**GNC Strategy to Capture, Stabilize and Remove Large Space Debris**

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**ABSTRACT**

To suppress increases in the population of space debris, it is necessary to improve the success rate of Post Mission Disposal (PMD) in future missions, but at the same time, Active Debris Removal (ADR) is also important. ADR targets large space debris in crowded orbits. These space debris are characterized by being non-cooperative targets with non-stationary rotational motion, and very heavy. Therefore, to achieve the ADR mission, several technical challenges must be overcome from the standpoint of Guidance Navigation and Control (GNC). The authors have devised GNC strategies that incorporate several new technical ideas to overcome these difficult problems and achieve the ADR mission at low cost. This paper describes the new ideas regarding the GNC strategies toward solving the problems and a specific GNC scenario in which to apply those strategies. The GNC strategies and GNC scenario are characterized by a combination of reliable and practical technologies, leading to lower economical thresholds for ADR missions.

**1 INTRODUCTION**

The Inter-Agency Debris Coordination Committee (IADC) predicts that the number of space debris will continue to increase due to collisions between space debris [1]. And as predicted by IADC, the increasing number of small debris measuring 1 mm to 10 cm in size that cannot be avoided or protected against may significantly limit human space activities in the future.

Liou [2] claimed that the active removal of large and massive debris in crowded orbits can effectively reduce the number of collisions largely responsible for the tendency toward a growing debris population. The results of calculations based on certain assumptions indicate that the active debris removal (ADR) of five large objects per year along with proper implementation of commonly adopted mitigation measures could stabilize the population growth.

Many studies have also shown that high compliance with post mission disposal (PMD) guidelines is necessary to control the increase in space debris [3][4]. At present, the PMD success rate is about 20% for payloads and about 60% for rocket bodies, with PMD countermeasures not being sufficiently widespread [5]. Thus, many efforts should be made to increase the PMD success rate. However, according to a study by Somma et al. [6][7], even if the PMD success rate is increased, the tendency toward more space debris in LEO will continue, thereby making it necessary to implement ADR in addition to PMD.

In recent years, many plans have been proposed for mega-constellations of satellites, thus raising concerns about their impact on the space environment [8][9][10]. According to NASA research [9], a very high PMD success rate of 90 - 99.9% may be required to limit the increase of space debris generated by mega-constellations. And with respect to this problem, ADR is one of the effective solutions. Using ADR spacecraft to remove failed satellites composing a mega-constellation will have an effective environmental improvement effect [10]. The ADR spacecraft that removes rocket bodies has many technical similarities to the ADR spacecraft that removes the failed satellites of a mega-constellation.

There are two types of large space debris targeted by ADR: inactive payloads and rocket bodies. The effective target of ADR is massive debris with high collision probabilities. According to a study by Somma et al. [7], the removal of rocket bodies can achieve twice the benefits for the long-term space debris population as compared with the removal of inactive payloads. And because rocket bodies are generally similar in shape and have few large protrusions, it is also relatively easy for ADR spacecraft to approach and capture them. Conversely, each inactive payload has a different shape, often with large protrusions typified by solar cell panels. Therefore, the authors consider it advantageous to carry out the initial ADR attempts with rocket bodies as targets for removal, particularly due to the both technical ease and efficient environmental improvement.
Several evaluation indicators have been proposed that quantitatively indicate the degree to which objects in orbit will contribute to future space debris population growth [11][12][13]. And several studies have listed space debris with particularly high scores based on those indicators. These lists provide a good reference for considering effective ADR removal targets to curb future space debris growth. According to these lists, the most influential group is Russian rocket bodies, which are dense at specific altitudes and orbital inclinations. Many are the upper stages of the SL-8 and SL-16 rockets (weighing about 1.5 tons and 9 tons, respectively). In considering the high environmental improvement effect, it is thus desirable for ADR spacecraft to remove these rocket bodies.

No country can touch an orbiting object of another country, however, without the consent of the country that owns the object. Activities such as ADR should be conducted with clear transparency after establishing an international framework based on international agreements among the parties concerned. But if the technology that realizes ADR is immature, there will be no serious discussion about an international agreement or the establishment of an international framework to implement it. Such discussions are considered to progress concretely only when the technical feasibility can be foreseen.

