NASDA's activities in space robotics

Dr. Yoshiaki OHKAMI and Dr. Mitsushige ODA

National Space Development Agency of Japan (NASDA)

Abstract: Space robots are indispensable tools for future space missions such as building/ operation of the international space station, realization of on-orbit satellite servicing (inspection, logistic support, repair, rescue from stranded orbit etc.), and lunar/planetary explorations. NASDA has various space robot related projects as follows.

- Retrieval of Japan's free flyer (SFU) by the shuttle's manipulator which was conducted by NASDA astronaut Wakata in January 1996 (STS-72).
- Manipulator Flight Demonstration (MFD) on the space shuttle which was conducted in August 1997 (STS-85).
- Space robot experiments which are being conducted on the Engineering Test Satellite7 (ETS-VII)
- A remote manipulator system (JEMRMS) for the Japanese experiment module of the international space station

This paper introduces these projects and shows the most up-to-date results of the ETS-VII robot experiments which are being conducted in space.

1. Retrieval of a free flyer (SFU) by the shuttle manipulator (Ref.1)

A team of Japan's national agencies (ISAS/ NASDA/ MITI) developed and launched a free flyer named SFU in March, 1995. Mission of SFU was to conduct material and life science experiments in the micro-gravity environment. This free flyer was designed to be launched by NASDA's H-II rocket and to be retrieved by the space shuttle.

The retrieval mission was conducted in January 1996 and a NASDA astronaut, Mr. Wakata manipulated the shuttle manipulator in this mission. In this retrieval mission, SFU made a slight orbital descent from its mission orbit to the rendezvous orbit (472km alt.) and waited there. The space shuttle made the ground-up rendezvous and approached SFU from beneath of it (R-bar approach). When the shuttle's manipulator was positioned ahead of SFU, RCS of the shuttle was disabled and the shuttle manipulator grasped SFU. SFU maintained its attitude using reaction wheels while the space shuttle approached and grasped it by the manipulator. After the shuttle's manipulator grasped SFU at its grapple fixture, the reaction wheels were run-downed and switched off. This mission gave us a lot of insight about the rendezvous docking and space robot operations.

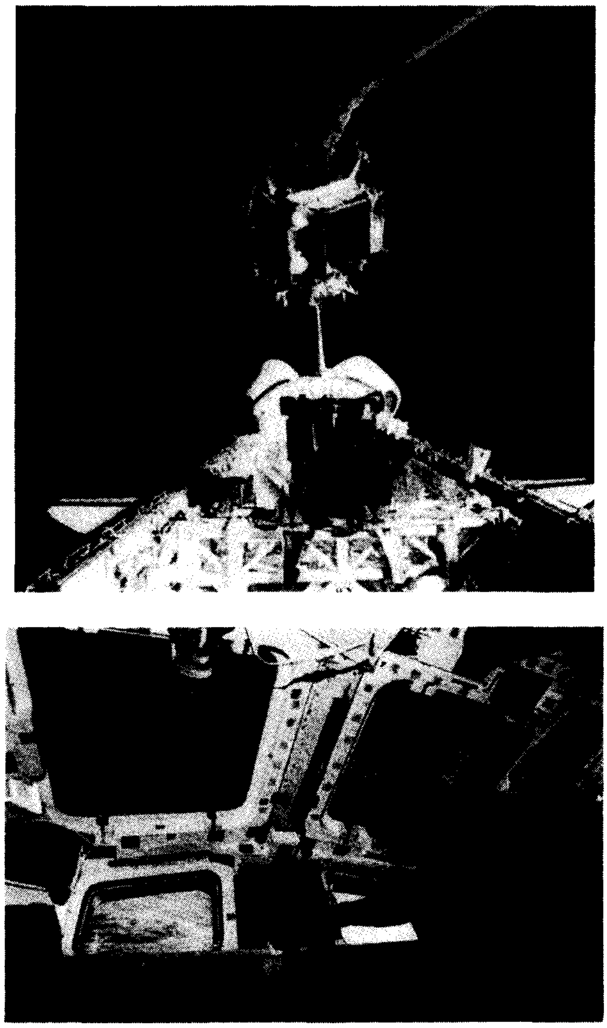

Fig.1 NASDA astronaut Wakata retrieved Japan's a free flyer(SFU) using the shuttle manipulator (STS-72 / 1996)

2. Manipulator Flight Demonstration (MFD) on the space shuttle (Ref.2)

NASDA is now developing the Japanese experiment module's manipulator system (JEMRMS) to be used on the international space station. In order to verify design of the JEM's manipulator and its operation system, NASDA conducted the manipulator flight demonstration (MFD) mission on the shuttle cargo bay in 1997 by STS-85.

