A STUDY ON ACTIVE REMOVAL SYSTEM OF SPACE DEBRIS

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ABSTRACT

Since the number of satellites in Earth orbit is steadily increasing, space debris will eventually pose a serious problem to near-Earth space activities if left unchecked, and so effective measures to mitigate it are becoming urgent. Equipping new satellites with an end-of-life de-orbit or orbital lifetime reduction capability could be an effective means of reducing the amount of debris by reducing the probability of collisions between objects. On the other hand, the active removal of space debris and the retrieval of failed satellites by spacecraft are other possible measures.

The Japan Aerospace Exploration Agency's (JAXA) Aerospace Research Directorate is studying a micro-satellite system for active space debris removal, and is examining the applicability of a GPS receiver and star tracker to orbital navigation and guidance.

This paper discusses the proposed space debris removal satellite system.

1. INTRODUCTION

Since the number of satellites in Earth orbit is steadily increasing, space debris, if left unchecked, will eventually pose a serious hazard to near-Earth space activities, and so effective measures to mitigate it are becoming urgent. Equipping new satellites with an end-of-life de-orbit and orbital lifetime reduction capability could be an effective future means of reducing the amount of debris by reducing the probability of collisions between objects, while using spacecraft to actively remove debris objects and to retrieve failed satellites are possible measures to address existing space debris.

The Japan Aerospace Exploration Agency's (JAXA) Aerospace Research Directorate is studying an active space debris removal system. Conceptually, this consists of a small spacecraft (a micro-satellite capable of piggyback launch with other payloads) that transfers large debris objects that occupy useful orbits to a disposal orbit. EDT (Electro-Dynamic Tether) technology is being investigated as a high efficiency orbital transfer system for this concept. An EDT package could be used to lower the orbit of the debris removal system without the need for propellant.

Capture is necessary for the retrieval of large space debris. It is common for large debris objects to tumble, since angular momentum may have remained in their attitude control systems when failure occurred. On-orbit satellite capture experiments have been carried out successfully by the ETS-VII satellite in 1999[(2)-(3)]. In these experiments, the target was equipped with visual markers and handles to facilitate grasping by a robot arm. While future satellites could be equipped with such features to assist active removal, in general space debris objects do not possess such conveniences — they are non-cooperative targets. In such cases, since conditions are not favorable, tracking errors will lead to loading of the robot arm when an object is captured. Active compliance of each joint of the arm and a flexible boom are therefore proposed to relieve loads at the time of capture.

This paper first describes the details of JAXA's proposed active space debris capture/removal micro satellite system, and presents the results of feasibility studies.

2. ACTIVE REMOVAL SYSTEM

The removal from orbit of rocket upper stages and satellites that have reached the end of their lives has been carried out only in a very small number of cases, and

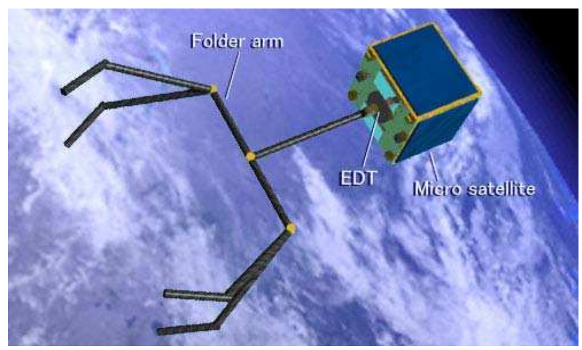

Figure.1 Space debris micro remover satellite

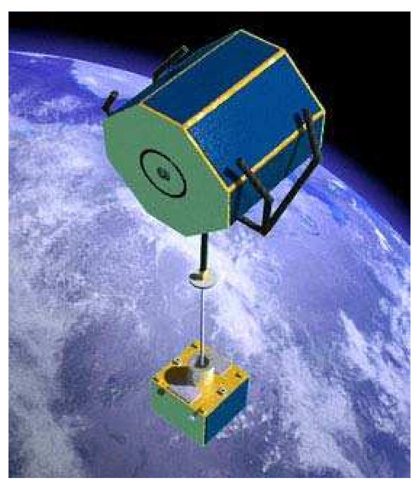
Figure 2 LEO debris removal concept

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most remain on-orbit. Explosions of residual propellants and collisions between satellite remnants or rocket upper stages can generate large quantities of smaller debris, which greatly increases the probability of further debris collisions by a cascade effect. Due to such cascade collisions, it is estimated that the amount of space debris will increase at an ever-greater rate from now on and will eventually jeopardize near-Earth space activities. The following countermeasures are therefore being considered for reducing the amount of space debris.

a. Designing space systems so that they do not become space debris; that is, positive end-of-life processing of satellites and the establishment of proper disposal procedures for rocket upper stages.
b. Processing existing debris that has no self-removal capability; that is, removing large-size satellite remnants from economically and scientifically useful orbits to disposal orbits.