Based on the understanding described above, the authors examined an ADR mission to remove orbiting rocket bodies from crowded orbits, and considered Japanese rocket bodies as the target of the technology demonstration mission. Rocket bodies are so-called non-cooperative targets that are also very heavy. Thus, there are a number of technical challenges in terms of guidance navigation control (GNC) to realize this mission. The authors devised several new technical ideas to overcome those challenges and realize the mission at the lowest possible cost.

As a precondition, this paper first describes the design reference mission that we set up for this ADR technology demonstration. Then it describes the GNC strategies to solve the difficult technical problems. It also presents a GNC scenario in which these strategies are applied, along with some numerical simulation results.

2 DESIGN REFERENCE MISSION FOR DEMONSTRATION

This design reference mission is intended to demonstrate practical and effective ADR technology for improving the space environment. For this purpose, the upper stage of Japan’s H-IIA rocket was selected as the target of removal. The mass of the H-IIA upper stage weighs about 3 tons, which is sufficient for the ADR technology demonstration. Rocket bodies at higher orbital altitudes above 800 km are effective removal targets for improving the space debris environment. However, since this technical demonstration mission marks the first attempt, a candidate at an altitude of around 600 km was selected. This is because even if new debris objects are generated when unintended contact is made with the target, the influence on the environment can be minimized. There are currently six specific H-IIA upper stages that meet these requirements.

The mission requirement is to lower one of these six upper stages from the initial orbit to a sufficiently low orbital altitude, and then make a safe and controlled reentry. Completing this mission requires all the technologies necessary for practical ADR. Specifically, this entails technology for rendezvous with the non-cooperative target, capture technology, technology for orbital maneuver of an extremely heavy object, and technology for safe controlled reentry back to the surface of Earth.

3 GNC STRATEGY

Implementing the design reference mission defined in the previous chapter poses several technical challenges related to GNC. If these challenges are met by using a conservatively designed ADR spacecraft using a proven chemical propulsion system as the main means of propulsion, such a spacecraft will be very huge and thus expensive. Therefore, the basic policy is for the authors to incorporate technical ideas intended to reduce costs as much as possible in the GNC strategies. Table 1 summarizes the GNC technical challenges and strategies (From A to F).

<table>
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<tr>
<th>Technical challenges</th>
<th>Strategies</th>
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<td>A. The target does not have dedicated markers and retroreflectors for relative navigation sensors. This makes reliable relative navigation difficult.</td>
<td>• Safe relative orbit design</td>
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<td>• Angles-only navigation</td>
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<td>• Infrared camera navigation</td>
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The target may rotate too fast for the ADR spacecraft to make a relative motion synchronized with the target’s rotation and complete mechanical capture. • Detumbling by plume impingement

The target does not have a dedicated docking mechanism. • Dedicated docking mechanism to capture payload attachment fitting of the target • Dedicated relative navigation sensor for payload attachment fitting of the target

A large amount of fuel is needed to lower the altitude of the heavy target. This makes it difficult to reduce the cost of the ADR satellite. • Combined utilization of efficient electric propulsion system and atmospheric drag

Disturbance torque induced on the large target is so strong that powerful attitude actuators are needed. This makes it difficult to reduce the cost of the ADR satellite. • Torque equilibrium attitude concept

A large amount of fuel and a high-thrust propulsion system are needed to perform controlled reentry, which typically needs around 100 m/s delta-V. • Minimum delta-V reentry using atmospheric drag

Strategy A:
The orbital rocket bodies do not have built-in markers for image processing or retroreflectors for laser sensors. As a result, it is technically difficult to establish reliable relative navigation. Consequently, the possibility of temporarily losing relative navigation due to the unexpected reflection of light should be taken into consideration. The most basic approach to this problem is to design a safe relative approach trajectory [14]. A very effective way to solve this problem is to carefully design a relative orbit where the ADR spacecraft will not collide with the target in case various events occur. For instance, such events to consider include the execution of passive aborts and insufficient or excessive acceleration by the propulsion system. And given the high uncertainty of the reflection intensity of light from the target surface, angles-only navigation (AON) using the very powerful illumination of sunlight and a visible light camera are particularly suitable for far-range rendezvous operation [15]. A thermal infrared camera that detects the thermal radiation of the target is also effective as it can overcome uncertainties related to the reflection characteristics of the target, and can be used continuously in an eclipse.

