Space Robot Dynamics and Control: To Orbit, From Orbit, and Future

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Abstract

The Engineering Test Satellite VII (ETS-VII), launched by National Space Development Agency of Japan (NSADA) on November 1997, has been successfully flown and carried out a lot of interesting orbital robotics experiments with a 2 meter-long, 6 DOF manipulator arm mounted on this un-manned spacecraft. The ETS-VII should be noted as one of remarkable outcomes of research effort on space robots, particularly characterized as a *orbital free-flying robot* which concept was brought in early 80s. This paper provides overview and summarize the ideas around dynamics and control proposed for such a free-flying space robot and what has been recently tested and verified on ETS-VII. The ETS-VII flight mission is an important milestone, but not a goal. The goal will be robotic service to satellites in orbits, including an emerging number of communication satellites spreading out to the low-earth orbital networks or constellations. Which aspect of technology is now verified and which is left over for future satellite servicing are also discussed.

1. A History

The Space Shuttle Remote Manipulator System (SRMS) has a longest history in technology and flight missions in space. It was firstly tested on the second mission of the Space Shuttle (STS-2) in 1981. Since then, the SRMS has been demonstrating promising capability and utility of robotics in space operations. Immediately after the SRMS first flight, a report titled *Space Applications of Automation, Robotics and Machine Intelligence System (ARAMIS)* [1] was published in 1982 and 83, which called a special attention of a robotics community toward a free-flying space robot by a fascinating concept named Telepresence Servicer Unit (Figure 1).

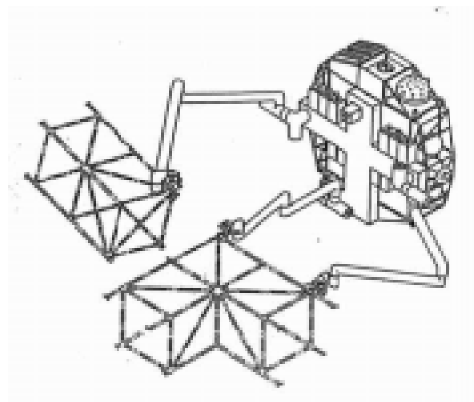

Figure 1: Telepresence Service Unit [1]

A unique characteristics of such a space robot is found in its motion dynamics. According to the motion of the manipulator arm, the base spacecraft moves due to the action-to-reaction principle or the momentum conservation. The reaction of the arm disturbs its footing, then the coupling and coordination between the arm and the base becomes an important issue for successful operation. This idea brought a sort of paradigm leap from the terrestrially based industrial robots. Interesting concepts for modeling and control, including Virtual Manipulator and Generalized Jacobian for example, were proposed and discussed. The non-holonomic characteristics of the angular momentum conservation was also highlighted, which called further attention in the non-linear mechanics community. Major research topics were collected in the book titled *Space Robotics: Dynamics and Control* published in 1993 [2].

Possible flight missions of a free-flying space robot have been discussed and planned in space agencies of the world. Examples are Orbital Maneuvering Vehicle (OMV) and Flight Telerobotic Servicer (FTS) in NASA, U.S.A., however they were all canceled unfortunately. In 1993, DLR, Germany has successfully flown the ROTEX, the first remotely operated space robot, but the mission was performed inside the spacelab module on the space shuttle [3]. And now fortune favors to Japan. The ETS-VII, launched by NASDA in 1997 and the mission is continuing till 1999, should be noted as a real successor of the concept initially studied in the ARAMIS report.