Proc. Fifth International Symposium on Artificial Intelligence, Robotics and Automation in Space, 1-3 June 1999 (ESA SP-440)

A 6-dof robot arm of about 1.5m stretched length which is a replica of the JEMRMS small fine arm was mounted on the shuttle cargo bay using the Multi-Purpose Experiment Support Structure(MPESS) as shown in Fig.2a. The robot arm was operated from the control station in the aft flight deck of the shuttle as shown in Fig.2b. The control station includes a CCTV monitor, a pair of 3-dof joysticks, switch panel and other control electronics. Tasks conducted were handling (removal/install) of ORU(see Fig.2c), open/close of a hinged door. These contact operations were conducted using the compliance control capability of the MFD robot arm.

Beside these onboard operations by the shuttle astronauts, teleoperation experiments were conducted from the ground. Experiments were to control the robot arm using commands files which were generated on ground and sent to the shuttle during the mission. Visual inspection and other tasks which did not require the contact operations were conducted using this ground commanding.

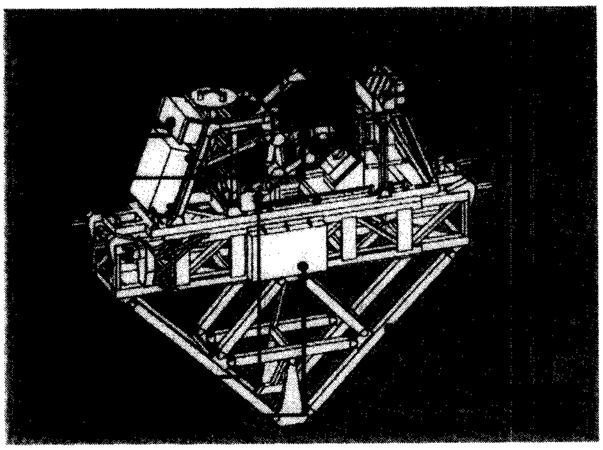

Fig2a MFD system

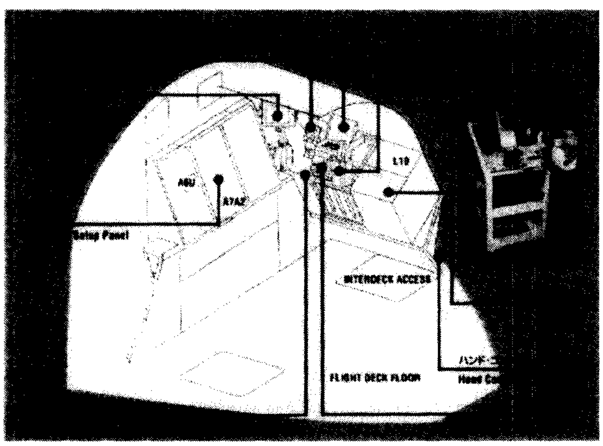

Fig.2b MFD operation system

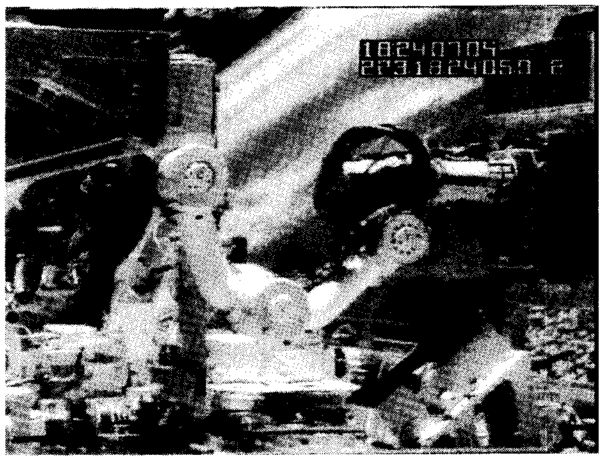

Fig.2c MFD mission on STS-85 in 1997

3. Engineering Test Satellite 7 (ETS-VII)

The engineering test satellite No.7 (ETS-VII) was launched on Nov.28, 1997 to conduct the rendezvous docking and space robot technology experiments. ETS-VII consists of two satellites named the chaser and the target. Mass of the satellites are 2.5t and 0.4t respectively. Both satellites fly together for most of its mission life. The target satellite is released from the chaser satellite during the rendezvous docking experiments and is captured again at the end of each rendezvous docking experiments using the docking mechanism. The orbit of the satellites is 550km altitude and 35degrees inclination. Mission life of the satellite was 1.5 years after the