DEMONSTRAITION MISSION OF A SATELLITE SERVICING SYSTEM

Mitsushige Oda and Noriyasu Inaba

Engineering Test Satellite VII Project Team
National Space Development Agency of Japan
2-1-1, Sengen, Tsukuba, Ibaraki, 305-8505 Japan
phone:+81-298-52-2855, fax:+81-298-60-6718
e-mail: Oda.Mitsushige@nasda.go.jp

Abstract

On-orbit service such as refueling, repairing and re-orbiting is highly required for space activities not only from economical view point but also from environmental view point, since recycle type space activity saves launch cost in a long term and bears fewer space debris. The Japanese Engineering Test Satellite VII (ETS-VII) was launched in 1997 to conduct on-orbit servicing experiments. Based on the results of the experiments using ETS-VII, the over all scenario to provide on-orbit services to spacecraft on orbit, including non-cooperative target like a failed satellite is presented. Technologies to be studied and actions to be taken are also reviewed not only from technical view points but also from political view points to enhance contents and quality of on-orbit servicing provided in accordance with the scenario above.

Key words: On-orbit servicing, ETS-VII, Refueling, Space Debris

1. Background

Number of satellite and spacecraft which will be launched into space is increasing year by year. Most of them will conduct their mission and some of them are not because of anomalies of the system. As missions go on, some spacecraft requires logistic support during their mission lives. Every satellite will end their mission after or before conducting their mission. Most of these satellite and spacecraft will require at least one of the following services.

(1)Logistic support such as fuel supply and/or equipment exchange
(2)Recover of mission either by transporting the spacecraft from a current orbit to the desired one, acquiring satellite attitude stability and/or fixing a failed part of the spacecraft
(3)Removing spacecraft from the occupied orbital position or orbital altitude after the mission

In a case of launcher's miss insertion to an orbit, it is also welcomed to recover a mission by re-boot the satellite from the unexpected orbit to the goal orbit. This potential needs for the re-boost is quite large especially in a case that the satellite is very expensive. Although a low cost commercial satellite is not cost worth to conduct recover works, it is quite important to remove them from the occupied orbit because of the following reason. Development of constellation satellite for pan-earth communication will bring many satellite in orbit. Those satellite will finish their mission in some years. If those unused satellite stayed in orbit, risk of colliding them will become higher and higher. Therefore removal of those satellites become important.
NASDA developed and launched Engineering Test Satellite VII (ETS-VII) to test and demonstrate primarily on-orbit servicing technologies which are essential to provide services mentioned above(1).

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

2. Satellite servicing system

Rendesvous and docking techinique used in ETS-VII requiers a user satellite to have special sensors (GPS receiver and large markers for rendezvous sensors) and equipments. (docking mechanism, etc) In addition to this, components can be replasable only by an unit of ORU which is conveniently designed for manipulator handling.
These request for the user is a strong "user penalty" in terms of cost, size and weight. Moreover, this techinique can not be used for a target which lost it's controll like a failed satellite. This penaly still seems to be a strong barier to promote the concept of on-orbit servicing. Therefore, a technique to approach, capture a non-cooperative target is highly required to promote the concept of on-orbit servicing. A strategy to provide an on-orbit services to non-cooperative target is presented in this chapter.

2.1 Overall strategy for Satellite Servicing

An overall strategy to approach and capture a non-cooperative target in a future mission is illustrated in Fig. 1. The detail of each step in the strategy is discussed in the following sections.