2. Dynamics of a Free-Flying Space Robot

The equation of motion of a free-flying space robot as a multibody system is, in general, expressed in the following form:

$$\begin{bmatrix} \boldsymbol{H}_b & \boldsymbol{H}_{bm} \\ \boldsymbol{H}_{bm}^T & \boldsymbol{H}_m \end{bmatrix} \begin{bmatrix} \ddot{\boldsymbol{x}}_b \\ \ddot{\boldsymbol{\phi}} \end{bmatrix} + \begin{bmatrix} \boldsymbol{c}_b \\ \boldsymbol{c}_m \end{bmatrix} = \begin{bmatrix} \mathcal{F}_b \\ \boldsymbol{\tau} \end{bmatrix} + \begin{bmatrix} \boldsymbol{J}_b^T \\ \boldsymbol{J}_m^T \end{bmatrix} \mathcal{F}_e \quad (1)$$

where we choose the linear and angular velocity of the base $\dot{\boldsymbol{x}}_b = (\boldsymbol{v}_b^T, \boldsymbol{\omega}_b^T)^T$ and the motion rate of the manipulator joints $\dot{\boldsymbol{\phi}}$ as generalized coordinates. And,

$\boldsymbol{H}_b \in R^{6\times 6}$: inertia matrix of the base.

$\boldsymbol{H}_m \in R^{n\times n}$: inertia matrix for the manipulator arms (the links except the base.)

$\boldsymbol{H}_{bm} \in R^{6\times n}$: coupling inertia matrix.

$\boldsymbol{c}_b \in R^6$: velocity dependent non-linear term for the base.

$\boldsymbol{c}_m \in R^6$: that for the manipulator arms.

Especially in the free-*floating* situation, the external forces/torques on the base which can be generated by gas-jet thrusters, and those on the manipulator end-point are assumed zero; i.e. $\mathcal{F}_b = \boldsymbol{0}$, $\mathcal{F}_e = \boldsymbol{0}$. The motion of the robot is governed by only internal forces/torques on the manipulator joint $\boldsymbol{\tau}$, and hence the linear and angular momenta of the system $(\mathcal{P}^T, \mathcal{L}^T)^T$ are kept constant.

$$\begin{bmatrix} \mathcal{P} \\ \mathcal{L} \end{bmatrix} = \boldsymbol{H}_b \dot{\boldsymbol{x}}_b + \boldsymbol{H}_{bm} \dot{\boldsymbol{\phi}} \quad (2)$$

3. To Orbit: Concepts Ever Proposed

3.1. Virtual manipulator

The integral of the upper set of the equation (1) gives the momentum conservation, which is composed of the linear and angular momenta. The linear momentum has further integral to yield the principle that the mass centroid stays stationary or linearly moves with a constant velocity. The *Virtual Manipulator* [4] is a concept to model the kinematics of the space manipulator paying attention to this fact. The centroid of the system is chosen as a stationary basis and the length of each link is modified to the virtual length, according to the mass property of the system. But the virtual manipulator doesn't describe the angular momentum of the system then the attitude motion of the base has to be considered by other means.

3.2. Angular momentum

The angular momentum equation doesn't have the second-order integral hence provides the first-order non-holonomic constraint. The equation is expressed in the form with the angular velocity of the base $\boldsymbol{\omega}_b$ and the motion rate of the manipulator arm $\dot{\boldsymbol{\phi}}$:

$$\tilde{\boldsymbol{H}}_b \boldsymbol{\omega}_b + \tilde{\boldsymbol{H}}_{bm} \dot{\boldsymbol{\phi}} = \mathcal{L} \quad (3)$$

where $\mathcal{L}$ is the initial constant of the angular momentum, and the inertia matrices with tilde are those modified from equation (2). $\tilde{\boldsymbol{H}}_{bm} \dot{\boldsymbol{\phi}}$ represents the angular momentum generated by the manipulator motion. This equation provides a basis for further discussion.

3.3. Generalized jacobian

The velocity of the end-point of the manipulator arm is expressed as:

$$\dot{\boldsymbol{x}}_e = \boldsymbol{J}_m \dot{\boldsymbol{\phi}} + \boldsymbol{J}_b \dot{\boldsymbol{x}}_b \quad (4)$$

Then an idea came to combine it with (2), to yield the equation directly connect the manipulator joints and end-point with canceling out the base variables:

$$\dot{\boldsymbol{x}}_e = \boldsymbol{J}_g \dot{\boldsymbol{\phi}} \quad (5)$$

$$\boldsymbol{J}_g = \boldsymbol{J}_m - \boldsymbol{J}_b \boldsymbol{H}_b^{-1} \boldsymbol{H}_{bm} \quad (6)$$

where $(\mathcal{P}^T, \mathcal{L}^T)^T = \boldsymbol{0}$ is assumed for simplification. The matrix $\boldsymbol{J}_g$ is termed *Generalized Jacobian* [5] or here we can call *Space Jacobian,* and with using it the manipulator end-point can be operated by resolved motion-rate control (RMRC) or resolved acceleration control (RAC) allowing the base reaction without a special care.