launch. However, since the satellite is healthy after its original mission life, mission is extended to 2 years till end of Nov. 1999. Fig.3a shows in-orbit configuration of ETS-VII during the planned capture/berthing experiment which is to grasp the target satellite by the onboard robot arm. Fig.2b shows ETS-VII satellite on the H-II rocket. A folded down robot arm is mounted on the chaser satellite. The target satellite was mounted on top of the chaser satellite.

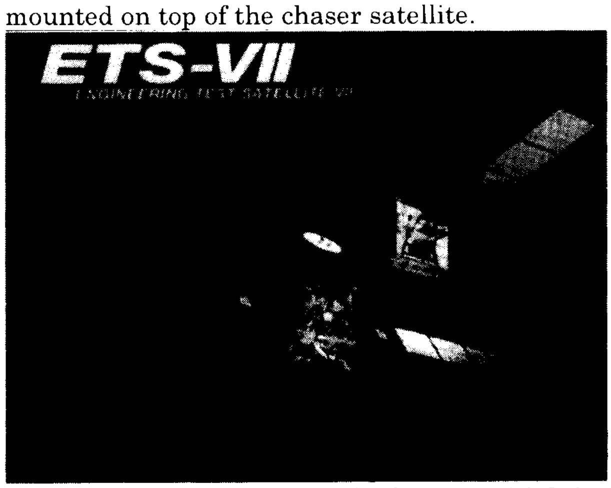

Fig.3a ETS-VII chaser(left) & target (right)

Fig.3b ETS-VII on top of the H-II rocket

3.1 Satellite operations

Satellite operations including experimental rendezvous docking and robot operations are conducted from NASDA's Tsukuba space center. Communication between the ETS-VII satellite and the on-ground control station is established using a data relay satellite (NASA's TDRS) in the geo-stationary orbit. The overall ETS-VII experiment system is shown in Fig.4. Since this communication network is realized by a lot of computers onboard the satellites and on-ground, a time delay of about 6 to 8 seconds in return existed in the robot control loop. Fluctuation of the time delay of up to 2 seconds is observed. This fluctuation is absorbed by the data buffer in the onboard and on-ground robot control computers.

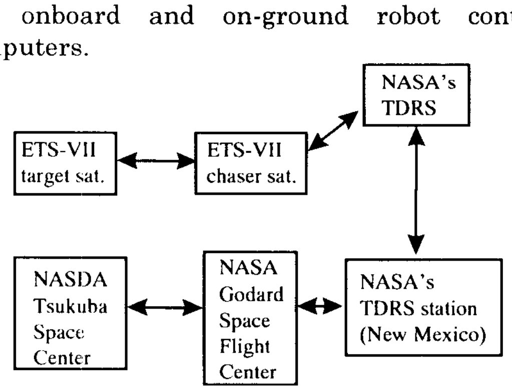

Fig.4 ETS-VII experiment system

Since not only NASDA but other agency (MITI: Ministry of International Trade and Industries) and national laboratories (NAL: National Aerospace Laboratory, CRL: Communication Research Laboratory) also conduct robot experiments on the ETS-VII satellite, ETS-VII's teleoperation system was designed to allow other experiment users to use their own on-ground robot control facility. Those users brought their own on-ground robot operation facility to NASDA Tsukuba Space Center and their experimental commands are sent to the satellite through NASDA's on-ground robot operation facility. NASDA provided telemetry data and video data from satellite to these users' facility.