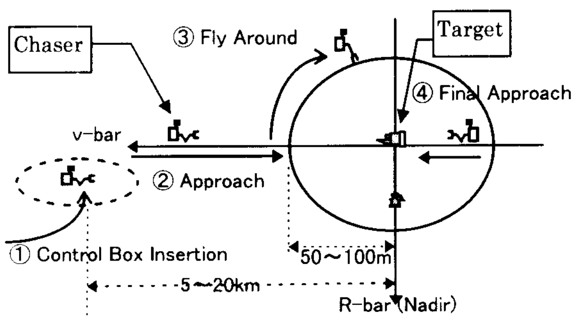

Fig.1 A Strategy to approach and Capture a Target

2.2 Ground Based Observation

A servicing vehicle (chaser) is launched and inserted into an orbit guided by on ground radar observations. Fig. 2 shows a sample of ground based observation of ETS-VII orbiting 550km in height. The image was taken by a German ground radar and provided to NASDA under a collaboration between German Aerospace Center (DLR) and NASDA. The attitude motion of a satellite as well as orbital elements can be estimated from a series of ground based observations. Since ground based orbit determination includes an error, an insertion point of the chaser is generally set 5 to 20 kilometer behind or ahead of a target satellite in the Euler-Hill's frame to ensure that the target is inside of the navigation sensor's field of view at the time of the control box insertion.

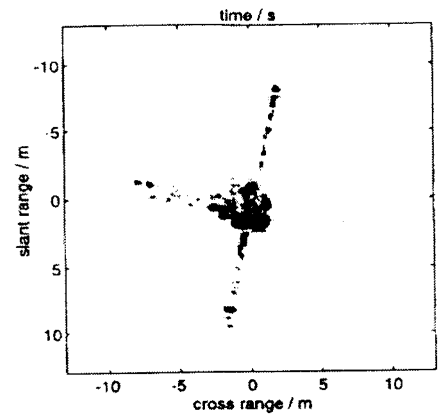

Fig.2 A Ground Radar Image of ETS-VII

2.3 Rendezvous to a Target

The chaser approaches to the target based on the navigation sensor's information. Well known CW guidance technique [2] is a convenient way to guide a chaser to the target with a small consumption of fuel. A radio radar is a conservative choice as a navigation sensor in this approaching phase, since it is usable all around the orbit including a solar eclipse period. But it raise the cost of the system. Therefore, it is preferable that necessary measurements are conducted from general CCD camera images of a target satellite to reduce the total cost of the system.
A fly around maneuver is conducted to observe the condition of the target and also to get information necessary for a final approach. Final approach is made to capture the target. The approaching direction and maneuvering mode are depend on the motion pattern of the target.

2.4 Capturing

After the final approaching phase, the chaser tries to keep the constant distance and attitude relative to the target unless the motion of the target is too fast. By doing so, the capture by a manipulator will be easy. It is not so unrealistic to assume that the motion of the target is not so rapid. Because an rigid body object on a low earth orbit will orient it's minimum axis of inertia toward nadir by the influence of the gravity gradient torque in accordance with energy dissipation regardless of the initial condition.
An action to dump the excessive momentum will be

conducted using a flexible mechanism or other equipment attached to the tip of a manipulator in a case that the target has too large momentum to be captured immediately. An Extra Vehicular Activity to dump a excessive momentum of NASA's SMM satellite gives us a good hint to design a same kind of rescue mission conducted by a robot satellite.[3] Appropriate part of a target satellite should be chosen as a capturing point which can endure the stress in a capturing process and ensure the collision free path planning of the endeffector of the manipulator. Under the assumption that the chaser is keeping constant distance and orientation by station keeping maneuver, the collision free path plan of the manipulator is relatively easy. Because the environment around the manipulator is static. An off line path planning can be done based on the environment model which is stored on ground data base and updated by in-situ observations. Visual servoing technique is also important to compensate model error and to guide the endeffector finally to the grasping point. An strategy of final approach and capturing is illustrated in Fig.3.