3.4. Non-holonomic path planning

A cyclic motion of the arm so that the end-point draws a circle yields the change of attitude. This is a typical characteristics to show the non-holonomic behavior. An approach for non-holonomic path planning to obtain a specified goal state (base attitude and arm posture) from an arbitrary initial state was firstly proposed by [6] for this class of space robot. Since then, an intensive research effort has been made to the non-holonomic issue.

3.5. Manipulation with minimum disturbance to the base

From a practical point of view, the attitude change in the operation is not desirable, then the manipulator motion planning methods to have minimum attitude change on the base are also well studied. The *Disturbance Map* [7] is one of such approaches, and provides an intuitive chart.

3.6. Manipulation with zero disturbance to the base

An ultimate goal of minimum disturbance operation is completely zero disturbance. And such operation is possible from the insight of the angular momentum equation. The angular momentum equation with zero initial constant $\mathcal{L} = \mathbf{0}$ and zero attitude disturbance $\boldsymbol{\omega}_b = \mathbf{0}$:

$$\tilde{\boldsymbol{H}}_{bm}\dot{\boldsymbol{\phi}} = \mathbf{0} \tag{7}$$

yields the following null-space solution:

$$\dot{\boldsymbol{\phi}} = (\boldsymbol{I} - \tilde{\boldsymbol{H}}_{bm}^{+}\tilde{\boldsymbol{H}}_{bm})\dot{\boldsymbol{\zeta}} \tag{8}$$

The joint motion given by this equation is guaranteed to make zero disturbance on the base attitude. Here the vector $\dot{\boldsymbol{\zeta}}$ is arbitrary and the null-space of the inertia matrix $\tilde{\boldsymbol{H}}_{bm}$ is termed *Reaction Null-Space* [8].

3.7. Feed-forward to base attitude control

In a real spacecraft, multiple reaction wheels are mounted and a PD or PID feedback control is used for attitude maintenance against any disturbance. The manipulator reaction is also counted as one of disturbance, however which magnitude is so larger than others like gravity gradient or solar pressure that a conventional feedback control cannot provide a good performance. But the manipulator reaction is easily predicted by the momentum equation. Equation (7) is divided into the manipulator (m) and the reaction wheel (rw) parts:

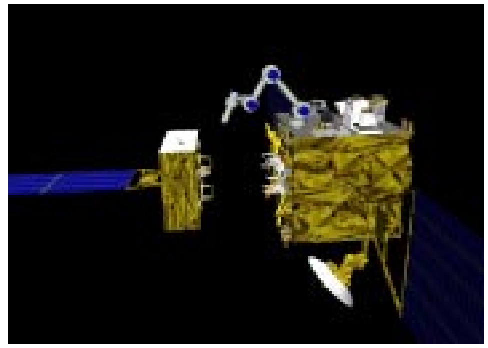

Figure 2: ETS-VII – this simulation graphics was created by the Space Robotics Lab. of Tohoku University for possible target capture operation with the on-board manipulator arm.

$$[\tilde{\boldsymbol{H}}_{bm}]_m\dot{\boldsymbol{\phi}}_m + [\tilde{\boldsymbol{H}}_{bm}]_{rw}\dot{\boldsymbol{\phi}}_{rw} = \mathbf{0} \tag{9}$$

and the solution for $\dot{\boldsymbol{\phi}}_{rw}$ when the $\dot{\boldsymbol{\phi}}_m$ is given is fed forward to the attitude control system to anticipate the reaction from the manipulator. This basic idea is initially discussed in [9] and the application to ETS-VII is well studied by [10]. The feed-forward control is now implemented and tested on ETS-VII under the name of *Coordinated Control.*