3.2 Onboard robot system of ETS-VII

ETS-VII's onboard robot experiment system consists of 6 dof(degrees-of-freedom) robot arm and many robot arm's experimental payloads which are shown in Fig.5. Besides NASDA's equipment (Robot arm, ORU, taskboard, target satellite handling tool), other agency(MITI, NAL,CRL)'s experimental equipment is also mounted on ETS-VII for their own robot experiments. (Ref.6)

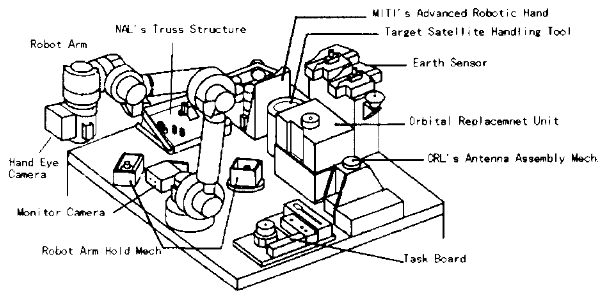

Fig.5 ETS-VII onboard robot equipment

The robot arm is about 2m stretched length and its joints are driven by combination of DC brush-less motor, harmonic drive gear and a resolver. An end-effector with three latching fingers and the force-torque sensor is mounted on the robot arm. A pair of hand eye cameras are also mounted on this end-effector. ETS-VII robot arm has following control modes;

- joint angle / velocity control mode
- arm tip position / attitude control mode
- compliance control mode (incl. force control, active limp and impedance control)

These control modes were tested in orbit and showed good performance. The positioning accuracy (repeatability) of robot arm was better than 1.5mm.

A hand eye camera is mounted on the end effector. Another monitor camera is mounted on the first joint. The first joint acts as camera's pan unit. Up to five video images per a second (5 f/s) are sent to ground using the JPEG compression format.

Add-on tools: ETS-VII robot arm's end-effector is designed to be most suitable for the tasks like ORU handling. However it is not suitable to handle small equipment or to grasp a floating object like the target satellite. 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 equipment on the task-board (slider, mechanical switches, surface for tracing). A target satellite handling tool which has large two fingers is used to grasp the target satellite. MITI's advanced robotic hand can also be attached to this robot arm.(Ref.5)

3.3 Coordinated robot and satellite attitude

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 410 kg (target satellite). Attitude of the satellite platform is maintained within a few tenth degree by the reaction wheels and the gas jet thrusters 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.6 shows this coordinated control system. (Ref.8)

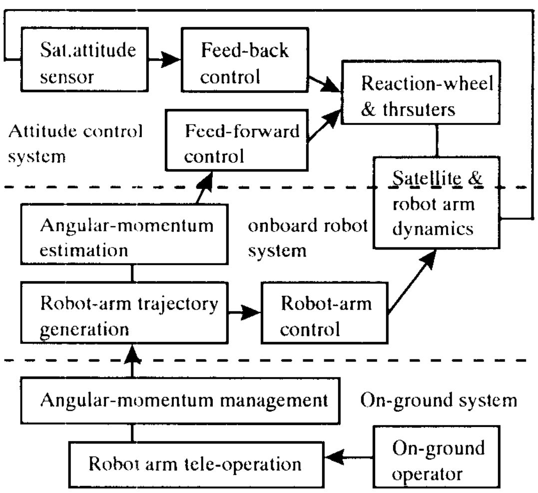

Fig.6 Coordinated satellite and robot control system

3.4 Teleoperation system

NASDA's robot teleoperation system has two operation modes, the "supervised control mode" and the "telemanipulation mode". In the supervised mode, instructions 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 and generates robot arm's tip trajectory. Then it calculates 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, automatic task execution is realized using this control mode. In this mode, the command sequences are written using the graphical user interface(GUI) into a flowchart. This commands sequence is verified using the built-in onboard robot simulator of the robot operation facility which simulates operations of the onboard robot system. In the actual operation, each command is automatically sent out each after the previous command is successfully sent and verified its execution. On-ground operator's task is to supervise this automatic task execution and if necessary to intervene and modify the process. This operation method is simple and safe, and is recommended for most of space robot's tasks which are well defined. Fig.7 ETS-VII shows robot teleoperation facility.(Ref.7)

