Contactless and Multiple Space Debris Removal by Micro to Nano Satellites

Junichiro Kawaguchi

***Abstract*—**Space debris problems have emerged and threatened the use of low earth orbit around the Earth owing to a large number of spacecrafts.. The robots should be sophisticated enough to access automatically the debris articulating the attitude and the translation motion with respect to the debris. This paper presents the idea of using the torpedo-like third unsophisticated and disposable body, in addition to the first body of the servicing robot and the second body of the target debris. The third body is launched from the first body from a distance further than the size of the second body. This paper presents the method and the system, so that the third body is launched from the first body. The third body carries both a net and an inflatable or extendible drag deceleration device and is built small and light. This method enables even micro to nano satellites to perform contactless and multiple debris removal even via a single flight.

***Keywords*—**Ballute, Debris Removal, Echo satellite, Gossamer, Gun-Net, Inflatable Space Structure, Small Satellite, Un-cooperated Target.

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I. Introduction

THE debris removal via atmospheric drag deceleration is well known and not new. It is represented, for instance, by the inflatable ballute device and an extendible membrane. Historically the Echo satellites were built as ballutes, inflated balloons by NASA in the old days. Also, the use of a net to capture the debris is conventional and not innovative. It is merchandised as a Gun-Net or Net-Gun (hereafter Gun-Net) on the market. Therefore, the combination of two devices is an automatic idea that can be easily come up with. Such a combination never presents the function of contactless and multiple space debris removal by a micro to nano servicing satellite. The novelty in this method lies in the use of the third body that can be unsophisticated and disposable and is launched from the servicing satellite from a distance further than the size of the target debris. The combination of two kinds of the devices is an automatic idea. However, the idea of the use of the third body that can be unsophisticated and disposable and carries both devices is not straightforward. The conventional scenario draws the use of the propulsion system to deorbit the target debris, even when it is captured as shown in Fig. 1.

Popular Mechanics posted an article published by the BBC [1] that discusses the current situation related to space debris removal. The article is titled ‘Space Junk Net Successfully Completes Capture Test.’ In its review of the current scenario and associated difficulties, the article summarizes: “Despite promising technology demonstrations, there is no one-size-fits-all solution for the growing problem of taking out the orbital trash” [1].

There is an idea concerning the atmospheric decelerator [2]. As it is well known, NASA launched two Echo satellites in the early stages of the space developments. These Echo satellites are inflated balloons. So, the use of ballute for debris removal is quite straightforward. From this point of view, it is of little surprise that the Global Aerospace Corporation [2] has acquired the intellectual property. But the essence of the idea here does not lie in the use of the Gossamer atmospheric deceleration device. The study [2] presents the use of atmospheric deceleration, such as a ballute, inflatable device. However, it fails to combine the use of a net. Besides, it does not look at the third disposable device equipped with the doubled capabilities which this paper proposes. Analytical Mechanics Associates, Inc. [3] relates to the restraint schemes. It deals only with the fastener mechanism, and has nothing to do with contactless-ness feature. It does not state anything about the use of the third body equipped with capturing and deceleration capabilities.

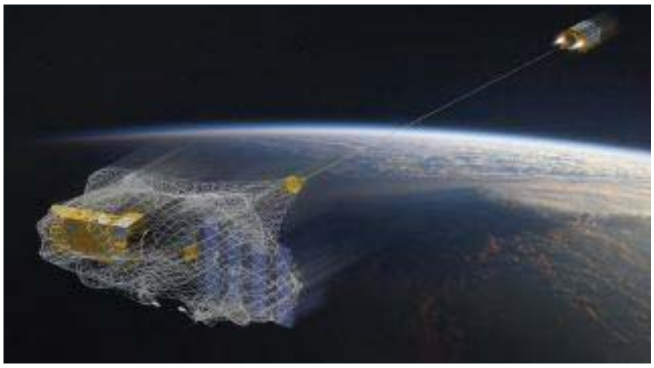

Fig. 1 ESA Debris Removal via Net Capture [10]

There also exists a lot of research and studies about capturing space debris by nets [4]. It is so obvious and is a straightforward approach. The essence of the idea here does not lie just in the use of nets. Reference [4] studied the use of a gun onboard the spacecraft. However, it does not deal with the use of nets. Reference [5] studied the use of tethered nets. But the idea here uses an untethered scheme instead of tethered scheme and realizes contactless removal. The studies [6] and [7] focused on the capture scenarios using nets. However, they failed to provide a deorbiting strategy. Reference [8] deals with a completely different removal scheme, the electromagnetic

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approach, which increases the complexity more. It is a tethered approach and inevitably accompanies direct contact. As these references indicate, it is almost automatic to combine these two devices in applications to the debris removal and it is likely the scheme is one that anyone can easily come up with. However, those existing methods still request that the servicer spacecraft must perform a difficult contact action with the target debris. And those existing methods fail to solve the problems which this paper discusses and presents the solutions to.