4. From the Orbit: ETS-VII Flight Experiments

4.1. A quick review of the mission

The mission objective of ETS-VII is to test robotics technology and demonstrate its utility for un-manned orbital operation and servicing tasks. The mission consists of two subtasks [11][12]:

4.1.1. Autonomous rendezvous and docking (RVD)

A 400kg sub satellite is separated in orbit from the 2000kg main satellite. The sub satellite performs a it cooperative target, in the sense that the attitude is maintained, fixtures and visual markers are mounted, and reflective to the signals, while the main satellite performs a *chaser.* Autonomous soft-docking is tested with GPS, laser radar, and vision sensor technologies.

Three trials in total are successfully done for V-var approach (FP-1, FP-2) and R-var approach (FP-6). Especially in FP-2 in August 1998, there happened a contingent situation but it turned out a good opportunity to test hazardous avoidance and recovery maneuvers.

4.1.2. Robot experiments (RBT)

The robot experiments are carried out with a 2m-long 6 DOF manipulator arm mounted on the earth facing-side of the main satellite. The experiments contains the following focuses:

<u>Teleoperation with Large Time-Delay</u>

The manipulator arm is remotely operated from Tsukuba Space Center (TKSC) of NASDA via an US data relay satellite (TDRS). The round-trip time delay is about 5 to 6 seconds. Various type of teleoperation schemes, including supervisory control, shared autonomy, predictive display, compliance control, and imaginary guide, are developed and tested by several organizations, and valuable knowledges are accumulated [14].

<u>Coordinated Control</u>

The coordinated control of satellite attitude and robot arm is successfully carried out for various situations. The experiments show relatively nice performance against a simplified on-board algorithm with an approximated momentum estimation and a fixed or variable feed-forward gain.

<u>Robotic Servicing Tasks</u>

Robotic servicing tasks are successfully demonstrated with specially designed components and task boards on the manipulator-mounted surface. The tasks include visual inspection with a hand camera, exchange of ORU (orbital replacement unit), liquid transfer to and from ORU, component assembling, structure deployment, handling of a large payload (a 400kg target satellite), and dexterous manipulation such as peg-insertion and wire-handling.

<u>Capture/Berthing of a Target Satellite</u>

A spectacular focus of the ETS-VII mission is to capture and retrieve a target satellite by the onboard manipulator arm. A whole sequence of the target capture was not tested, but some essential sub sequences were tested separately. In March 1999, the sab satellite was picked up and handled by the manipulator arm from the stored (docked) position and returned back to the docking port. In August 1999, the sub satellite was released into the envelope of half-opened docking mechanism, then it was successfully retrieved by the manipulator arm under visual servo-tracking. The former experiment represents a berthing operation and the latter a capture.

Table 1: Identified inertia parameters of ETS-VII

Base						
[kg]	[kg m^2]					
m	I_{xx}	I_{yy}	I_{zz}	I_{xy}	I_{xz}	I_{yz}
2552	6206	3541	7087	48.16	78.52	-29.22

Arm	1	2	3	4	5	6
m	35.01	22.45	21.89	16.54	26.00	18.49
I_{zz}	1.69	3.75	2.53	0.072	0.129	0.259

4.2. Some analysis of the flight data

The present author had a chance to make post-flight analysis on some of flight data, from the kinematics and dynamics point of view of the multi-body system.

4.2.1. Kinematic calibration

The end-point position and orientation of the arm is visually measured in some precision around the target markers. Kinematics calibration is carried out with accumulated flight data, to yield less than one-millimeter accuracy around specific marked-points.

4.2.2. Dynamic parameter identification

Mass and inertia property is identified from the relationship between acceleration and force/torque in a terrestrial manipulator generally. However ETS-VII does not equip sensors to provide reliable measurement on accelerations or joint torques. However, paying attention to a special characteristics that system momenta are conserved in a free-flying space robot, the identification of the dynamic parameters is possible from rate (velocity) data based on equation (3). From this view point, the author identified the principle inrtia parameters as listed in Table 1 and utilized them for further experiments.