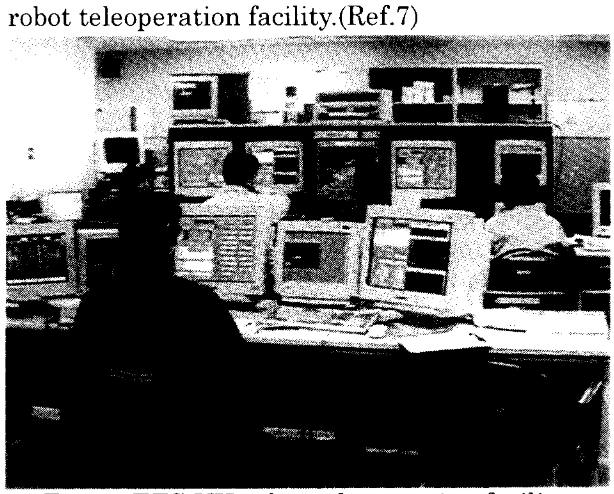

Fig.7 ETS-VII robot teleoperation facility

(2) Telemanipulation of the robot arm

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. The onboard robot control system generates the robot arm's trajectory by interpolating these data. If one data is missing by 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.

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

- predictive computer graphics which shows how the robot arm will move if a command will be executed. This 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 robot arm's individual 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.

3.5 Tasks conducted

Within NASDA's robot experiments, following robotic tasks were conducted.

(1) visual inspection of onboard equipment: Since ETS-VII's robot system is easy to teleoperate, satellite engineers who are not specialist of robotics can easily conduct inspection of onboard equipment using the hand eye camera of the robot arm.

(2)Handling of orbital replacement unit(ORU) and fuel supply experiment: ORU is widely used on the international space station to exchange equipment in orbit. Size and mass of ETS-VII's ORU are similar with those of a microwave oven. Fig.6 shows ORU handling by the onboard robot arm. This ORU houses fuel tank, valves, liquid connector and electrical connector to connect with other tank in the ORU port. A simulated fuel supply experiment was successfully conducted using this equipment.

Fig.8 ORU handling by the robot arm

(3) handling of small equipment by the robot arm: There are many small experimental equipment on the taskboard such as a slider, mechanical switches, hole for peg-in-hole and others. These equipment is handled by adding the taskboard handling tool which has two fingers and a fixed peg. Fig.9 shows handling a metal ball by the taskboard handling tool on the robot arm.

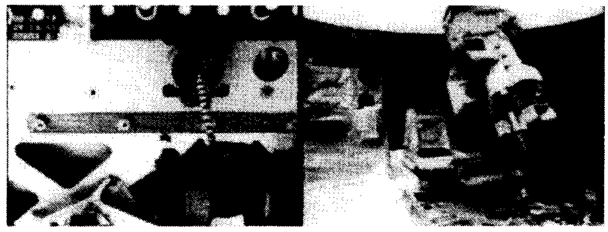

Fig.9 Handling of small parts using add-on tool

(4) Telemanipulation experiments by shuttle astronaut: NASDA's shuttle astronaut, Mr. Wakata who conducted retrieval of free flyers using the shuttle manipulator on STS-72 (Jan.1996) conducted the telemanipulation experiments on ETS-VII. He also received through training of MFD robot arm's operation even though he was not assigned a crew of the mission. This experiments was to compare these robot arms. Tasks asked in this experiments were to trace a surface of the taskboard and to handle a truss structure by telemanipulating the robot arm. These tasks require control of robot arm's position/attitude and also force/torque between the objects. Mr.Wakata could satisfactory conduct these tasks even though he could spent only 2 days for training and there was a time delay of 6 to 8 seconds. This shows that ETS-VII robot system is easy to learn and to operate. Fig.10 shows the surface tracing experiment by astronaut Wakata which was conducted on March 16,1999.

