A SCENARIO AND TECHNOLOGIES FOR SPACE DEBRIS REMOVAL

Shin-Ichiro Nishida
Graduate School of Engineering
Tottori University
E-mail: nishida@mech.tottori-u.ac.jp

Naohiko Kikuchi
Graduate School of Information System
University of Electro-Communication

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 the 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. We are studying a micro-satellite system for active space debris removal, and is examining the applicability of electro-dynamic tether (EDT) technology as its high efficiency orbital transfer system. A small EDT package provides a possible means for lowering the orbits of objects without the need for propellant. Capture is indispensable for the retrieval of large space debris objects, and we propose a light weight robot arm with a simple flexible end-effecter for this purpose. This paper discusses a space debris removal satellite system, and describes the functional allocation of sensing and robot arm for capturing non-cooperative targets.

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.

We are studying an active space debris removal system. Conceptually, this consists of a small spacecraft (a micro-satellite capable of piggyback launch) that transfers large debris objects that occupy useful orbits to a lower orbit. EDT (Electro-Dynamic Tether) technology is being investigated as a high efficiency orbital transfer system for this application. A small EDT package is being developed that consists of a bare conductive tether, which collects electrons from the ambient plasma, and FEAC (field emitter array cathodes), which emit electrons. This package could be used to lower the orbit of the debris removal system without the need for propellant.

Capture is an indispensable task for the retrieval of large space debris. 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. In general space debris objects do not possess convenient features like target markers — they are non-cooperative targets. In this case, since the conditions are not favorable, tracking errors will lead to loading of the robot arm when the object is captured. Active compliance of each joint and a flexible boom are therefore proposed to relieve load at the time of capture. This paper first describes the details of a proposed active space debris

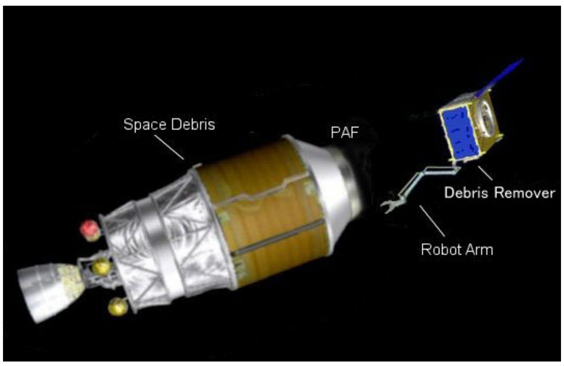

Fig.1 Concept of space debris capture

capture/removal micro satellite system, and presents the results of feasibility studies. Finally, we introduce basic technologies for capturing a large debris object.

2. Mission Scenario for Active Debris Removal

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 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 collisions by a cascade effect. Due to such cascade collisions, it is estimated that the amount of space debris will increase an ever-greater rate from now on, and will eventually jeopardize near-Earth space activities. The following countermeasures are therefore being considered as 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, the removal of 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 or rocket upper stages from useful orbits is also in progress.

2.1 Method for Removal of 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 by lowering their altitude to 650km or less, from where they will eventually re-enter the atmosphere and burn up. Geostationary orbit altitude is too great to allow this, so in this case, the effective disposal method is further to raise the orbital altitude of satellite remnants by 300km or more, to disposal orbits that are of no practical use.

2.2 Target Debris for Removal

In LEO, the influence of the earth's geomagnetic field is strong, and so use of an electro-dynamic tether is practical.[(4)-(5)] Considering the probability of debris collision, low earth orbits effective for earth observation (especially sun-synchronous orbits) have the greatest risk, and so measures to reduce the number satellite remnants or rocket upper stages in such orbits are a priority. In consideration of this, we are studying a system with the emphasis on the retrieval and removal of rocket upper stages from sun-synchronous low earth orbits.

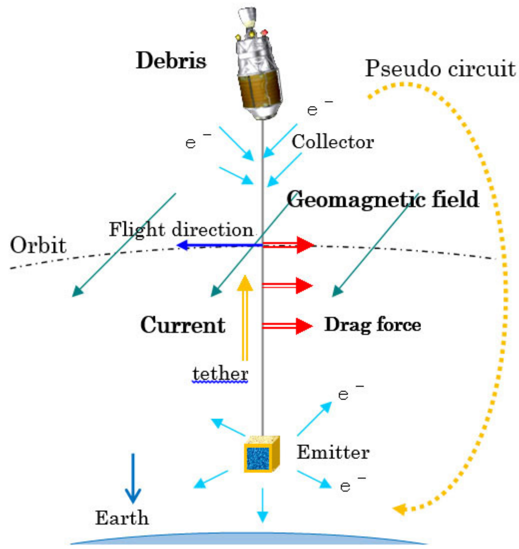

Fig.2 Principle of electro-dynamic tether

2.3 Strategy

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

a. Use of a conductive disposable type tether. (Principle: Fig. 2.)
b. The remover vehicle itself as the tip mass of the tether
c. A capture mechanism as the other side of the tether.
d. Piggyback launch of debris removal micro-vehicles with new earth observation satellites into sun-synchronous orbits useful for earth observation.

