Capturing a Space Debris by Space Robot

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ABSTRACT

In most cases, the detailed mass and inertial characteristics of a target debris will be unknown, and this makes impedance matching of the capture arm force control system difficult.

This led to us to devise “joint virtual depth control” algorithm for robot arm control which brakes the rotation of a target with unknown inertia. This paper deals with method for capturing and braking a tumbling non-cooperative target space debris.

We propose a new brush type contactor as end-effecter of a robot arm for reducing the rotation rate and tumbling motion of target debris. As a means for relieving the loads generated during target tapping, we propose a new control method which controls the arm tip force according to a contact force profile.

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[1].

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 that transfers large debris objects that occupy useful orbits to a lower orbit. EDT (Electro-Dynamic Tether) technology[2] 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[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. Therefore, before the capturing, the rotation of a target have to be reduced by tapping with the robot arm. Active compliance of each joint of the arm and a flexible boom are therefore proposed to relieve loads at the time of tapping and capture.

This paper first describes the details of JAXA’s proposed active space debris capture/removal satellite system, and presents the results of simulation and experiments.

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 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.

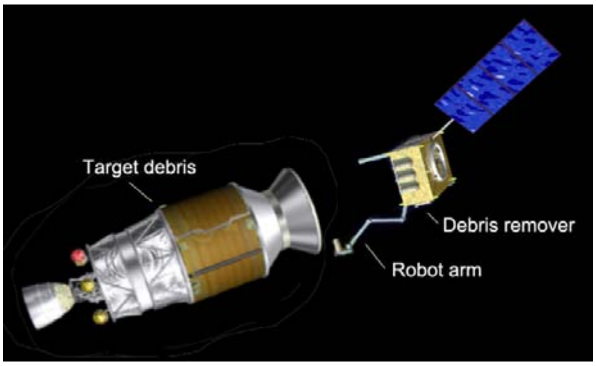

Figure.1 Space debris remover satellite

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 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.

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 vehicle 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 attaches a tether module to debris.

2.3 Mission Scenario for Debris Removal System

The mission profile of the conceptual LEO debris removal system, named MSDR (Multiple Space Debris Remover), is described below.

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 a medium sized robot arm.
d. Extend an EDT installed at the tip of the capture hand.
e. Autonomously control tether inclination to regulate thrust and avoid tether instability.

2.4 Remover Vehicle Composition

The MSDR vehicle has the following features:

a. Compact shape and low mass to allow a dual 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. Light weight robot arm for debris capture.
e. Debris removal by an EDT package attached by the robot arm.

2.5 Space Debris Capture by Robot Arm

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:
   Light arm to capture the debris object

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 2. The target rotating rate can be presumed by the observation from the ground in advance. 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 3.

Most of exhausted upper stage of launch vehicle has axial symmetric cylindrical form. Therefore, most of them are in gravity gradient stable attitude. In such case, the remover flies around the target to its on-axis location. After that the remover will do motion synchronizing rotation to the target.

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[9].

3. ARM CONTROL METHOD

3.1 Joint compliance control

A joint compliance control system enables active compliance at the arm tip using information gathered by torque sensors at each joint. During target capture,

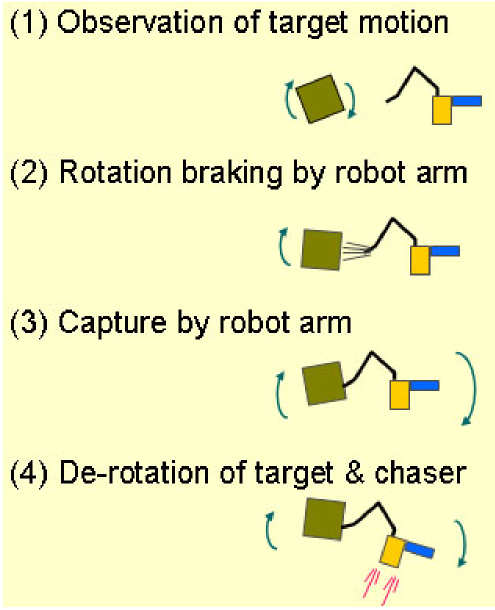

Figure 2 A typical target capture scenario

contact points on the grasper make contact with the selected grasping point on the target, and correct a position gap along with a V-guide by means of compliance control. In order to realize a virtual stiffness at the arm tip by means of impedance control at each joint, the value calculated by the following formula serves as a target for the virtual twist stiffness of a joint.

A block diagram describing joint compliance control is shown in Figure 4.

3.2 Joint Virtual Depth Control

In addition to the shock relief function enabled by high response of the joint compliance control system, we newly devised a joint virtual depth control method which transfers robot arm force positively to the target and brakes movement.

3.3 Slowdown by Brush Contact

Once the object has been grasped, braking force is applied according to a computed slowdown profile to smoothly receive momentum from the target. The

