor and to re-acquire the three-axis attitude stability were sent immediately. Then in the next communication window, commands to re-start tracking of the solar cell paddles towards the Sun were sent. In the 4th communication windows (6 hours after the accident), onground engineers confirmed that the satellite returned to the normal operations.

(2) Troubleshooting

Extensive troubleshooting was conducted to identify cause of the problem and to identify the countermeasures to the problems. The concluded error mechanism is as follows.

- Data received by AOCE (Attitude and Orbit Control Electronics) from the inertial reference unit included spiky noises. Cause of the noisy data could not be identified.
- The noisy data were misunderstood by the attitude control software as the rapid satellite attitude motion. FDIR system switched off RW and selected RCS as the attitude control actuators to correct such a large attitude motion.
- The FDIR system of ETS-VII was designed to cope with a single trouble. It was not designed to cope with multiple troubles. After the FDIR system detects one problem (in this case, excess torque commands to the

reaction wheel caused by the noisy gyro data), the FDIR system conducts simplified monitoring of the satellite operation status. (Design of the one-fail-operational)

- However, another problems were occurred successively. By unknown causes (high energy particle or other) caused switch off the earth sensor. However the simplified processing of the FDIR system after finding one problem could not detect this switch off. This caused the irregular telemetry data of the satellite attitude.
- Design of the ETS-VII satellite attitude control software did not consider a case that both primary and backup earth sensor are switched off. Attitude control software considered invalid data from the earth sensor to be a large attitude error. This caused unnecessary thruster firing commands to put the satellite into spin motion.
- Shut down of the solar cell paddle drive was caused by rush current that happened after the FDIR system switched the solar paddle drive from the primary system to the backup system when the power generation level became unstable by the satellite's spin motion.

(3) Countermeasures

In order to avoid further troubles, onboard software of the satellite attitude control system was modified as follows. Satellite operations were stabilized after these improvements

- Add filter to remove noisy data from the inertial reference unit.
- Improve check algorithm to identify Earth sensor's switch off even after finding a problem.
- Improve equipment control algorithm to surely switch-on the redundant equipment in case of troubles.

4.2 Problem in the communication system

ETS-VII uses a data relay satellite in the geo-stationary orbit during the rendezvous docking and space robot experiments. NASDA originally intended to use NASDA's experimental data relay satellite named COMETS (Communication Engineering Test Satellite). COMETS was originally to be launched several months before ETS-VII. However, launch of COMETS was delayed after ETS-VII by some technical reasons. Therefore, NASDA asked NASA to rent its data relay satellite named TDRS as a back-up satellite. COMETS was designed to support the inter-satellite communications in S and Ka bands. NASA's TDRS supports S and Ku bands. NASDA selected S-band for ETS-VII considering that TSRS might be used as a backup of COMETS. This was a right decision. NASDA quickly established data relay network as shown in Fig.3.

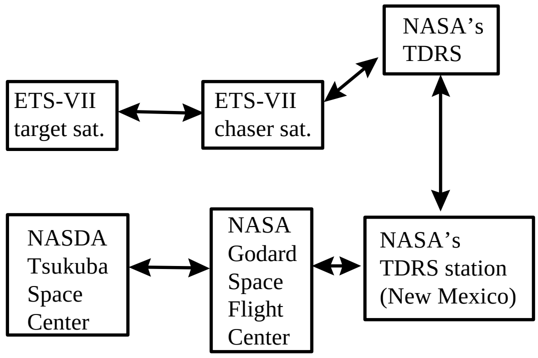

Fig.3. Communication network of ETS-VII

(1) Trouble in the communication equipment

After successful completion of the initial checkout of satellite platform, engineers started checkout of the inter-satellite communication system using TDRS, and they soon found that the output power of ETS-VII's inter-satellite communication transponder was weak. Troubleshooting was concluded that the cause of this problem went back 2 years when the satellite was under the vacuum chamber test. A problem in a power supply plant caused interruption in operations of the vacuum chamber and degraded vacuum level caused electrical discharge in the band rejection filter of the communication system. This problem was not identified during the onground test since the discharge did not occur again after resumption of the vacuum chamber test. This electrical discharge occurred again in orbit. However, TDRS had enough margins to receive ETS-VII's weak signals. Communications between ETS-VII and TDRS was disturbed several times by this weak signal and by other reasons such as by on-ground human errors and network problems. However most of the rendezvous docking and space robot experiments did not receive serious effect. The electrical discharge stopped several months later by unknown reason.

(2) Launch failure of the data relay satellite

The experimental data relay satellite, COMETS was launched in February 1999, 3 months after launch of ETS-VII. However problem with the second stage of the rocket put COMETS into a low eclipse orbit. COMETS could not be used as a data relay satellite in that orbit. Some communication experiments were conducted using COMETS in this orbit. NASA's TDRS was originally borrowed until COMETS would become operational. Launch failure of COMETS forced NASDA to use TDRS throughout ETS-VII's mission. COMETS was originally insured against total loss. However, risk management of ETS-VII mission asked that the insurance should cover costs of using TDRS in cases that COMETS could not be used as a data relay satellite. This decision was correct. Cost of borrowing TDRS was covered by the insurance.