A large number of satellite remnants and rocket upper stage 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. The removal micro-vehicle will remove a debris object by capturing it using a robot arm then de-orbiting, taking the debris with it.

2.4 Debris Removal System Concept and Missions Scenario

The mission profile of the low-earth-orbit debris removal system named SDMR (Space Debris Micro Remover) is described below.

a. Rendezvous with the 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 a capture mechanism
d. Extend an electro-dynamic tether fixed at the root of the folder arm.
e. Autonomous control of tether inclination.

It is premised on the following scenarios as promotion system attachment work to the space debris.

(1)To measure a posture and movement of target from the point back about 30m on the orbit of the target space debris where relative station keeping is carried out (Reason: Since the influence of measurement on safety and an orbital error can be easily reduced compared with the case where target posture and movement are measured, by CW solution ellipse circumference by the Hill system)

(2)To do fly-around to the front of the EDT attachment part of the target

(3)To perform an approach flight to the target attachment part, and relative station keeping is carried out in the good attainment range of the capture arm mechanism to the attachment part

(4)To capture the target and to attach an EDT to it according to a capture arm mechanism

(5)To perform a secession flight from the target and the electro-dynamic tether wire is extended simultaneously (from a passive reel)

In addition, when making the H-II launch vehicle upper stage into the target space debris, an object is in the state which stood mostly to the earth, and it is thought that there are many states where head for the first time in movement is slightly carried out near the perpendicular attitude.

(Reason: Since the H-II launch vehicle upper row has the large aspect ratio of inertia, converge on a perpendicular posture mostly to the earth by gravity-gradient torque according to the time progress from a launch)

Moreover, EDT attachment has the desirable lower part to the rocket upper stage in the state where it stood to the earth. Two kinds when the rocket nozzle has turned to the case where PAF has turned to the rocket upper stage below, and the contrary, below are assumed. For this reason, as for the relative position posture measurement system for the target capture mechanism and capture, it is desirable that it can deal with both PAF and a rocket nozzle.

3. Key Technologies

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:
   Simple light weight arm to capture the debris object

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

3.1 Tether Reel Mechanism

A system for applying a constant braking force was investigated. The required level of braking force is small and control of extension rate by changing the friction of the tether wire is very difficult, with the result that a shock force may still occur at the end of extension. An experimental system using passive rotation braking equipment in a two-part reel was therefore developed which applies a braking force only at the end phase of wire extension. By using a passive non-contact braking element, stable braking performance was achieved. The non-contact braking reel is realized by using an eddy current brake wheel. With this mechanism, the braking torque is proportional to the rotation rate. Since the tether is slowed down sufficiently when it reaches the end of its extension, hardly any jerking force is produced.

3.2 Navigation and Guidance for Non-cooperative Target

Debris removal is targetting the space debris with an altitude of 700-800km. For this reason, a GPS receiver is used for approach guidance for an object as main sensors. Moreover, a target debris is a non-cooperative object which outputs neither a beacon radio wave nor position information, and does not have a reflective marker etc. For this reason, to approach guidance for the target debris, the relative position measurement by a micro wave radar or an optical sensor is indispensable. It is thought from a viewpoint of necessary resources, such as mass and power consumption, that optical sensors, such as star tracker, are promising. Therefore, it is based on using a GPS receiver and star tracker for navigation and guidance.

3.3 Attitude and Motion Measurement of Space Debris

3.3.1 Measurement system

The following sensing system are held as candidates of hardware who performs the attitude and motion measurement of the target debris.

a. Single vision camera

b. Stereo vision camera (two to 9 eye)
c. Laser range finder (scanned type)
d. Laser range finder (one shot type)

A trade study of all directions type is shown in Table 1. Since it is simple composition, it is considered to be good to be based on measurement with a single vision camera. In addition, it is thought that it is a promising choice to carry two or more cameras as a flight demonstration to serve also as direct distance measurement, and to also add a stereo measurement function. In addition, although picture measurement with a camera on the low earth orbit if as for about 1/the time of 3 goes into the shade and remains as it is cannot be performed, vision sensing is possible if stroboscope light is applied.