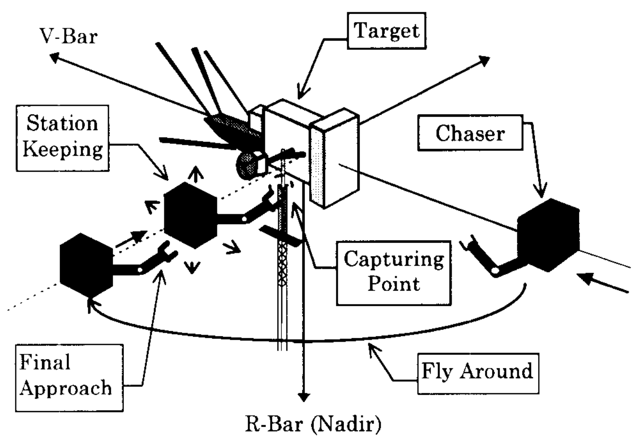

Fig. 3 A Strategy of Final Approach and Capture

An important point is that a small "user penalty" like a handle with vision marker installed on the ETS-VII target (Fig. 4) will make this grasping process easy and sure to a large extent.

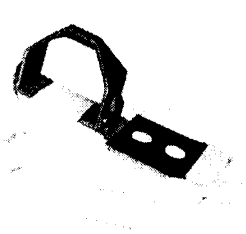

Fig. X ETS-VII's Capturing Handle

2.5 Servicing

Following on-orbit services can be supplied to the target:

- Inspection
- Changing ORUs and components
- Refueling
- Re-orbiting or De-orbiting

Since current ORU design requirements give not a small impact to satellite system's design in terms of mechanical size and clearances between components, an effort to mitigate these system impact is necessary by increasing a dexterity of a manipulator and setting an appropriate robotics work-site interface NASA's standard of extra vehicular activity (EVA) interface[4] is a good example to think about a world wide robotics interface standard for on-orbit servicing.

3. precursor experiment on ETS-VII

On orbit servicing experiments using NASDA's ETS-VII are reviewed to confirm demonstrated technology and also to clarify the direction to be followed in this area.

3.1 Rendezvous to cooperative target

Unmanned and autonomous rendezvous docking technology was developed and verified in ETS-VII's RVD experiments. The chaser approached and finally docked to the target from maximum 10km separated point. Using three kinds of navigation sensors, GPS receivers, laser radar and proximity sensor. A typical flight path plan of a RVD experiment is shown in Fig. 5.

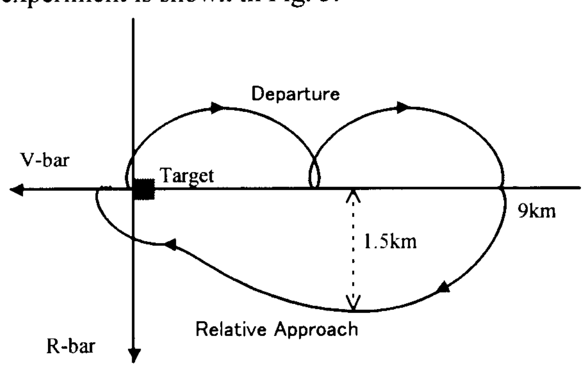

Fig 5 Rendezvous Flight Profile

Visual inspections of the target were also conducted during RVD experiments. Fig.6 shows a image of the target separated from the chaser by 13[m] .

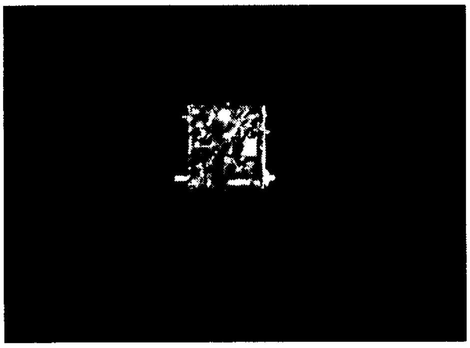

Fig. 6 An Image of Target Satellite

As a advanced rendezvous experiments, a fly around inspection experiment is planned. The plan is to release the target satellite from the chaser satellite and then conduct “fly-around and visual inspection experiment” of the target satellite.

