JAPAN'S RESEARCH PROGRAMS ON THE DEBRIS REMOVAL SYSTEM

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ABSTRACT

Recently, the importance and urgency of the space debris issues have been fully recognized and related studies are being conducted extensively among the space-faring organizations. This paper describes the status of Japan's research programs on the space debris removal systems and the on-orbit servicing system and also briefly introduces ongoing related technology development activities.

1. INTRODUCTION

Space debris can pose a serious hazard to near-Earth space activities. Since the number of satellites will increase drastically in future, effective measures to mitigate or minimize debris generation are indispensable. End-of-life de-orbiting and orbital lifetime reduction capability will be implemented to reduce the probability of collision with other debris, but the active removal of space debris and the retrieval of defunct or malfunctioning satellites are still necessary to ensure the safety of space activities.

Encouraged by the success of Engineering Test Satellite-VII (ETS-VII) rendezvous and docking, and space robotics experiments, several organizations in Japan have just started studies on the debris removal systems such as:

- Orbital Maintenance System for Next-generation LEO system (OMS for NeLS) by Communications Research Laboratory (CRL/TAO)
- Retrieval, Repair, and Disposal System (RRDS) by National Aerospace Laboratory (NAL)

In addition to the debris removal operation, possibility of on-orbit servicing is being pursued from environmental and economical viewpoint:

- On-orbit Servicing Satellite (OSS) by National Space Development Agency of Japan (NASDA).

First, the reason why the on-orbit servicing system including space debris removal should be studied, will be discussed in this paper. The breakthroughs necessary for realization and the key issues of these systems are also discussed. Secondly, the research programs currently promoted in Japan, and the contrivances to reduce the cost and the technological difficulties will be introduced. The component technology development activities are also briefly mentioned.

2. SPACE DEBRIS REMOVAL

Recently, the threat of space debris has come to the reality and the effective and reasonable mitigation means are indispensable to the future space development activities. There are many debris mitigation options available to spacecraft manufacturers, and disposal, or post mission de-orbiting is considered to be the acceptable strategy. Debris population prediction also indicates that the disposal is effective enough to keep the level of the debris population today. Therefore, post mission de-orbiting is considered to be implemented in near future.

However, there remains a discussion whether implementation of post mission de-orbiting capability to all satellites is the realistic and best strategy. Because:

- it poses cost and weight penalty to each satellite and gives large impact to the satellite design. So it might be unacceptable for some satellites.
- it is difficult to manage the amount of the residual propellant or assure the reliability of another propulsion system if implemented after long mission period.
- it is impossible to de-orbit the failed satellite or the post mission systems already exist on orbit.

In addition, the disposal strategy itself has the following issues to be solved:

- Debris population prediction study depends on some models such as traffic and breakup, which have large inherent uncertainties. As a result, the future debris

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population cannot be predicted accurately and disposal strategy alone may not be enough to solve space debris problems.
- Even though disposal strategy will be effective for a while, it is not a permanent solution because the space debris remains in orbit, especially in case of re-orbiting.
- Disposal to the 25-year-lifetime orbit endanger the spacecraft in low orbit, where the manned vehicles are often orbiting.

The active removal of the space debris by another vehicle is obviously effective strategy to solve space debris issues, because it removes from the orbit the significant mass that could produce countless small space debris by collision or explosion in the future. It also has the following advantages:

- Not only just keeping the present debris population level, it can make the environment cleaner than that of today. As a result, it will relieve all manned space systems of heavy, bulky bumper and other measures against the space debris in the future.
- The same technologies can be used for on-orbit servicing such as repairing and refueling of the satellite. Consequently, extremely high reliability required to current space systems will not be needed.

Both of them are expected to reduce the cost of total space system.

Although the active removal system has a lot of advantages, as mentioned above, there exist many problems to be solved for its realization. The removal of inert objects requires an active maneuvering vehicle with the capability to rendezvous with and grapple an inert, tumbling, and non-cooperative target and the ability to move the object to a disposal orbit. Because these operations require highly sophisticated automation technology, and the operations costs are to be kept reasonable, any removal system has not yet reached the stage where it can be considered feasible or practical. However, active removal is needed to be studied because it is a promising strategy to solve space debris issues only if it become acceptable both in technological and economical viewpoints. Therefore, several organizations in Japan have already started the study on the contrivances for reducing the cost and the required component technologies.