For the disposal of rocket upper stages, a promising approach is for the stage to decelerate by re-starting its engine using fuel remaining after the payload has separated. Research and development of systems to remove large-sized satellite remnants from useful orbits is also in progress.

2.1. Method for Removing Satellite Remnants

Earth-orbiting satellites typically occupy either low Earth orbits (LEO) or geostationary orbits. Satellite remnants and rocket upper stages in LEO may be removed within 25 years by lowering their altitude to 650km or less, from where they will eventually re-enter the atmosphere and burn up.

2.2. Target for Retrieval / Removal

In LEO, the influence of the Earth’s geomagnetic field is strong, and so use of an electro-dynamic tether to generate thrust to lower the orbit is practicable. Low Earth orbits effective for Earth observation (especially sun-synchronous orbits) have the greatest risk of debris collision, and so measures to reduce the number satellite remnants or rocket upper stages in such orbits are a priority. In consideration of this, JAXA is studying a system with the emphasis on the retrieval and removal of satellite remnants from sun-synchronous low Earth orbits.

2.3 Strategy

A large number of satellite remnants remain near such orbits from past launches, and it is considered possible for a debris removal satellite to be able to retrieve and remove debris objects by transferring them to lower orbits. A removal micro-vehicle will remove an object by capturing it using a robot arm then de-orbiting, taking the debris with it. The concept is shown in Figures 1–3.

The following concepts for a retrieval/removal system were studied, concentrating on methods that can be realized in the near term.

a. Piggyback launch of debris removal micro-vehicles alongside new Earth observation satellites into sun-synchronous orbits useful for Earth observation.
b. Use of EDT to generate thrust for lowering orbit.
c. A capture mechanism as the other end of the tether.
d. The vehicle body itself as the tip mass of the tether.

Regarding the selection of EDT as the actuator to effect the orbital change for debris removal from LEO, the results of a trade-off study are shown in Table 1.

Table 1 Trade-off study of actuator for debris removal

Method	Merits	Demerits	Cand i-date
Chemical Thruster	Use of BUS components	*Low ISP *Attitude control required	
Ion thruster	High ISP	*High elec. power consumption *Attitude control required	
Solid motor	Compact	*Low durability due to propellant ageing *Spin-up needed *Generates Al particles	
Electro dynamic tether	It works in spite of S/C function loss	Principle is un-proved on orbit	X
Air bag	Simple constitution	*Huge size *Low durability	

2.4. Debris Removal System Concept and Missions Scenario

The mission profile of the conceptual LEO debris removal system, named SDMR (Space Debris Micro Remover), is described below (see Figure 2).

a. Rendezvous with a debris object (target) and measure its motion.
b. Fly around the target, and make a final approach to capture it.
c. Capture the target using an extensible folder arm.
d. Extend an EDT fixed at the base of the arm.
e. Autonomously control tether inclination to regulate thrust and avoid tether instability.

2.5. Remover Vehicle Composition

The SDMR vehicle has the following features:

a. Compact shape and low mass to allow a piggyback launch with an Earth observation satellite using the surplus payload capability of the launch vehicle.

b. Simple rendezvous navigation system consisting of a GPS receiver, a star tracker and vision sensors.
c. Small thrusters for maneuvering between orbits.
d. Extensible light robot arm for debris capture.
e. Debris removal by an EDT package incorporated into the base of the robot arm.

The key specifications of the vehicle are summarized in Table 2.