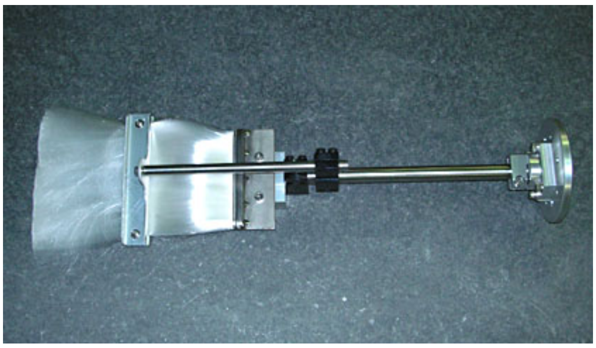

Figure 3 Prototype of brush-contactor

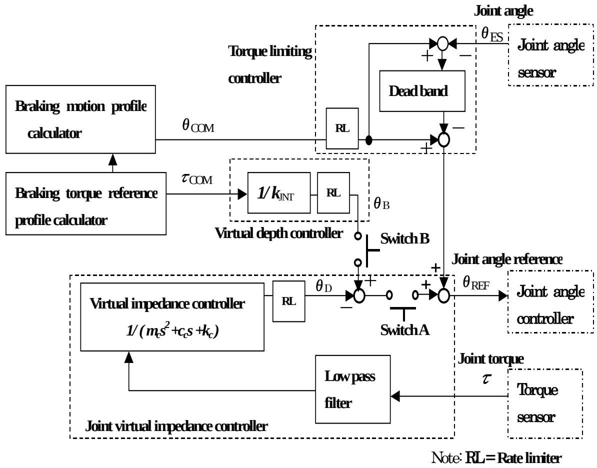

Figure 4 Block diagram of Joint virtual depth control

required braking deceleration is determined such that the target's rotation is slowed during the period in which the grasping point faces the servicer. Generally, since the target's mass characteristics and the characteristics of flexible appendages such as solar arrays are unknown, they set up a contact force profile based on the braking force which can be applied to the target and the arm at the time of tapping.

Joint virtual depth control was devised for the contact force operation.

A block diagram of the joint virtual depth control system for each joint is shown in Figure 4. By the setting of two switches, control is switched easily between joint angle control, joint compliance control, and joint virtual depth control.

4. EXPERIMENT

4.1 Experiment configuration

The composition of examination equipment and the picture of examination equipment are shown in Fig. 8. The rotation target was constituted in the cylinder form with a diameter of 0.8m, was supported with single-ball bearing and the vertical lever of a seesaw form, and floated the whole on a flat floor with three air pads. Thereby, a target is supported by 6-DOF freely and has the composition that rigid body movement can be performed in response to external force.

Movement of the rotation target is measured by vision tracker by non-contacting.

To the rotation target, a brush contactor contacts +X on a visual tracker coordinate system, and from +Y, as shown in Fig. 10. Moreover, contact force in case a brush contacts the rotation target is measured by the force /torque sensor installed on the base of the brush contact About a force/torque sensor coordinate system, as shown in Fig. 10, - Z-axis is set as the approaching direction of the brush by making the center of the force/torque sensor into the starting point.

4.2 Experiment Case

Let the forcing direction to the rotation target of the brush be the direction offset in the +X direction of the force/torque sensor coordinate system to the direction of the rotation center of the rotation target.

The force / torque measurement cycle is 20Hz and vision tracker's measurement cycle is 100Hz.

The experiment case carried out on the basis of the precondition beyond an examination case is as follows.

Let the amount of forcing of the brush be the amount of movements of linear stage until the brush stops from the position which contacted first.

Two types of experiments were conducted. One is fixed base case which the base of the rotation target is fixed to the flat floor. The other is floating case which the base of the rotation target is floated on the flat floor by three air-pads. In addition, it measured also about the braking characteristic of a rotation target in case there is no contact of a brush which free deceleration.

4.3 Results and Discussion

Though the contact force by the brush was fluctuated because of the elasticity of the brush, the contact state of the brush with the target was maintained. The rotation rate of the target debris was slowed down by braking force generation along the brush contact. The difference of the results between fixed case and floated case is small.

5. CONCLUSION

The JAXA Aerospace Research Directorate is studying an active space debris removal system, and is investigating the applicability of EDT technology as its high efficiency orbital transfer system.

As the result of these activities, a new active space debris removal system is becoming more feasible. We have conducted analyses of space debris capture and braking operation using a space robot arm where the impact load is relieved by the use of joint virtual depth control. Dynamical simulations were performed of the smooth braking effect of joint virtual depth control at the time of contact of the rotating target, even though the offset of contact point to the center of mass plane of the target is large.

REFERENCES

[1] S. Kibe, S. Kawamoto, F. Terui, S. Nishida and G. Gilardi; "R&D of the Active Removal System for Post-Mission Space Systems", IAC2003, Bremen, 2003

[2] J.R. Sanmartin, M. Martinez-Sanchez, E. Ahedo: "Bare wire anodes for electrodynamic tethers", J. of Propulsion and Power, 1993

[3] M. Oda, S. Nishida et al.: "Onboard Local Compensation on ETS-Ⅶ Space Robot Tele-operation", AIM'99, 1999

[4] S. Kitamura, Y. Okawa, et al.: "Preliminary Study on Field Emitter Array Cathodes for Electro-dynamic Tether Propulsion", Asian Joint Conf. on Propulsion and Power 2004

[5] Y. Okawa, S. Kitamura and Y. Iseki; "Preliminary Testing of Carbon-Nanotube Field Emission Cathodes for Electro-dynamic Tethers", The 9th Spacecraft Charging Technology Conference, 2005

[6] S. Nishida, S. Kawamoto, F. Okawa, F. Terui, A. Nakajima and S. Kitamura: "R&D Status of the Active Removal System for Space Debris", IAC2005, Fukuoka, 2005

[7] S. Kawamoto, T. Makida, F. Sasaki, Y. Okawa and S. Nishida; "Precise numerical simulations of electro-dynamic tethers for an active debris removal system", Acta Astronautica 59 (2006), pp.139-148

[8] F. Terui, S. Nishida; "Relative Motion Estimation and Control to a Failed Satellite by Machine Vision", Space Technology Vol.27 No.2-3, pp.90, 2007

[9] S. Nishida and T. Yoshikawa; "Capture and Motion Braking of Space Debris by a Space Robot", ICCAS2007, Seoul, 2007

[10] S. Nishida, S. Kawamoto, F. Okawa, F. Terui, and S. Kitamura: "Small Satellite for Space Debris Removal", IAC2006, Valencia, 2006