3. CONCEPT OF EACH PROGRAM

In this section, three debris removal programs conducted now in Japan, will be introduced briefly.

3.1 <u>Orbital Maintenance System for Next-Generation LEO System by CRL/TAO</u>

First, the Orbital Maintenance System for Next-generation LEO System (OMS for NeLS) is introduced [1].

Communications Research Laboratory (CRL) has been studying a satellite servicing concept, which is called Orbital Maintenance System (OMS). OMS is a servicing satellite to inspect and repair failed satellites, or to remove them from orbit. On the other hand, the Telecommunications Advancement Organization of Japan (TAO) is planning the Next-Generation LEO System (NeLS), a high-bandwidth multimedia telecommunications system which consists of a constellation of 120 satellites in low earth orbit (LEO) at an altitude of 1200km. For such mission with a number of satellites, de-orbiting of the post mission or malfunctioned satellites is indispensable because those satellites can pose hazards to both of other satellites and NeLS themselves, by occupying the useful orbit slots. Here CRL found the need for OMS, and ``OMS for NeLS'', a servicing system for NeLS is being studied.

To reduce the technological difficulties and the cost of this system, they are proposing the following elaboration:

- To reduce risks and difficulties in the capturing operation, NeLS satellite is to be equipped the rescue package, elaborated equipment package which includes a handle for capturing and a small attitude control system.
- To reduce the launching cost, the servicing satellite to be launched with the replacement satellite as a piggy-back payload,
- mass production of servicing satellites,
- short lifetime of servicing satellites.

Fig. 1 shows the de-orbiting service for NeLS. When the NeLS satellite which is preinstalled the rescue package failed, the rescue package will be awaken by the command form the ground, and control the attitude of the NeLS satellite. At the same time, the servicing satellite will be launched with the replacement satellite as a piggyback payload. The servicing satellite rendezvous with the failed satellite, and capture it using the marker and the handle on

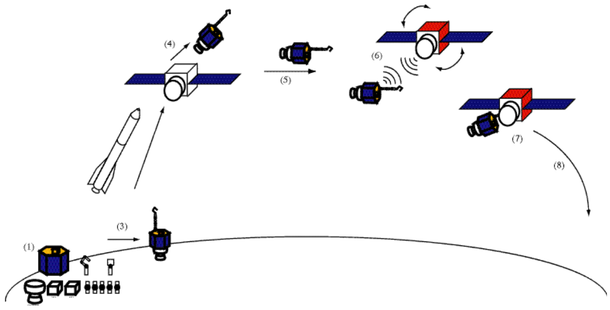

Fig. 1. De-orbiting service for NeLS

the rescue package for de-orbiting and repairing operation.

3.2 On-orbit Servicing Satellite by NASDA

Not only environmental but also economical viewpoint, NASDA is studying the on-orbit servicing such as refueling, repairing and re-orbiting [2].

Engineering Test Satellite VII (ETS-VII) was launched in 1997 to test and demonstrate the on-orbit servicing technologies. It successfully conducted many experiments including automatic rendezvous docking, capturing the free-flying satellite by robot arm, exchanging ORU, and refueling experiment. Fig. 2 shows the ETS-VII conducting automatic capturing experiment. A robot arm on the chaser satellite grasped a small handle on the free-flying controlled target satellite automatically, by feed-back control using on-board hand eye camera's information of a marker near the handle at the rate of 2Hz.

These experiments requested the target satellite to be cooperative, but now the technique to approach, capture a non-cooperative target is being studied. For rendezvous with a non-cooperative target, applicability of radio radar is being pursued since it is usable all around the orbital period. For capturing, they demand small penalty of marker and handle installation of the satellite to be serviced, like the ETS-VII target satellite. This will make the capturing process easy and reliable to a large extent.