<u>Gravity Gradient Effect</u>

Momentum conservation with zero initial momenta is commonly assumed, such as (9), in academic papers. But in reality, roll and pitch momenta are not constant due to the effect of gravity gradient torques. But this momentum change is relatively easy to measure, or even useful to obtain important information on the mass property of the spacecraft: i.e. the roll gradient torque is in proportion to I_{yz} and the pitch to I_{zx}.

4.3. Extensive experiment opportunity

The official mission experiments were successfully completed by the end of May 1999. But as the ETS-VII was still operational in a good condition, an extensive mission period was set up till the end of November 1999. In this period the opportunity was opened for academic proposals and several research groups from universities, including the present author, are given the time to do thier own flight experiments. The present author proposed the following experiments to focus the dynamic characteristics of the base/arm coupling and coordination, and successfully obtaied important flight data.

4.3.1. The classics

Two of classic concepts are tested in a free-drift state where the reaction wheels and thrusters are turned off, so that the total momenta of the system are almost zero. One is a terminal control operation with a specified arm configuration and base attitude at the destination. For this operation we take a non-holonomic path planning method based on the bi-directional approach by Nakamura and Mukhajee [6]. The other is a straight-line continuous-path operation of the endpoint in the inertial frame. For this operation, the generalized Jacobian (or space Jacobian) by Umetani and Yoshida [5] is applied.

4.3.2. Zero disturbance manipulation

The zero disturbance or reactionless manipulation obtained by equation (8) is tested. It should be beneficial to confirm that this class of manipulator paths save energy and settling time for attitude recovery. Since the number of DOF of the manipulator arm is only six without any redundancy and there are many restrictions on the manipulator motions (velocity and access limits), the reactionless characteristics are not always satisfied for arbitrary point-to-pint operations. But we compute and test a set of reactionless motions that make access to the given onboard components and a target satellite to be captured.

4.3.3. Alternative idea for coordinated ontrol

The coordinated control of the manipulator and base attitude using the angular momentum feedforward is developed by Oda for ETS-VII [10] and tested already although, the present author has an alternative idea without feedforward compensation. The idea is not always to keep the attitude zero, but actively tilt the base attitude according to the manipulator momentum during the manipulation. This will result faster recovery of the attitude with less effort after the manipulator motion finished. This is compared to the situation that a person tilts one's body backward, not being straight up, when the one anticipates the speed brake on a running train.

4.4. Result of the extensive experiments

The proposed extensive experiments were successfully carried out on September 30th, 1999. The present author was given three windows of the orbital flight paths of ETS-VII, that is almost 60 minutes for net experiments.

Here some of very typical results are presented.

Figure 3 depicts the experimental flight data to compare the conventional and reactionless manipulations. This experiment was done with the attitude maintenance using reaction wheels. The top graph shows the velocity of the manipulator endtip. The middle shows the reaction momentum induced by the manipulation. And the bottom shows the attitude motion. The graphs cover three sets of manipulation, where the first one is the conventional manipulation generating a relatively large momentum and attitude disturbance, while the other two are the reactionless manipulation yielding very small, almost zero reaction and disturbance.

It should be noted that not only the maximum attitude change is remarkably different, but the time for recovery after the manipulation is also different. This waiting time for the attitude recovery in the conventional manipulation is not negligible and degrade the efficiency of the operation. However, the reactionless manipulation provides almost zero attitude disturbance and almost zero recovery time, thus assuring a very high operational efficiency.