4.3 Malfunction of gas jet thrusters

As mentioned in the section 3.1(2), gas jet thrusters of the ETS-VII chaser satellite became unusual during the 2nd rendezvous docking experiment. During the rendezvous maneuvers, attitude and location of the satellite must be controlled using many gas jet thrusters. After several thrusters went wrong during the 2nd rendezvous docking experiment, modification of the onboard software was made to generate equivalent control thrust using only healthy thrusters. Control thrust that is to be realized by the fatal thrusters are realized using combination of other healthy thrusters in such a way of vector synthesis. This quick response was possible since there was a simulator of onboard control system on the ground.

Onboard software of the satellite attitude control system and the robot control system were also modified several times during the mission to improve their performance and to strengthen their capability to assure mission success.

5. Lessons learned

ETS-VII finished its mission successfully by the end of 1999 even though the satellite encountered several critical problems. Lessons learned from this project were as follows.

(1) Risk management

In conducting successful mission using complicated system, risk management is essential. It includes identification of risks, evaluation of criticality and possibility of each risks, and preparation against each likely risk. Troubles in the communication network including an experimental data relay satellite was identified in advance. Therefore, S-band that both COMETS and NASA's TDRS support was selected and launch of COMETS was insured to cover the cost of using TDRS. Since ETS-VII was NASDA's first satellite that used a data relay satellite, disruption of communication link was also considered as likely. Therefore, designs and procedures to cope with sudden disruption of the communication like were also prepared.

(2) Design of FDIR

FDIR system was rather new technology in satellite design. In designing a FDIR system, identification of possible malfunctions, and preparing against then at best within possible resources are essential.

(3) Onboard software

Capability of rewriting onboard software helped resolving problems of ETS-VII. Onboard computer, onboard software, communication system and on-ground facilities should be designed to support rewriting of onboard software.

6. Future plan

The automated rendezvous docking technology that was demonstrated by ETS-VII is now used to develop the H-II Transfer vehicle that carries logistics to the international space station. ETS-VII robot experiments showed that the robot system could work successfully in the space environment for more than one year. No other robot system demonstrated such capability. This will be a healthy base for the JEM remote manipulator.

Satellite servicing such as inspection, capture, supply / exchange of equipment, de-orbit and others is an application of ETS-VII technologies. However, in order to realize the actual satellite servicing, various technological and economical hurdles still exist. Rendezvous and capture non-cooperative target are most technologies that must be developed.

Generalization of space traveling by scientists and general publics besides professional astronauts might request us to assure safe space travel, collision free from debris. Removal of unused satellite, rockets and related debris from out of orbit might be urgent needs from the future space activities. Results of ETS-VII will be most suitable for such missions. Possibility of capturing a failed satellite by a robot satellite is discussed in Ref.-8.

Conclusions

The ETS-VII satellite successfully conducted its all planned and additional missions. Various problems encountered during the mission were overcome by extensive efforts of engineers and satellite operators. However, those efforts might have been useless if extensive risk management was not conducted in advance. The FDIR system helped ETS-VII satellite operation very well. These experiences will help in planning / developing future space missions.

References

(1) http://www2.gol.com/users/stever/orihime.htm
(2) M.Mokuno, I.Kawano, T.Kasai "Experimental Results of Autonomous Rendezvous Docking on Japanese ETS-VII Satellite", Proc. of 22nd Annual AAS Guidance and Control Conf. Feb.3-7, 1999, Colorado, AAS-99-022
(3) M.Oda, "Experience and lessons learned from the ETS-VII robot satellite", Proc.of 2000 IEEE Int. Conf. On Robotics and Automation, San Francisco, CA, April 2000, pp.914-919
(4) K.Machida, H.Nishida and K.Akita, "Precise

Telerobotic System for Space Experiment on ETS-VII", 49th Int. Astronautical Congress, IAF-98-U.5.05, 1998

(5) K.Matsumoto, S.Wakabayashi, L.Penin, M.Nohmi, H.Ueno, T,Yoshida and Y.Fukase, "Teleoperation Control of ETS-7 Robot Arm for on-Orbit Truss Construction", Proc. of I-SAIRAS'99 (ESA-SP-440), June 1-3, 1999, ESTEC, The Netherlands, pp.313-318

(6) S.Kimura and S.Tsuchiya, "Antenna-assembly experiments using ETS-VII", Proc. of I-SAIRAS'99 (ESA-SP-440), June 1-3, 1999, ESTEC, The Netherlands, pp.307-313

(7) M.Oda, "Mission design of an in-orbit satellite inspection - Feasiblilty of the IN-Orbit satellite servicing-", AAS/AIAA Space Flight Mechanics Meeting, 11-14 February 2001, Paper #: AAS 01-224