3.2 Capture and Berthing with manipulator

ETS-VII has a capability to feed back the on-board hand eye camera’s information at the rate of 2 [Hz] to a path planning controller of a robot arm. A hand eye camera image taking a special vision marker is once converted into a black and white image under a threshold which is commanded from the ground. By extracting the marker’s sizes and centroids from the black and white image, the relative position and orientation between the camera and the marker are measured at the rate of 2[Hz] with a “H32” 32bit space qualified processor. Once the marker’s position in a image is found, the search area on a CCD is narrowed to avoid miss-detection of the marker from the next search. The relative velocity between the camera and marker is taken into account to decide the search area on the CCD.

Based on the measurement, an arm planning controller generates a desired arm position and orientation command automatically. Digital filtering techniques are used to abandon a faulty data while keeping the rapid tracking capability, since on-board camera images are much influenced not only by an aspect of direct lights from the sun and the earth but also by unpredictable reflections. The major functions of the digital filter is as follows:

- Low-pass filter
  low-pass filter with “ if then loop ” to avoid an excessive motion of the arm and also to abandon faulty data
- feed forward
  Compensation of the time delay of the vision sensor

The block diagram of the ETS-VII visual servoing is shown in Fig. 7.

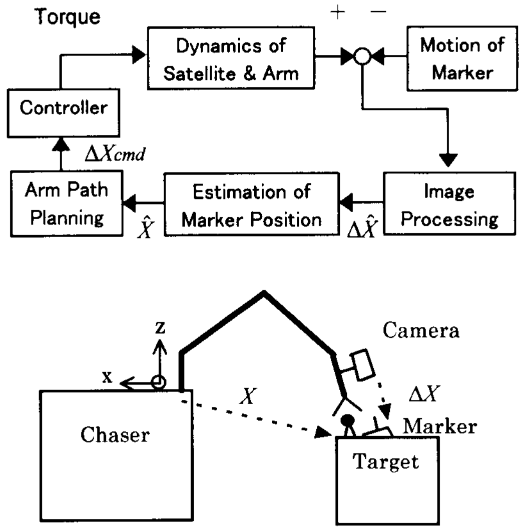

Fig. 7 Block Diagram of the Visual Servoing

There are basically three control modes to keep the satellite attitude while the arm is moving. First one is basic feed back control independent from the arm control. The second one is feed-forward control in which predicted disturbance angular momentum due to the arm motion is fed forward to the satellite attitude controller. The third one is free motion mode in which no attitude control is conducted. Appropriate attitude control mode is chosen depending on the task performed.

The basic function of the ETS-VII visual servoing was confirmed on January 1999 under a real on-orbit lighting condition. The sequence of event of an experiment was carefully designed so that the visual marker used for the image processing is stably illuminated by the Earth albedo. In the experiment, a robot arm on the chaser satellite approached and grasp the handle on the target satellite automatically under the condition that the target satellite is fixed to the chaser by a docking mechanism. The approach initiated from a position approximately 0.7 [m] above the capturing position with 0.3 [m] position error in off-axis direction. The robot has a function to start a capturing sequence by closing the fingers of the endeffector after confirming that the arm reached the aiming point relative to the target marker. The mode transition of this automatic capturing function is shown in Fig. 8.

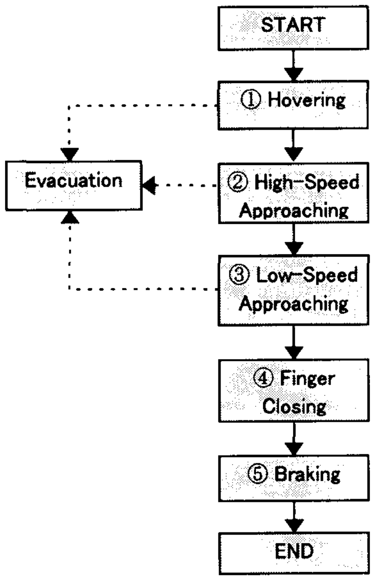

Fig. 8 Mode transition of Automatic Capturing

Images of hand-eye camera during the experiment are shown in Fig. 9.