Strategy B
According to previous research [16], a rocket body in orbit generally loses its kinetic energy and angular momentum gradually due to eddy current torque. And finally, the gravity-gradient torque converges the attitude motion into pendulum-like movement around the vertical direction. And according to the statistical evaluation of light curve observations, there is also a small proportion of low-orbit objects having clearly confirmed high-speed rotation [17]. However, the attitude motion of the specific target (ex. H-IIA upper stage) is not well known. Without information on the assumed maximum value of the target’s angular velocity, it is difficult to make a detailed design of the ADR spacecraft. In order to solve this problem, we employ the strategy of reducing the target’s angular velocity to below an acceptable value by applying an RCS thruster plume to the target and allowing the external torque to act on it. [18]. This method is safe because the angular velocity can be reduced without making contact with the target or approaching very close to it. And because proximity operation of the ADR spacecraft with the target inevitably requires RCS propulsion system, this method also diverts it to the detumbling application. Thus, there is no need to develop a new detumbling device and install it on the ADR spacecraft for this dedicated detumbling purpose only. In that sense, this is an efficient and practical solution.

Strategy C
The target H-IIA upper stage is not designed to be captured. However, as a common feature, it has a payload attachment fitting (PAF) for mounting payloads. The PAF has a standardized shape and a tough structure. Therefore,
it is suitable as a structure to be captured. For that reason, we are studying a dedicated mechanism to capture the PAF [19] for this mission. Our strategy is to use specialized mechanisms and sensors focused on the PAF, rather than expensive robotic arms that can perform complex tasks and handle a variety of objects.

Strategy D

The target H-IIA upper stage weighs about 3 tons. A large amount of propellant is required to make a large change in orbital altitude using a low-ISP chemical propulsion system while the ADR spacecraft is combined with the heavy target. As the propellant mass increases, the weight of the structure that supports it and the attitude control actuator that controls the structure become larger, and the entire ADR spacecraft becomes heavier and more expensive.

A high-ISP electric propulsion system can effectively prevent this situation, as it can greatly reduce the propellant mass. However, the electric propulsion system is a so-called consumable. Since the thruster is worn out by plasma sputtering, the total impulse output of the electric propulsion system is limited. If the electric propulsion system requires excessively large total impulse output, then its power and weight will increase, and the ADR spacecraft will become expensive.

For this reason, we employ a hybrid strategy of lowering orbits by electric propulsion at higher orbital altitudes where the atmospheric density is relatively low, and lowering orbits by atmospheric drag at lower altitudes where the atmospheric density is relatively high [20]. This strategy makes it possible to prevent the ADR satellite from becoming large and achieves a sufficient descent of the orbital altitude within a realistic period.

Strategy E

The target H-IIA upper stage weighs about 3 tons, is about 4 m in diameter, and about 10 m in length. On the orbit, the target is affected by disturbance torque commensurate with its size and weight. In contrast, the ADR spacecraft is relatively small and lightweight. This makes it difficult to manage the angular momentum of the ADR spacecraft combined with the large and heavy target. The dominant disturbance torque is the gravity-gradient torque when the orbital altitude is high, and the air-drag torque when the orbital altitude is low. While thrust is generated by the electric propulsion, angular momentum management is possible by controlling the thrust vector of the electric propulsion thruster using a gimbal system. This is a proven technology and there are no major problems.

Electric propulsion is turned off, however, in the phase of orbital descent due to atmospheric drag. At this time, usually two methods are conceivable to manage the angular momentum while receiving a large disturbance torque. One is to use the RCS thruster with the disadvantage of consuming valuable propellant over a long period of time. The other is to mount an insanely large magnetic torquer on the ADR spacecraft. Both methods increase the size of the ADR spacecraft and the cost.

As a solution without these disadvantages, the authors employ a strategy of setting the pitch attitude angle at which the gravity gradient torque and atmospheric drag torque are balanced as the reference attitude for control [21]. Such an attitude angle is referred to as Torque Equilibrium Attitude (TEA). As the orbital altitude decreases, the atmospheric density becomes large, so the TEA angle changes accordingly. As a result, even with small reaction wheels and magnetic torquers, angular momentum management is possible in a state where the ADR spacecraft and the huge target are combined.