Fig.10 Shuttle astronaut, Mr.Wakata(center) conducted surface tracing task by telemanipulation
(Top left: hand eye camera's image, right: shoulder camera's image, Lower right: CG image of robot)

(5) Handling of the target satellite by the robot arm: The target satellite whose mass is

410kg was handled by the onboard robot arm on the chaser satellite. This experiment was conducted as follows by the coordination of the on-board and on-ground robot arm rendezvous docking control systems. At first, a target satellite handling tool was is attached to the robot arm and this tool grasped a handle on the target satellite. After releasing the target satellite by the docking mechanism, the robot arm move the target satellite up and down to give the maximum disturbance to check the coordinated satellite attitude control capability which is explained in next section. After these tasks, the target satellite was moved to the docking position by the robot arm and the docking mechanism grasped the target satellite. Chaser satellite's attitude was properly maintained throughout this experiment. Fig. 11 shows this experiment

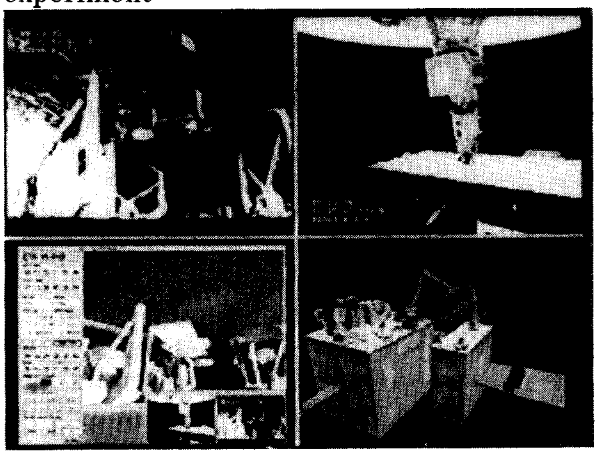

Fig.11 ETS-VII robot arm on the chaser satellite handles the target satellite
(Upper left: image from a docking camera (upper/target, lower/chaser),Upper right: image from a shoulder camera (target satellite handling tool is attached to the robot arm and grasps a handle on the target satellite)

3.6 Other agency's experiments

Since ETS-VII is a rare opportunity to conduct robot experiments in space, many institutions conducted space robot experiments.

- Ministry of the International Trade and Industries: They conducted the advanced robotics and experiments.
- National Aerospace Laboratory: They conducted handling of truss structures by the onboard robot arm
- Communication Research Laboratory: They conducted antenna assembling experiments using the onboard robot arm and the antenna assembling mechanism
- European Space Agency(ESA) and NASDA conducted the joint robot experiments using NASDA's onboard / on-ground equipment and ESA's on-ground equipment.
- German Aerospace Center(DLR) and NASDA conducted the joint robot experiments using NASDA's onboard / on-ground equipment and DLR's on-ground equipment.

During these experiments, experimental commands were generated by user's own on-ground robot operation facility and were sent to NASDA's robot operation facility. NASDA's robot operation facility checked these commands in a real time whether the collision would not happen nor satellite attitude would not be disturbed. If the command was proper, then it was sent out to the satellite. Telemetry data and video data from the satellite were distributed to user's facility from NASDA's facility. This teleoperation system realized the user-friendly teleoperation system. Details of these experiments will be presented by these agencies. Fig.12 shows these users' experiments.

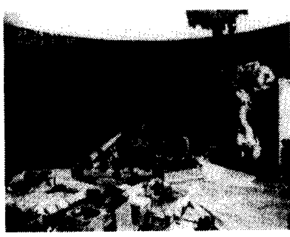


Fig.12a (left) Deployed truss structures of NAL and MITI's small robot arm with the advanced robotic hand. Upper is NASDA robot arm's end effector and the Earth. Fig.12b(right) MITI's teleoperation system


Fig.12c(left) NAL's teleoperation system
Fig.12d(right) CRL's teleoperation system

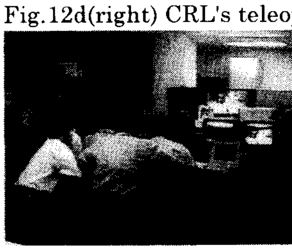
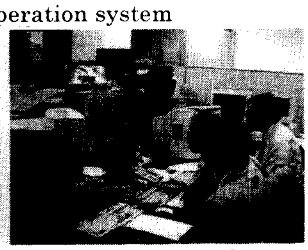