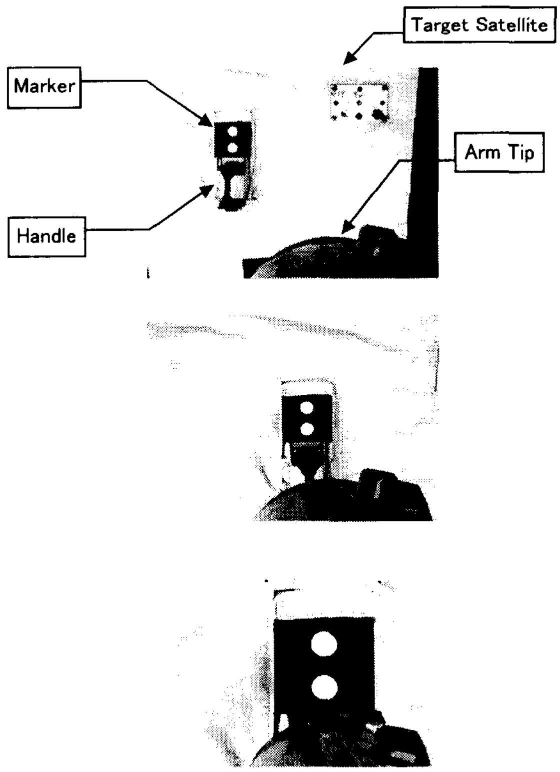

Fig. 9 Hand-eye Images during Visual Servoing

Based on the data obtained from the experiment and other preparatory experiments conducted, an automatic satellite capturing experiment using robot arm is planned as one of the extra experiment in the extended mission life of ETS-VII satellite. The target satellite of ETS-VII which is separated and floating on an orbit will be captured by the robot arm on the chaser satellite using this visual servoing technique. An image of satellite capturing experiment is shown in Fig.10.

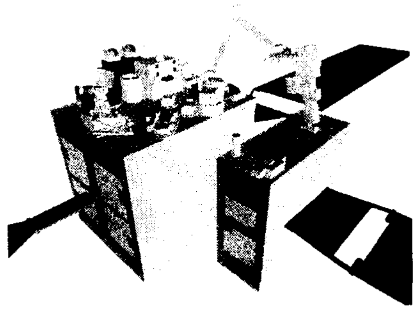

Fig. 10 Automatic Satellite Capturing

3.3 ORU Change and Refueling

An experimental On-orbit Replacement Unit (ORU) was separated from an ORU port attached to the satellite surface and connected to the port again by the manipulator. Fig. 11 shows the on-board camera image taken during the experiment.

Pairs of an electrical connector and a liquid quick disconnector are installed between the ORU and the ORU port. Disconnection and re-connection of these connectors were surely confirmed during the experiment.

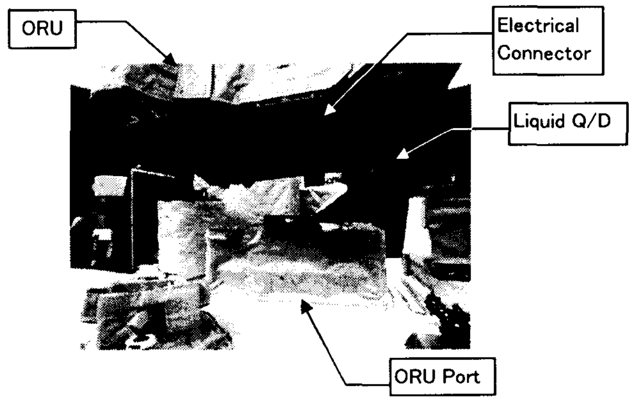

Fig. 11 Image of the ORU replacement

An fuel transfer experiment was also conducted. Because of its physical characteristics similar to hydrazine, water was used for this fuel transfer experiment. Approximately 0.7 [kg] of water inside of a supplying tank was transferred to the receiving tank. The receive tank is inside of the ORU while supplying tank is inside of the ORU port. These two tanks were connected by the quick-disconnector. The procedure of the fuel transfer experiment is illustrated in Fig. 12.