3.3.2 Measurement accuracy

The following error factors influence the attitude of the space debris, and the accuracy of movement measurement.

(1) Change of Relative Position with Object
(2) Alignment Error of Camera
(3) Lens Focal Length Error of Camera, Aberration, Distortion, Dotage
(4) Stray Light and Flare Light of Camera
(5)Image Pick-up Noises (Dark Current Noise etc.)
(6) Resolution of Pixel

About (2) and (3), it can rectify to some extent by the calibration the ground before a launch, and on an orbit among these. As for template matching, the amount of operations needs many amounts of operations. For this reason, the application of a system which reduces the degree of picture information and performs reduction of the amount of operations or the amount of necessary memories by the eigenspace method is effective and realistic[11]. An example of various posture images of rocket upper stage before projection to eigen space is shown in Fig.3. Moreover, a gap of matching resulting from fine ups and downs and the specular-reflection component of the space debris system causes an error.

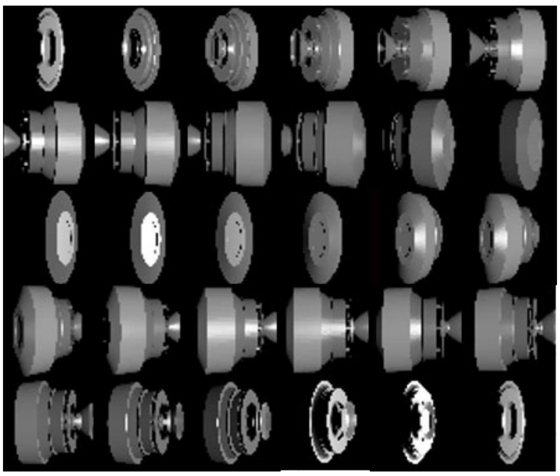

Fig.3 An example of various posture images of rocket upper stage before projection to eigenspace

For this reason, even if it removes the error of above-mentioned (1) - (4), in attitude measurement with one shot image, generating of the error (3 axis composition) of about 5 degs is assumed.

By performing continuously this attitude and motion measurement, and performing extended Kalman filter processing, motion and a attitude are presumed satisfactorily and an attitude estimated error can also be reduced low a single figure.

The position measurement based on center of mass is influenced of attitude measurement, and since it is thought that an equivalent error occurs, it is considered to be the accuracy of about 0.05m (3 axis composition) from "11/2*sin0.5° ≒0.05" to the rocket upper stage with a full length of about 11m.

3.4 Capture of Space Debris

Complicating the capture problem, most space debris objects will be non-cooperative targets without handles for grasping and visual markers to assist capture, and the mass characteristics might not be known correctly beforehand. Moreover, there will be error in the measurement of relative movement and in the rendezvous control.

3.4.1 System composition

As a mechanism in which the target debris is captured, the following mechanisms are listed as candidates.

a. Precision robot arm
b. Simple robot arm
c. Extensible capture mechanism
d. Net
e. Pile

It is considered that the simple robot arm system which has the advantage that it can capture steadily with simple composition is promising.

3.4.2 Composition of a mechanism

The conceptual figure of a simple robot arm is shown in Fig. 4. As stated previously, two cases of the attitude which turned the rocket nozzle below as a attitude of the rocket upper stage which is a debris for removal, and the posture which turned PAF below are assumed. As for attachment of an EDT, it is desirable to attach in the target nadir side (lower end). For this reason, the capture by the simple robot arm needs to correspond to both a rocket nozzle corn and a PAF. These parts are shown in Fig. 5.

3.4.3 Guidance and measurement in capture work

Because of capture, it is made to approach for a work machine and a position, and the guidance and control which carry out attitude control are required. Moreover, course control of the robot arm of capture work and grasping control are required. Following methods are listed as candidates of the method of the position and attitude measurement for capture.