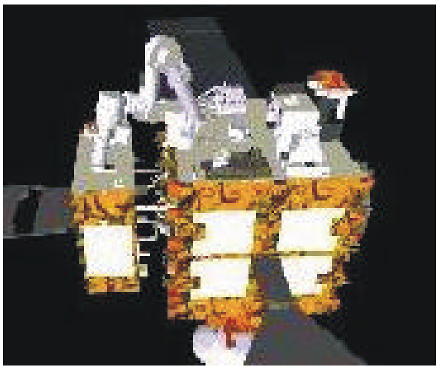

Fig. 2. ETS-VII automatic capturing of a controlled satellite.

3.3 Retrieval, Repair, and Disposal System (RRDS) by NAL

NAL has been promoting the research program on Space Environment Preservation and Utilization Technology since 1998 with high priority and concentrating its efforts on pursuing the debris removal system, which includes not only system study but also developments of component technologies [3].

NAL is studying the system intended to dispose non-cooperative satellites and does not pose any requirements on the target systems. It is even applicable to the space debris launched in the past and orbiting now. The servicing satellite will be launched and conduct rendezvous with a target object, and fly around it for inspection. If it is possible to repair the target satellite, the servicing satellite will repair it or tag to the space station, and if not, it will de-orbit to a disposal orbit, the orbit where the orbital lifetime is less than 25 years. The concept of the system is shown in Fig. 3.

First, the effect of removing the debris from the crowded orbit was investigated taking the current debris population

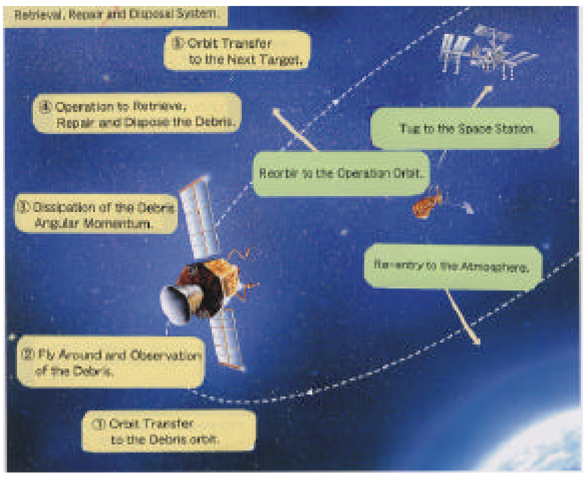

Fig. 3. Concept of the system studied in NAL

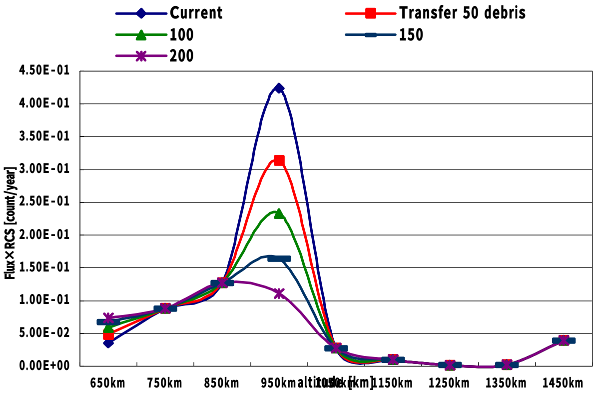

Fig. 4. Change in total collision possibility when the space debris are removed

distribution into account. It is shown that by transferring the debris in 800-900km orbit to the 650km orbit where the orbital lifetime is about 25 years, the total collision risks are significantly reduced. Fig. 4 shows the change in collision possibility in each altitude, when some debris are transferred. It shows that when at most 10^2 debris are moved, the total collision risk would be reduced by about 30%, no matter what the debris are.

One servicing vehicle is expected to deal with multiple debris, because the cost of the vehicle would be prohibitive when only small reduction in the debris population could be achieved. The cost effective orbit maneuvering are needed to transfer from the initial orbit to the target orbit to de-orbit debris, and to rendezvous with the next target. If this operation includes change of the orbital plane, enormous Δv will be required. But fortunately, there are many satellites in the orbits with almost the same inclination, which makes it possible to remove them with one servicing vehicle. In case each target satellite has the different right ascension of ascending node, Ω, the secular variation in Ω due to J_2 perturbations due to the difference in altitude can be utilized. The orbit transfer to change altitude cannot be realized using the conventional propulsion system due to the large propellant consumption, thus the possibility of ingenious propulsion systems is being studied, as mentioned in Sec. 4.1.