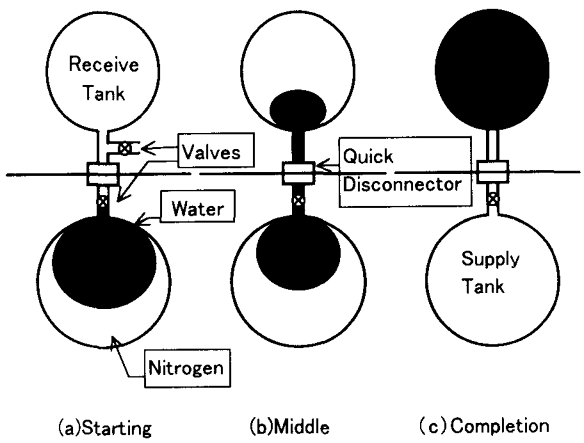

Fig. 12 Procedure of the Refueling Experiment

4. Future Scope

Although there are several merit of the on-orbit servicing system in terms of space environment and also the cost in a long term taking an inexpensive future reusable launch system into account, it is fact that there is no urgent and concrete requirement from users to use it. This is mainly because the "user penalty" is still too large to receive the on-orbit services. Therefore, following actions are required to promote the on-orbit servicing system.

4.1 Technologies to be Studied

- Reducing User penalties

It is highly required to study a rendezvous technique to approach and capture a non-cooperative target which does not have special sensors nor equipment for rendezvous mission. Unnecessity of those sensors and equipment greatly reduces the user penalty.
A radio radar or laser radar is a good candidate for a rendezvous sensor in a long range while image sensor which can measure relative distance and orientation from a CCD image of a target is a candidate for the sensor in proximity operations.

A rendezvous technique in a non-circular orbit is also required to serve a satellite in non-circular orbit such as a faulty inserted satellite.

- Robotics work site technology

It is important to choose an appropriate robotics work site interface to keep the total cost of the on-orbit servicing system minimum by avoiding a servicing robot to be too dexterous while reducing the user penalty to an acceptable level.

4.2 Political Strategy

- Demonstration Mission

A demonstration to users and taxpayers is important to show the feasibility of more convenient on-orbit servicing capability and to persuade them to choose the on-orbit servicing concept. The target satellite for the demonstration mission will be an actual failed satellite on-orbit or an experimental satellite specially designed for the mission. It is needless to say that the former is more sensational than the latter if possible.

- Future Vision

It is also important to lead the users by showing the long term vision and merit of choosing on-orbit servicing that sweep away a choice based on a short term benefit.

Unfortunately, the fear of space debris problem does not seems to be an urgent factor that can persuade general users to choose on-orbit service immediately. Because some studies show that the continuation of the current launch rate does not lead to a phenomena of cascading of debris in near future.

Refernces

(1)Oda, M. "ETS-VII a Rendezvous Docking and Space Robot Technology Experiment Satellite." Proc. of the 46th International Astronautical Congress, Oslo, Norway, 1995, IAF-95-U.2.01.
(2)Clohessy, H., and Wiltshire, S. "A Terminal Guidance System for Satellite Rendezvous", Aero/Space Science, Vol.,27, 1960. P563.
(3)Kevin, G. "The dynamics of solar maximum mission spacecraft capture and redeployment on STS41-C." AAS-85-060.
(4)STS 07700, vol. XIV appendix.7,NASA.
(5) Inaba, N., and Wakabayashi, Y. " Automatic Satellite Capture and Berthing with Robot Arm", I-SAIRAS' 94, pp205-208, 1994.