Fig.12e(left) Teleoperation from ESA's terminal
Fig.12f(right) Teleoperation from DLR's terminal

3.7 Rendezvous docking experiments

The rendezvous docking experiment is the another main mission of ETS-VII. It is characterized by autonomous rendezvous and soft docking. ETS-VII's chaser and the target satellite were launched together and were separated during the rendezvous docking experiments. The chaser satellite measures the relative distance and relative rate of both satellite using the GPS receiver and the rendezvous radar. Then the chaser satellite autonomously generate trajectory to approach the target satellite and control the satellite to fly on that trajectory. At the docking, chaser's latching mechanism grasps the target's docking handle and connect the target satellite to the chaser. Fig.7 shows the docking of the chaser and the target satellite during the first rendezvous docking experiment. Details of the rendezvous docking experiments are shown in Ref.9.

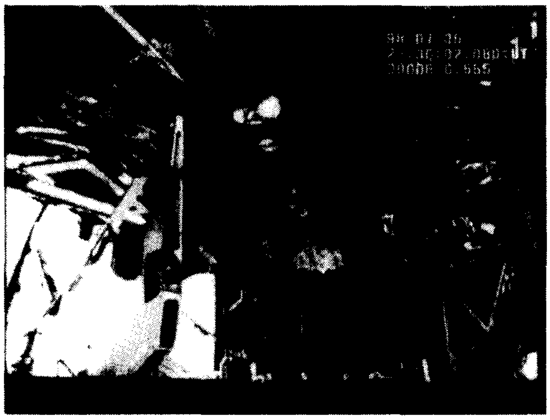

Fig.14 Docking of the ETS-VII chaser (bottom) and target satellite(upper)

4. JEMRMS (Japanese Experiment Module Remote manipulator System)

JEM(Japanese Experiment Module) including JEMRMS is the Japan's contribution to the international space station. Fig.15 shows the overall JEM including JEMRMS. JEM will be launched in three parts in Oct. 2001, Jan.2002, and June 2002. Development of JEM is in the final phase. Fig.16 shows JEMRMS engineering model(EM) under the JEM's system level test which was conducted in June 1998. (Ref.13)

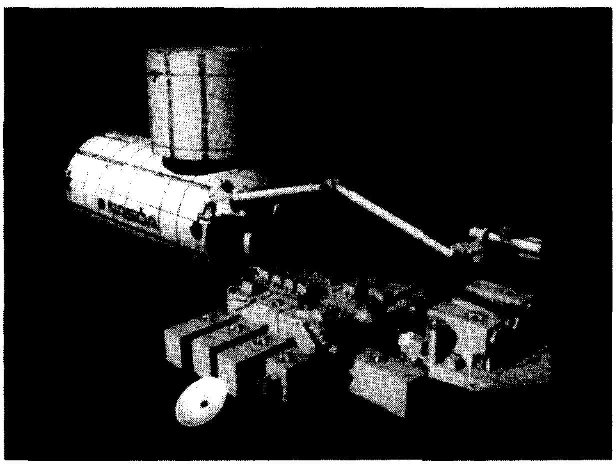

Fig.15 Japanese Experiment Module of the International Space Station

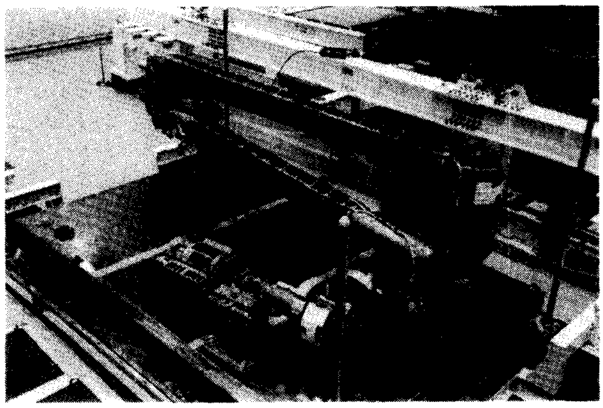

Fig.16 JEMRMS Engineering Model

5. Studies for future missions

Above mentioned are projects that their developments and operations are funded. NASDA is also conducting research activities for future possible robotic missions. Those include the ETS-VII follow-on mission which will demonstrate the in-orbit satellite servicing capability against troubled satellites. Service may include visual inspection, capture, attitude stabilization, orbital transfer, removal from orbit. Some preparatory experiments may be conducted using ETS-VII.