Strategy F

Normally, controlled reentry from a low Earth orbit is performed by impulse maneuvers and requires about 100 m/s delta-V. The ADR spacecraft needs to complete such large reentry maneuvers with the heavy 3-ton target. Therefore, the ADR satellite must be equipped with a large amount of propellant and a chemical thrust system with large thrust. This increases the size and cost of the ADR spacecraft. In order to mitigate this difficulty, the authors apply the “minimum delta-V reentry” method of reducing a spacecraft’s orbital altitude by utilizing atmospheric drag as much as possible. The last small delta-V impulse maneuver corrects the reentry trajectory error caused by the atmospheric density prediction error. According to a previous study, this method may reduce the delta-V required for reentry to about 11 m/s [22].
4 GNC SCENARIO AND SIMULATIONS

In the previous chapter, we presented GNC strategies that solve the technical challenges of the design reference mission. This chapter presents a specific GNC scenario based on these GNC strategies, and introduces some numerical simulation examples of the phases that constitute it. Figure 1 shows a GNC scenario that reflects the GNC strategies presented in the previous chapter. The scenario consists of 16 phases.

Phase 1 ("Ground-based observation campaign")
Prior to the launch of the ADR satellite, a campaign for optical and radar observations from the ground will be conducted to collect as much information as possible about the attitude motion of the target.

Phase 2 ("Launch and early operation") and Phase 3 ("Rendezvous (TLE/SGP4+GPSR")
A coarse target orbital element in TLE format can be obtained from the Combined Space Operations Center (CSpOC) of the United States. Based on this TLE information, the rocket is launched toward the target, and the ADR spacecraft is separated into the orbital height and orbital plane appropriate for rendezvous to the target. The predicted orbital elements of the target are calculated by SGP4 based on the TLE. Conversely, the orbital elements of the ADR spacecraft can be obtained with high accuracy by an onboard GPS receiver. The ADR spacecraft then starts approaching the target using both orbital elements.

Phase 4 ("Rendezvous (Angles-only navigation)") and Phase 5 ("Hold point")
The target begins to be seen from about 100 km to several hundred km by the onboard visible light camera. The distance at which it begins to appear is highly dependent on the optical characteristics of the target surface, the attitude of the target, the direction of the sun and other factors, and is highly uncertain. And even if it starts to appear, it is not always visible, but only at the proper argument of latitudes in an orbital revolution. According to the authors' study, the target upper stage may be visible at least 100 km at the optimal argument of latitude.
The ground operator identifies the target from the acquired image and starts AON. With AON, the accuracy of relative navigation will improve as the ADR spacecraft approaches the target. As shown in Fig. 2, the ADR spacecraft approaches the target with a dual-coelliptic orbit and is thrown into a point about 1 km in the along-track direction of the target.

There are two candidates for the relative orbit approaching along the along-track direction of the target from the 1-km point: “spiral orbit” and “V-bar hopping” [14]. As shown in Fig. 3, the passive abort trajectories of these relative orbits are both safe. In addition, the spiral orbit is more robust than the V-bar hopping against collisions. To some extent, the ADR spacecraft will not collide with the target even if maneuvers exceeding the planned values are implemented. On the other hand, the V-bar hopping is a relative orbit closer to a straight line, making it easy to design the attitude of the ADR spacecraft and the field of view of the relative navigation sensor.

The ADR spacecraft takes one of these relative orbits, approaches the target from the 1-km point, and temporarily stops at a point of about 30 m.

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**Fig. 2. Dual-coelliptic rendezvous with angles-only navigation**

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**Fig. 3. Safe approach trajectory (blue line: nominal trajectory, green line: passive abort trajectory, X: along-track direction, Y: opposite direction to normal orbit, Z: geocentric direction), a) spiral approach (bird’s eye view), b) spiral approach (Y-Z plane), c) v-bar hopping approach [14]**
Phase 6 (“Inspection and motion estimation”)

At this 30-m point, the ADR spacecraft takes time and shoots many images of the target. The ground operator analyzes the images and then confirms the attitude motion of the target, as well as the state of surface deterioration and damage.

Phase 7 (“Contactless detumbling”)

When the angular velocity of the target is fast, it is difficult for the ADR spacecraft to make a relative motion synchronized with the target’s rotation, and to capture it. In order to solve this problem, as shown in Fig. 4, the angular velocity of the target is reduced to an acceptable level by appropriately applying the plume of the RCS thruster on the target surface [18].