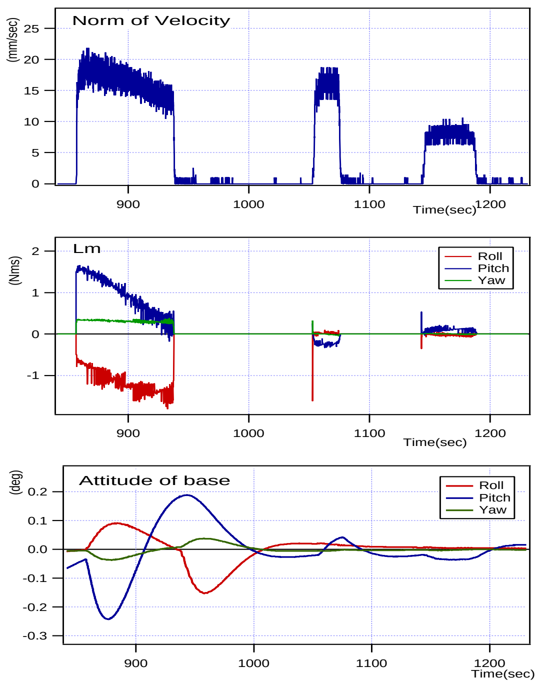

Figure 3: Experimental flight data for the reactionless manipulation

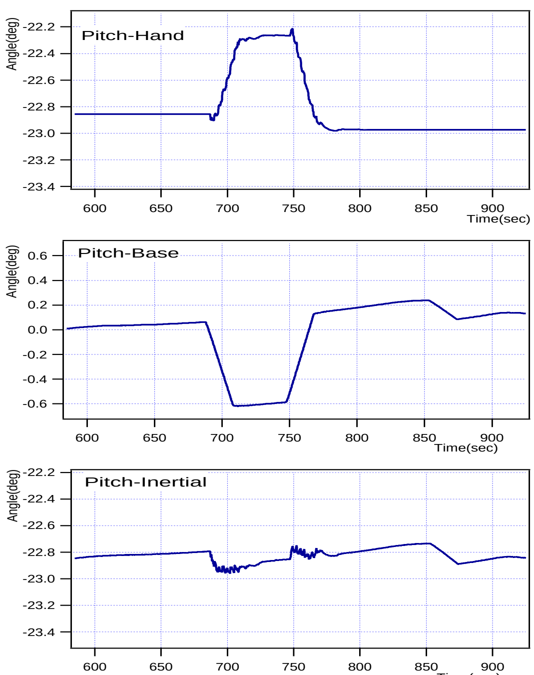

Figure 4: Experimental flight data for the inertial manipulation with the generalized jacobian matrix

Figure 4 depicts the experimental flight data to demonstrate the manipulation with the space jacobian. This experiment was done under the free-floating environment without any base attitude control actions. The top graph shows a profile for the pitch angle of the manipulator endtip in the satellite base frame, controlled with the space jacobian, during the straight line path tracking. The middle shows the pitch attitude of the base satellite, disturbed by the manipulator reaction. The bottom is the summation of the top and the middle graphs, then represents the attitude of the manipulator endtip in the inertial frame. By means of the control with the space jacobian, the attitude of the endtip in the inertial frame is kept almost zero against a non-negligible satellite attitude disturbance.

In the middle and bottom figures, an upward trend of the background is observed. This trend is due to the gravity gradient torque that was mentioned in 4.2.2.

Both results well describe typical characteristics of the reactionlss manipulation and the control with the space jacobian, which were proposed theoretically and now confirmed on an actual flying space robot.

5. For Satellite Servicing in Near Future

5.1. A technical mission scenario for satellite capture and service

The ETS-VII flight mission is an important milestone, but not a goal. The goal will be robotic service to satellites in orbits. Here, let us make a quick review on which aspect of technology is now verified and which is left over for further research.