Table 2 Specifications of the SDMR

Item	Specification	Remarks
Dimensions	700×700×600mm	
Weight	140kg	Fuel: 25kg
Power	100W	Average
Attitude control	3-axis control	3 wheels
Thrusters	1N×8	
Rendezvous Sensors	GPS receiver Star tracker Stereo vision	

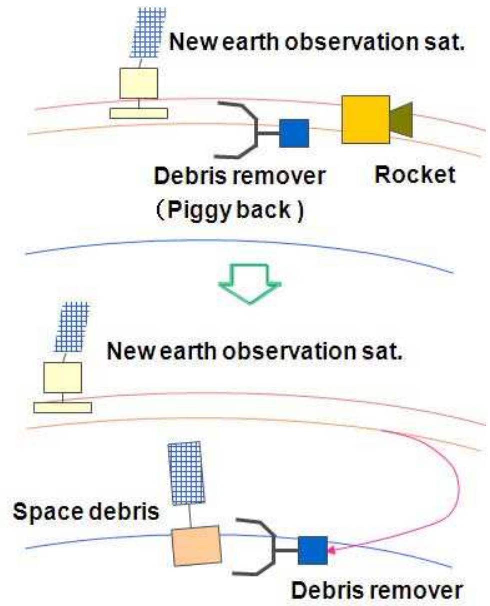

Figure 3 Concept of the Debris Remover

3. KEY TECHNOLOGIES FOR SDMR

The conceptual debris removal system requires the following key technologies.

a. An efficient orbital transfer technology:
   Electro-dynamic Tether
b. Navigation to and around the debris object:
   Machine vision/image processing
c. Robotic capture:
   Extensible light arm to capture the debris object

The development status of these technologies is described in the following sections.

3.1 Electro-Dynamic Tether

The system configuration for debris removal using an EDT package is shown in Figure 3. The performance goals of the EDT are shown in Table 3. Prototyping and testing of each hardware EDT element is progressing, aiming at an on-orbit demonstration in a few years' time.

Table 3 EDT Performance goals

Item	Performance	Remarks
Length	2km	
Max. current	1A	
Life	1 year	Residual probability >0.95

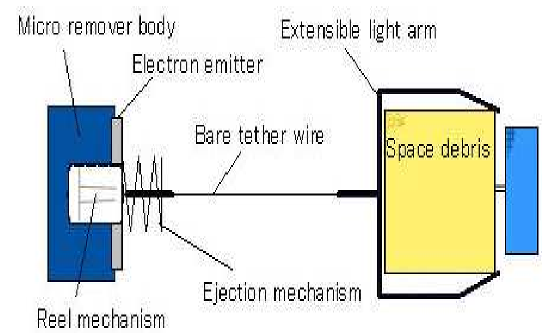

Figure 4 Configuration for debris removal using an EDT

3.2 Target approach and rendezvous method

The wreckage of an artificial satellite inserted into SSO will be typically be traveling on an orbit of which the inclination and ascending node will have shifted from the original. The orbits of satellite remnants are observed and published by NORAD TLE etc.

The rendezvous sequence with a space debris object on a sun-synchronous low Earth orbit is shown in Figure 5. A debris object to be removed is selected and the SDMR vehicle (remover) moves to the target object's published orbit using maneuvering thrusters, navigating using a GPS receiver. Since orbits change over time and the published data are only updated at intervals, the target object may not be in precisely the expected orbit. After moving to the published orbit, the relative position between the remover and the target can be measured by ground observation, and the orbital difference determined.

Images of the target can be acquired by a star tracker on the remover. The difference between the orbits of the remover and the target and their relative position can be calculated from the position of the remover obtained