4. KEY COMPONENT TECHNOLOGIES

The following are the list of key component technologies studied in NAL:

- Cost effective orbit transfer (Electrodynamic tether / Solar thermal thruster / Laser thruster / Ion thruster)
- Rendezvous and Observation
- Dissipation of the angular momentum
- Robot operation

Each of these is described below in some more detail.

4.1 Orbit Transfer

Several cost effective propulsion systems for de-orbiting operations are being developed and on-orbit dynamics are studied. In NAL, high efficient propulsion such as tether system, ion thruster, solar thermal thruster, and laser thruster have been studied. Especially, electrodynamic tether system is prospective because it can gain thrust large enough to transfer in realistic time period without much propellant by utilizing the interaction with Earth's magnetic field. After the debris is captured, it needs to be connected to the end of the conductive tether, and the tether is to be deployed. Because of the orbital motion, the induced current will runs when the closed circuit is constructed utilizing the plasma around it. Thus, interaction between the current and the Earth's magnetic field can reduce the orbital velocity and lower the altitude. When the altitude of the system become low enough, the tether will be cut to put the debris into a lower orbit, and then the reversed electric current will raise the altitude of the servicing satellite to reach the next target. Recently, the dynamics of the flexible tether is studied using numerical simulation. Fig. 5 shows the change in the altitude when the electrodynamic tether with the length of 10km with electrical current of 3A, is used to de-orbit the debris. The thrust is large enough to de-orbit the debris in weeks or months. Fig. 6 shows the dynamics of the tether after the debris is separated. It is shown that the tether libration occurs

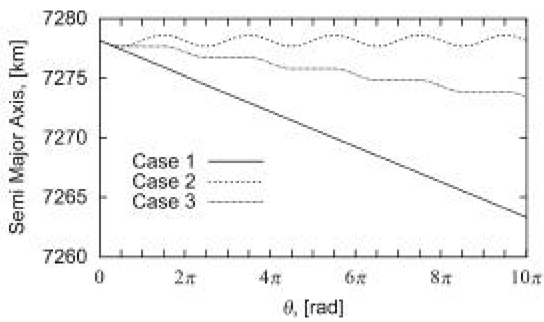

Fig. 5. Change in altitude using electrodynamic tether

in some cases, so the stability of the system needs to be secured.

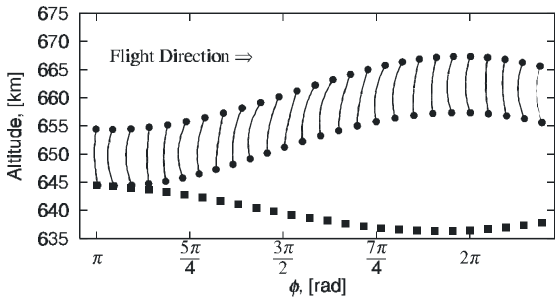

Fig. 6. Dynamics of flexible tether when the debris is separated.

4.2 Rendezvous and Observation

After inserted into the near orbit, the servicing satellite needs to rendezvous with the target object using the data obtained at ground observatories first, and using on-board sensors in the final approach. Because the NAL's target is supposed to be a non-cooperative without any marker or communication ability, the technologies to locate and recognize the target automatically are considered to be indispensable and being studied extensively. Many studies in this aspect are being conducted, and algorithm of target recognition by color information [4] and motion estimation [5] is to be verified using μ-LabSAT, a piggy-back satellite to be launched in 2001. Fig. 7 shows μ-LabSAT and released target object in orbit taking the image of the target using an on-board CMOS camera. The motion estimation technologies using time-series images are also studied. First, some points of the target are extracted by image processing, and then the estimation of the angular velocity and the inertial momentum ratio will be conducted by real-time Kalman filtering or off-line least squares methods utilizing target's CAD data. The study shows that if the image processing has

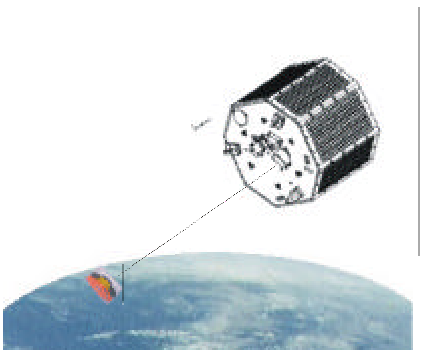

Fig. 7. μ-LabSAT and Target

the accuracy of 0.5%, the motion estimation can be done within the accuracy of 1 to 2 %.