a. Scanning laser sensor
b. One shot laser sensor

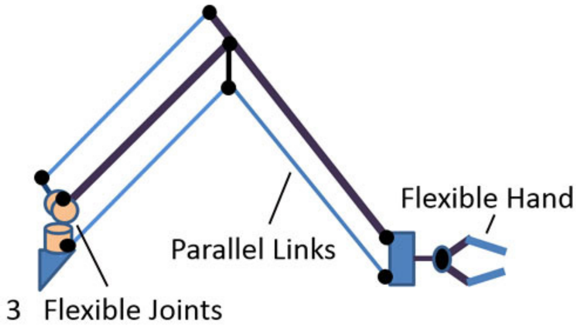

Fig.4 Concept of capture robot arm

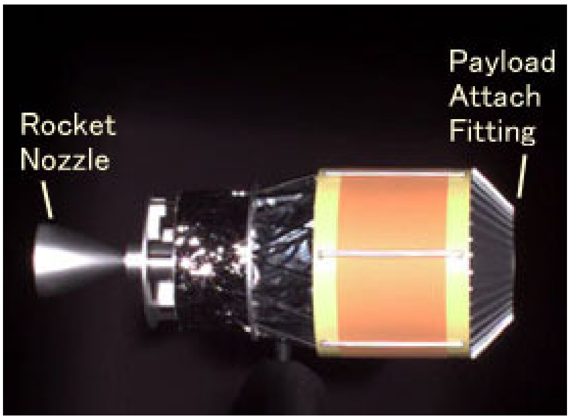

Fig.5 Grasping part of rocket upper stage

c. Vision sensor

It is thought from the simplicity of the composition of component, and the little of the amount of necessary calculation operation among these that image processing of using c is promising.

System which raised the reliability of measurement combining of monocular image processing and stereo vision processing is effective for fine measurement(12).

3.4.4 Capture motion control

It is required for not both the robot satellites for capture to necessarily stand it still completely, to absorb the action after the position gap by operation or the grasping, since it is thought that it is exercising, and to suppress generating of excessive power. Moreover, since the level difference which serves as a key at a capture part is scarce, it becomes a rocket nozzle corn with the grasping depending on surface friction of a hand. For this reason, it is necessary to carry out the grasping of the large area flexibly with the form which got used. From these reasons, a hand mechanism with softness and force control of a robot arm with high response is indispensable.

To achieve successful capture using a robot arm in such situations, the robot arm must be designed to buffer and brake residual motions which cannot be anticipated beforehand. The SDMR is equipped with a flexible robot arm. Its structural flexibility of joints and joint compliance control buffer the residual motion.

3.5 Extension Method of Electro-Dynamic Tether

After capturing the target debris for removal, it is necessary to extend the EDT which bundled the thin metal line. An EDT is which generates braking power by going around with the form which has arranged the mass to both ends with the posture which stood perpendicularly to the nadir direction. In the case of the small robotic satellite from which one space debris is removed by one set, it is appropriate to use the robotic satellite itself as an end mass of a lower end of EDT. For this reason, the work which extends a tether is required, moving the robot satellite itself below after capture. This extension work has a method by the flight by the thruster of the robotic satellite, and a method by discharge by the spring mechanism. If all give initial velocity and extend to the length more than fixed, after that, expansion will progress according to gravity-gradient power.

In addition, in order to avoid generating of the shock power by having been extended at the time of completion of expansion, it is necessary to prepare a brake style and an elastic part in the terminus part of the reel of a tether.

4. Composition of Remover Vehicle

Tether attachment is accomplished simultaneously with target capture by unification of the capture mechanism and EDT package. Once an EDT package is attached, the tether is extended and the target is then released. Each vehicle carries two or more EDT packages, allowing it to remove several pieces of debris.

The removal micro-satellite has the following characteristics:

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 system consists of a GPS receiver, a star tracker and vision sensors.
c. Small thrusters for maneuvering between orbits.
d. Simple light weight robot arm for debris capture.
e. Debris removal by electro-dynamic tether package incorporated into the root of the robot arm.

The satellite is small enough to be launched in cylindrical adapter for an earth observation satellite on an H-IIA rocket. Characteristics of the satellite are shown in Table 1.

Table 1 Characteristics of the SDMR

Items	Characteristics	Remarks
Size	700×700×600mm	
Weight	150kg	Fuel: 25kg
Power	100W	Average
Attitude control	3 axes control	3 wheels
Thrusters	1N×8	
Rendezvous Sensors	GPS receiver Star tracker Stereo vision	
Capture Mechanism	Simple Arm with Soft E/E	

5. Conclusion

The Institute of Aerospace Technology, Japan Aerospace Exploration Agency, is studying an active space debris removal system using micro-satellites, and is investigating the applicability of electro-dynamic tether technology as its high efficient orbital transfer system. A small EDT package is under development that consists of a bare conductive tether, field emitter array cathodes, a lightweight ejecting mechanism and a reel mechanism with a braking function. An optical motion measurement system, extensible folder arm and control system for robotic debris capture are also under development.

As the result of these activities, the realization of a new active space debris removal system is becoming more feasible. New technologies such as image processing for attitude and motion estimation using projection to eigenspace, image processing for optical navigation using combination of monocular image and stereo images and simple arm with flexible joints and flexible hand are applied to motion measurement and capture of space debris.

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