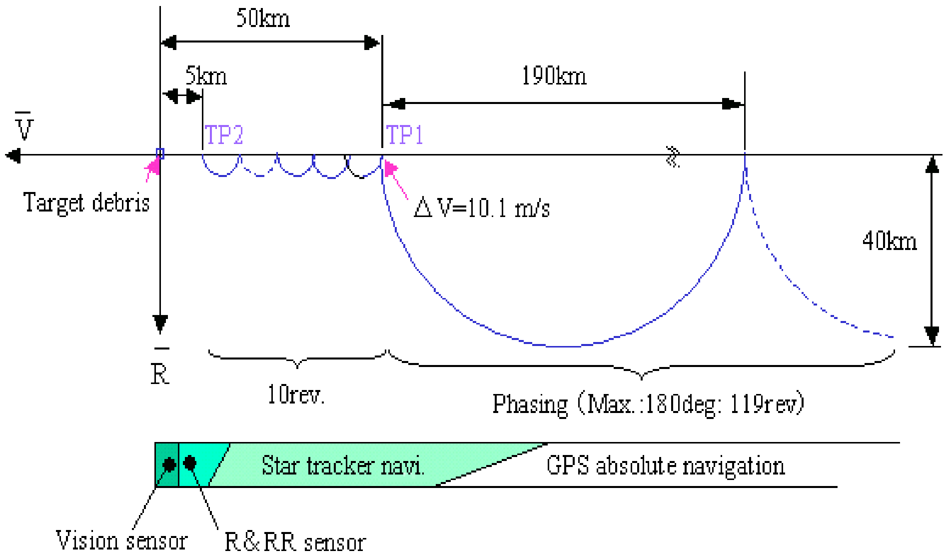

Figure 5 Rendezvous sequence with a space debris object

from its GPS receiver, and the history of the target direction viewed from the remover. The remover is then maneuvered to gradually approach the target based on this information. Once the remover has approached to within a few kilometers of the target, relative position can be measured by microwave radar or a vision sensor. The sensors used depending on relative distance are shown in Fig. 3. By this method, the remover is able to rendezvous with non-cooperative objects using comparatively small, low-cost apparatus, namely a GPS receiver, star tracker, and vision sensor.

Once the remover is in the vicinity of the target object, the target's motion is estimated from stereo images acquired by on-board cameras. The remover then maneuvers to match the target's rotational motion and captures it by a robot arm.

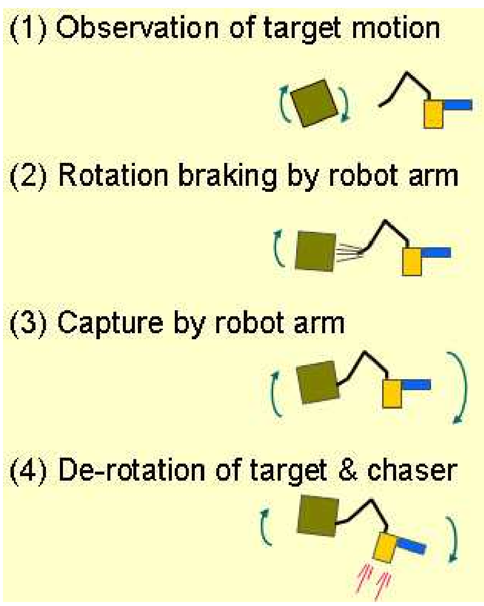

Figure 6 A typical target capture scenario

3.3 Space Debris Capture by Robot Arm

We now describe the development of a robot arm that uses a new force/torque control method for capturing tumbling non-cooperative targets. A typical target capture scenario is shown in Figure 6.

Failed satellites do not have functioning attitude control, and in many cases will be rotating due to the transfer of residual angular momentum from their control systems. Since fly-around by a debris removal vehicle or grappling the object by a robot arm will be difficult or impossible if the target debris object is rotating at high speed, it will be necessary to reduce the target's rotation to a rate at which capture can be accomplished by a robot arm using visual feedback control. A prototype of a "brush-contactor", a robot arm end-effecter that slows the target's rotation by tapping its surface, is shown in Figure 7.

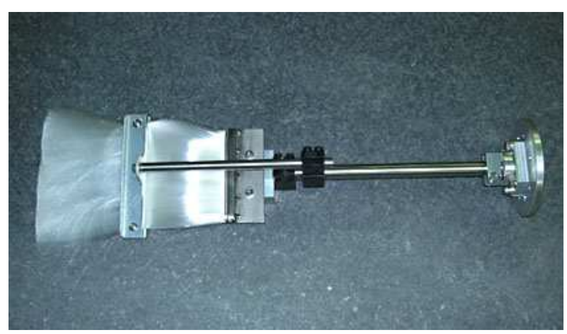

Figure 7 Prototype of brush-contactor

Complicating the capture problem, most space debris objects will be non-cooperative targets without handles or visual markers to assist capture, and their mass characteristics might not be known correctly beforehand. Moreover, there will errors in the measurement of relative motion and in the rendezvous control. To achieve successful capture by a robot arm in such situations, the arm must be designed to buffer and brake residual motions which cannot be known beforehand. The remover is therefore equipped with an extensible flexible robot arm which buffers residual motion by its structural flexibility and active joint compliance control.

4. CONCLUSION

The JAXA Aerospace Research Directorate is studying an active space debris removal system using micro-satellites, and is investigating the applicability of EDT technology as its high efficiency orbital transfer system. Prototyping and testing of each hardware EDT element is progressing. Dynamical simulation of target capture and braking are performed out about various cases.

As the result of these activities, a new active space debris removal system is becoming more feasible. Hereafter, technical development will be furthered by on-orbit demonstration using small satellites or a rocket upper stage.

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