4.3 Mechanical Impulse for Angular Momentum Dissipation

It is observed by ground observatories that some of space debris are not in a stable attitude, or even spinning around principal axis: they might exhibit complicated attitude motion such as nutation or tumbling. Because the robot arm cannot follow the quick motion, it is difficult to capture a non-cooperative target object possessing high angular momentum. Therefore, a method to reduce the angular momentum of the target before capturing using mechanical impulse is being studied [6]. For the mechanical impulses, various methods could be applied, such as the projection of a small and soft tethered object, and/or picking by the robot arm tip. By the repeated, well-timed mechanical impulses, the angular momentum of the target object can be gradually reduced into the slow single spin motion, which the space robot arm can access within reasonable mechanical load (Fig. 8).

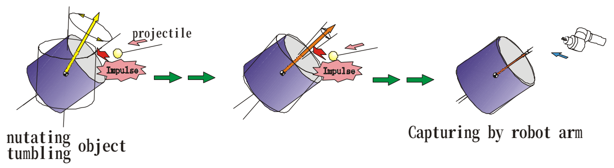

Fig. 8. Concept of mechanical impulse

The major advantages of this method are (1) No need for the precise estimation and measurement of the target motion, (2) No need for the complicated, real-time feed-back control, and (3) The robustness of the mechanical impulse point and timing. For the mechanical impulse method, the relatively rough estimation of the target motion is enough to decide the impulse timing and direction. The repeated impulse period could be set long enough to estimate the target motion after each mechanical impulse. It is demonstrated by numerical simulations that a nutating or tumbling object can be coaxed into a simple spin or even stopped altogether. It is also shown that this method is robust against errors, although when errors are included it will take longer to bring a target under control. Since the collision-force profile cannot be determined exactly, we have conducted experiments using a model satellite on an air table to investigate the effectiveness of this method.

4.4 Robot Operation

For capturing a free flying object on orbit, dexterous robot operation is indispensable in order to avoid distracting itself and making the condition of target's attitude motion worse in either case of automatic and tele-operation. To establish the basic tele-robotics technologies for on-orbit manipulation, tele-operation experiments were conducted using ETS-VII [7]. At present, the development of flexible-joints robot arm and the control algorithm are being studied. The capturing experiments using two 7DOF robot arms, an air table, and large X-Y stage (Fig. 9) are to be conducted in near future.

Fig. 9. Large X-Y Stage

5. CONCLUSION

This paper described space debris active removal and the status of Japan's research programs on the on-orbit servicing system. Ongoing related technology development activities are also briefly introduced.

CRL and TAO are studying OMS for NeLS, Orbital Maintenance System for the Next-Generation LEO System (NeLS). This system assumes the NeLS satellite should be implemented with a ``rescue package'', elaborated equipment package which includes a handle for capturing and a small attitude control system, to reduces risks and difficulties in the capturing operation. It also assumes the OMS is to be launched with the replacement satellite as a piggyback payload, which is expected to reduce the removal cost drastically.

NASDA proposes On-orbit Servicing Satellite (OSS) such as refueling, repairing and re-orbiting from both environmental and economical viewpoint. Based on the on-orbit servicing experiment for the cooperative target that was conducted successfully on ETS-VII, the technique to approach and capture a non-cooperative target is being studied.

NAL are studying Retrieval, Repair, and Disposal System (RRDS). It is intended to dispose satellites launched in the past and does not pose any requirements on the target systems. Not only the system study, but the key component technologies such as cost effective orbit transfer, rendezvous and observation, dissipation of the angular momentum, and robot operation, are also investigated.

6. ACKNOWLEDGEMENT

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