The Japanese Experiment Module (JEM) of the international space station is a platform for various scientific and engineering research. Robotic experiment is also under consideration and some preparatory work is being done by a team of NASDA, national laboratories, and universities. Details of these activities will be presented in other papers at i-SAIRAS'99.

References

More precise and up-to-date information on these projects can be got through the following web pages.

- http://www.nasda.go.jp/index_e.html (NASDA web page)
- http://oss1.tksc.nasda.go.jp/ets-7/index_e.html (ETS-VII web page)
- http://jem.tksc.nasda.go.jp/index_e.html (JEM web page)

(1) K.Ninomiya, M.Kawach, T.Yamaguchi, M.Sato, K.Tsukahara, "On-orbit operation of free flyer SFU's navigation, guidance and control system", Proc of AAS guidance and Control Conference,pp.1-15,AAS96-072, (1996)

(2) S.Wakabayashi, K.Matsumoto, Y.Horikawa, M.Nagatomo, "On the results of the manipulator flight demonstration for the JEM -Mission review and the results of the flght calibration experiment - IAF-98-T-2.03. 49th International Astronatical Congress (1998)

(3) M.Oda, et al.;"ETS-VII, the world first telerobotics satellite (Mission and its design

concept)", in Proceedings of the 2nd International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS'92), Toulouse, France, Sept.30-Oct.2,1992

(4) M.Oda, I.Kawano and F.Yamagata; "ETS-VII (Engineering Test Satellite VII) - a Rendezvous Docking and Space Robot Technology Experiment Satellite", 46th International Astronautical Congress (IAF'95), Oslo, Norway, Oct.2-6,1995, IAF-95-U.2.01

(5) M.Oda, et al.; "Development of the EVA End Effector, Grapple Fixtures and Tools for the Satellite-Mounted Robot System", Proc. of the 1996 IEEE/RSJ International Conference on Intelligent Robots and Systems(IROS'96), Nov.1996, Osaka, Japan, pp.1536-1543

(6) M.Nishida and M.Oda, "Space telerobot experiment system based on NASDA's ETS-VII satellite", Proc. of AIAA Guidance and Control Conference, Aug. 1997.

(7) M.Oda and T.Doi, "Teleoperation system of ETS-VII robot experiment system", Proc. of IEEE/RSJ International Conf. on Intelligent Robotics and Systems (IROS'97), pp.1644-1650, Sept.7-11, 1997, Grenoble, France

(8) M.Oda, "Motion control of the satellite mounted robot arm which assures satellite attitude stability", Acta Astronautica Vol.4, No.11, pp.739-750, 1997

(9) I. Kawano et.al., "First result of autonomous rendezvous docking experiments on NASDA's ETS-VII satellite", Proc. of 49th International Astronautical Congress, Sept.28-Oct.2,1998, Melbourne, Australia, IAF-98-A3.09

(10) K.Machida, H.Nishida and K.Akita, "Precise Telerobotic System for Space Experiment on ETS-VII," IAF-98-U.5.05, 49th Int. Astronautical Congress, pp.1-10, (1998)

(11) K.Matsumoto, et al., "Truss structure telemanipulation experiment using ETS-VII", Proc. of the 3rd int. symp. on artificial intelligence, robotics and automation in space, Oct.18-20,1994, Pasadena,CA,USA,pp.275-278

(12) S. Kimura, T. Okuyama, Y. Yamana, Y. Nagai, and H. Morikawa: Teleoperation System for Antenna Assembly by Space Robots, Telemanipulator and Telepresence Technologies V, ed. M. R. Stein, SPIE, 14-23 (1998)

(13) T.Matsueda, et al., "Development of Japanese Experiment Module Remote Manipulator System", Proc. of the 3rd International conference on artificial intelligence, robotics and automation in space (i-SAIRAS'94), Pasadena, CA., USA, Oct.18020,1994, pp.183-186