Figure 5 depicts a technical mission scenario to approach, rendezvous, capture and service a satellite. In the ETS-VII, the rendezvous and capture were carried out with a very cooperative target, in the sense that the target equips with well-defined fixtures, visual markers, signal reflectors, also with GPS and that its attitude is well maintained. Here we assume a relatively loose condition that a target satellite can be out of attitude control then may tumble at a relatively slow motion rate. It may not equip with a sophisticated fixture, but with a simple hold such as a handrail together with a visual cue marker. This assumtion seems very fea-

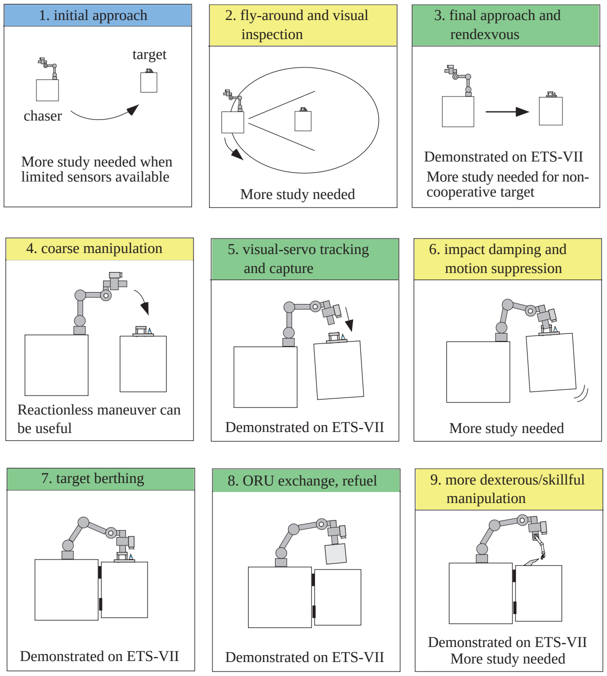

Figure 5: A technical scenario for satellite capture and service

sible in practical situations. Actually it is reported that the motion of a malfunctioning satellite in LEO (low earth orbit) is somehow damped out and most likely converge to a slow cyclic motion around the major inertia axis. The motion may be characterized as libration due to the gravity gradient torques.

1. The guidance and navigation control for initial insertion and approach is the issue of orbital mechanics, and there are a lot of experiences in space missions. Relatively precise operation without sophisticated sensors on the target will be the issue for further research.

2. Fly-around will be a typical maneuver to service a satellite, because it is relatively safe and stable from the orbital mechanics point of view and also very useful to observe the target from different angles. Visual inspection as well as attitude motion determination of the target with the CCD camera images taken from the chaser, are interesting subjects for further research.

3. Final approach and rendezvous have been successfully demonstrated by ETS-VII. In the close vicinity, the proximity sensor was mainly used, which is based on the CCD images of a specified target marker. But the technology can be extended to a non-specified, general feature of the target to measure the distance and the relative motion.

4. In order to capture the target by the on-board manipulator, the coarse positioning to a capture control box is necessary in this phase. However, the arm coarse motion generally yields reaction to disturb the base attitude, which is highly undesirable in such a critical phase of precise rendezvous. Here the reactionless manipulaton discussed in this paper will be very useful.

5. Visual-servo tracking and capture by a hand-eye system have been also successfully demonstrated by ETS-VII. However the attitude disturbance again can be a problem, because the attitude control should be turned off right before the capture due to the safety reason. Here the manipulator endpoint control based on the space Jacobian can be really useful.

6. Minimizing the impact force at the moment of contact and the motion damping and suppression after the capture are important research focus, especially in the case that the target has a tumbling motion or momentum even though its amount is very small.

7. Berthing to a docking port has been verified by ETS-VII. It is reported that the vibration of the manipulator arm becomes dominant issue of system dynamics because the arm holds a massive payload at the endpoint.

8. ORU (orbital excahnge unit) exchange and refueling missions have been also verified by ETS-VII.

9. More dexterous service operations, such as handling a wire and plugging a connector, have been tested on ETS-VII mainly by teleoperation. More skillful teleoperation is further issue.

5.2. Potential mision targets

It has been considered that robotic repair or maintenance of a commercial satellite was not a cost effective way when we compare the cost to develop such a space robot and that to develop a replacement satellite. However this was the story for the time when the number of target customers was small. Now the number of the commercial satellites is increasing dramatically, especially in the telecommunication field. For example, when a commercial venture plans to deploy a hundred of satellites in the same altitude of orbit, the cost can be compared to ensure 99.9% reliability for maintenance free, or reduce to 90% reliability with allowing robotic maintenance i.e. about 10 out of 100 satellites may have problem but recovered by a servicing robot.