![Fig. 4. Contactless detumbling by plume impingement. a) conceptual illustration, b) detumbling simulation results: target angular velocity reduced from 3 deg/s to less than 0.1 deg/s [18]](image)

Phase 8 (“Fly-around”) and Phase 9 (“PAF navigation and straight approach”)

After confirming that the target angular velocity is within an acceptable range, the ADR spacecraft begins the critical operation. First, as shown in Fig. 5, the ADR spacecraft performs a fly-around centering on the target and goes around to the PAF side of the upper stage. Then relative image navigation to recognize the PAF is started, and the ADR spacecraft approaches straight to the PAF. The ADR spacecraft then performs six-degrees-of-freedom control in order to keep its relative position and relative attitude to the PAF at a very close distance where the PAF can be captured.

![Fig. 5. Fly-around and PAF navigation/straight approach. a) simulated trajectory, b) simulated computer graphics images of onboard navigation camera at each distance from the target during straight approach](image)
Phase 10 ("Capture"):
In order to prevent control system instability due to contact, active control of the ADR spacecraft is cut off before the capture is performed. Then as shown in Fig. 6, the PAF dedicated capture mechanism [19] is activated to capture the target.

![Fig. 6. Concept of the capture sequence and mechanism, a) capture sequence, b) breadboard model [19]](image)

Phase 11 ("Rate damping") and Phase 12 ("LVLH attitude acquisition")
When the capture mechanism is fully extended, the control system of the ADR spacecraft is reactivated and the attitude rate is damped by RCS. After the rate damping is completed, the maneuver to Local-Vertical Local-Horizontal (LVLH) attitude is also performed by RCS.

Phase 13 ("EP descent")
The ADR spacecraft united with the upper stage turns on the Hall effect thruster (HET) and begins its orbital descent [20]. In order to alleviate the total impulse demand for the HET, the final orbital altitude of the electric propulsion descent is set to about 400 km, where the atmospheric density begins to rapidly increase. As shown in Fig. 7, it descends from 600 km to 400 km in about 200 days. At this time, angular momentum management can be performed by gimbaling the thrust vector of the electric propulsion system.

![Fig. 7. Illustration of the combination descent concept [20]](image)
Phase 14 ("Air-drag descent")

From an altitude of about 400 km, the ADR spacecraft turns off electric propulsion and descends using atmospheric drag. As shown in Fig. 8 a), the reference attitude is the TEA at which the gravity gradient torque and the mean atmospheric drag torque are balanced [21]. As shown in Fig. 8 b), by taking the TEA angle, it is possible to secure a large aerodynamic cross-sectional area so that the orbital altitude can be lowered in a short time while keeping the disturbance torque small.

![Fig. 8. Air-drag descent using TEA concept, a) orbital height and TEA angle, b) air-drag descent profile comparison between LVLH, LV and proposed TEA [21]](image)

Phase 15 ("Phasing and plane maintenance") and Phase 16 ("Impulsive dV for controlled reentry")

Using the "minimum delta-V reentry" method, controlled reentry to Earth's surface is performed with a small amount of propellant and small thrust [22]. The orbital plane and orbital phase adjustment starts about six months before the expected reentry date in preparation for reentry. The future atmospheric density is predicted, and the orbital altitude is finely adjusted so that the ground-track includes the landing target point on the expected reentry date. Then the final correction maneuver is performed several orbital revolutions before the predicted reentry time, and the trajectory difference generated due to the atmospheric density prediction error is corrected. Finally, the ADR spacecraft and the upper stage reenter the atmosphere near the target point on Earth.

5 CONCLUSIONS

There are a number of technical challenges related to GNC in the ADR mission targeting heavy and intact space debris, which will contribute to suppressing future increases in the space debris population. Based on the basic policy of aiming for a low-cost realistic ADR spacecraft, new ideas were devised about GNC strategies to solve these technical challenges. In addition, a sequential GNC scenario of the ADR mission that embodies those GNC strategies was presented. The GNC strategies and GNC scenario presented in this paper are both characterized by a combination of reliable and practical technologies. This proposal allows a relatively small ADR spacecraft to remove uncooperative and heavy large debris from their initial orbits.

6 REFERENCES

4. Dolado-Perez et al., “Sensitivity analysis of the long-term evolution of the space debris population in LEO,”