The other potential mission target is found in a multi-purpose un-manned space platform. The platform provides a common-bus for mission payloads which will be maintained, updated and replaced with the robotic assistance in some frequency. This concept is suitable for earth environment monitoring in LEO that requires very long term observation by up-to-date instruments, and for a multi-purpose station in GEO where the orbital position is limited and valuable.

Anyhow, now we can say that a telerobotic orbital servicing is coming within the distance of a next step. Initiated by the US ARAMIS report, thrusted by the German ROTEX mission, and elaborated by the Japanese ETS-VII satellite, a practical free-flying space robot is becoming reality. And who takes the final step?

Acknowledgments

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References

[1] D. L. Akin, M. L. Minsky, E. D. Thiel and C. R. Curtzman, “Space Applications of Automation, Robotics and Machine Intelligence Systems (ARAMIS) phase II,” *NASA-CR-3734 – 3736,* 1983.

[2] *Space Robotics: Dynamics and Control,* edited by Xu and Kanade, Kluwer Academic Publishers, 1993.

[3] G. Hirzinger, B. Brunner, J. Dietrich and J. Heindl, “Sensor-Based Space Robotic-ROTEX and Its Telerobotic Features,” *IEEE Trans. Robotics and Automation,* Vol.9, No.5, pp.649–663, 1993.

[4] Z. Vafa and S. Dubowsky, “On the Dynamics of Manipulators in Space Using the Virtual Manipulator Approach,” *Proc. of 1987 IEEE Int. Conf. on Robotics and Automation,* pp. 579–585, 1987.

[5] Y.Umetani and K.Yoshida, “Continuous Path Control of Space Manipulators Mounted on OMV,” *Acta Astronautica,* vol.15, No.12, pp.981-986, 1987. (Presented at the 37th IAF Conf, Oct. 1986)

[6] Y. Nakamura and R. Mukherjee, “Nonholonomic Path Planning of Space Robots,” *Proc. of 1989 IEEE Int. Conf. on Robotics and Automation,* pp.1050–1055, 1989.

[7] S. Dubowsky and M. Torres, “Path Planning for Space Manipulators to Minimize the Attitude Control Fuel,” *Proc. of Int. Symp. on AI, Robotics and Automation (i-SAIRAS),* pp. 259–262, 1990.

[8] K. Yoshida, D. N. Nenchev and M. Uchiyama, “Moving base robotics and reaction management control,” *Robotics Research: The Seventh International Symposium*, Ed. by G. Giralt and G. Hirzinger, Springer Verlag, 1996, pp. 101–109.

[9] K. Yoshida and K. Kawai, “Feed-Forward Reaction Compensation Based on Computed Momentum: A Practical Spacecraft/Manipulator Coordination in Space Robots,” *Proc. of 1993 JSME Int. Conf. on Advanced Mechtronics,* pp.848–853, 1993.

[10] M. Oda, “Coordinated Control of Spacecraft Attitude and Its Manipulator,” *Proc. 1996 IEEE Int. Conf. on Robotics and Automation,* pp.732–738, 1996.

[11] M. Oda et al, “ETS-VII, Space Robot In-Orbit Experiment Satellite,” *Proc. 1996 IEEE Int. Conf. on Robotics and Automation,* pp.739–744, 1996.

[12] There are a number of papers reporting the ETS-VII flight experiments in *Proc. 5th Int. Symp. on AI, Robotics and Automation in Space, i-SAIRAS'99,* June 1999, ESTEC, Netherlands.

[13] I. Kawano et al, “First Result of Autonomous Rendezvous Docking Experiments on NASDA's ETS-VII Satellite,” Proc. of 49th Int. Astronautical Congress, *IAF-98-A3.09,* 1998.

[14] M. Oda and T. Doi, “Teleoperation System of ETS-VII Experiment System,” *Proc. 1997 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems,* pp.1644–1650, 1997.