A. Problem to Be Solved

First of all, in most cases, the servicing spacecrafts' robots need to be highly sophisticated to access the target debris. Second, the contact reaction force inevitably applies to the robots. These request the robots to be equipped with the sophisticated, vigorous and rigorous attitude and translational articulation and management capability. And the small satellites may not exhibit such performance and do not seem suitable.

There are two kinds of decelerating schemes. One is to propel the target debris together with the robots themselves. And the other is to increase the drag deceleration or to decrease the ballistic coefficient of the target debris. In case the robots perform the propulsive removal, they have to carry a lot of propellant. As a result, the size of the robots tends to be similar to or larger than the debris to be removed. And again, the small satellites may not seem suitable. These prevent the robots from removing multiple debris during a single flight. This is the third issue to be solved. These make the removal service cost extraordinary high Previous proposals have failed to overcome these difficulties.

Existing notions represented by [2] and [4] state that the removal is performed via either of propulsion or atmospheric drag. And the notions assume the use of the sophisticated servicing spacecrafts, the robots, which are restrained with the target debris firmly or tethered. The restraint inevitably accompanies with the counter reaction force applied. Once the restraint fails, the reaction force in turn excites the target debris motion and makes the next restraint much more difficult. The access with the un-cooperated target is the subject of the research area, and may not be so realistic in real applications except the most simplified configuration or at the laboratories. These difficulties derive from the contact with the target. The contactless removal has been expected.

In addition to the sophisticated system, when it comes to the propulsive removal, the propellant amount increases high and the robots may have to be big, sometimes much bigger than the that of the target debris. Debris removal by small satellites have not been practically designed for a hundred-kg class debris. And multiple debris removal capability using small satellites has been expected by now.

Current solutions fail to exhibit smallness, contactless-ness and multiple removal capabilities. This paper presents the debris removal that can exhibit smallness, contactless-ness and multiple removal capabilities. By this method, even a small-satellite-based robot can perform multiple debris removal even during a single flight. Without this method, no current solution can provide this kind of service. These significantly reduce the debris removal cost. Even startups can launch the removal servicers. This idea is hardly inspired. It is not automatic. Simply, the past and current notions assume two characters. One is a servicing spacecraft, a robot. And the other is a target debris. It is implicitly assumed and comprehensive, but is hardly applicable to practical and commercial service. Those notions are lacking in the use of the disposable third character launched from the first character, a robot from a distance further than the size of the target debris.

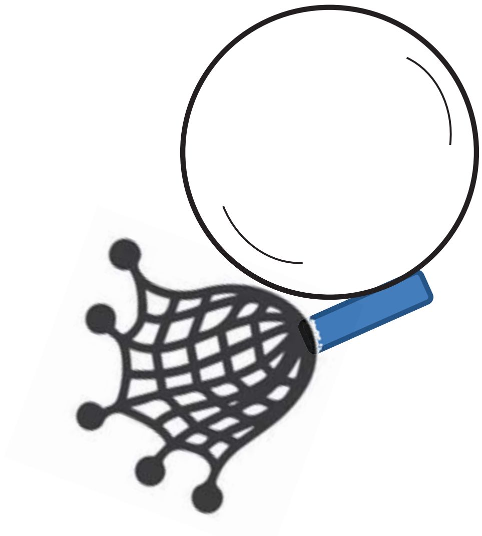

Fig. 2 Torpedo-like Third Body Carrying both Net and Ballute

By the proposed method, the world-wide debris removal business may drastically change and the existing debris removal demonstrations will be replaced. This is a plus for space developing countries. The debris removal service has now become a practical business. Small, micro to nano satellites can perform the business with modest investment. The business may obtain a lot of interest globally.

II. Technology Development

A. Outline

The proposed method aims at removing uncooperative space debris from Earth's orbit. The system consists of Gun-Net and Ballute devices on a third body, a projectile. So far, every removal business has assumed the servicer should be fastened and mated with the target debris to be decelerated together with it. This new technology enables the servicer spacecraft to be free from mechanically contacting the target debris. Moreover, it enables even micro satellites to provide debris removal services. It leads to the practical business. The flight demonstration via a 3-Unit nano satellite may happen.

B. Current Activities

The debris removal has been understood comprehensively these decades. The threat by the orbiting debris shall be swept away. The international regulation was established. The orbiting debris threatens the safe use of the low Earth orbit space. Besides, anti-satellite weapons may produce extraordinary debris and prevent the peaceful use of the region. And the debris removal became an immediate action that the space society should take. And the academic study has been intensively performed. Via micro satellites, even the university missions can demonstrate the usefulness.

Contemporary debris removal is straightforward with direct mechanical contact by the deorbiting servicer spacecraft. It somehow contacts and attaches to the target debris mechanically, and carries a significant propulsion capability to decelerate both the servicer spacecraft and the target debris quickly. The method proposed here realizes a contactless deorbiting service, which does not require the use of laser or radio. 'Mechanical but contactless' opens a door to new era of sustainability for low Earth orbit. The proposed method does not create any form of new debris at all.

C. Background of the Method

The proposed method does not assume the mechanical and contact service by a servicer spacecraft but by a projectile, a third spacecraft independent of the servicer.

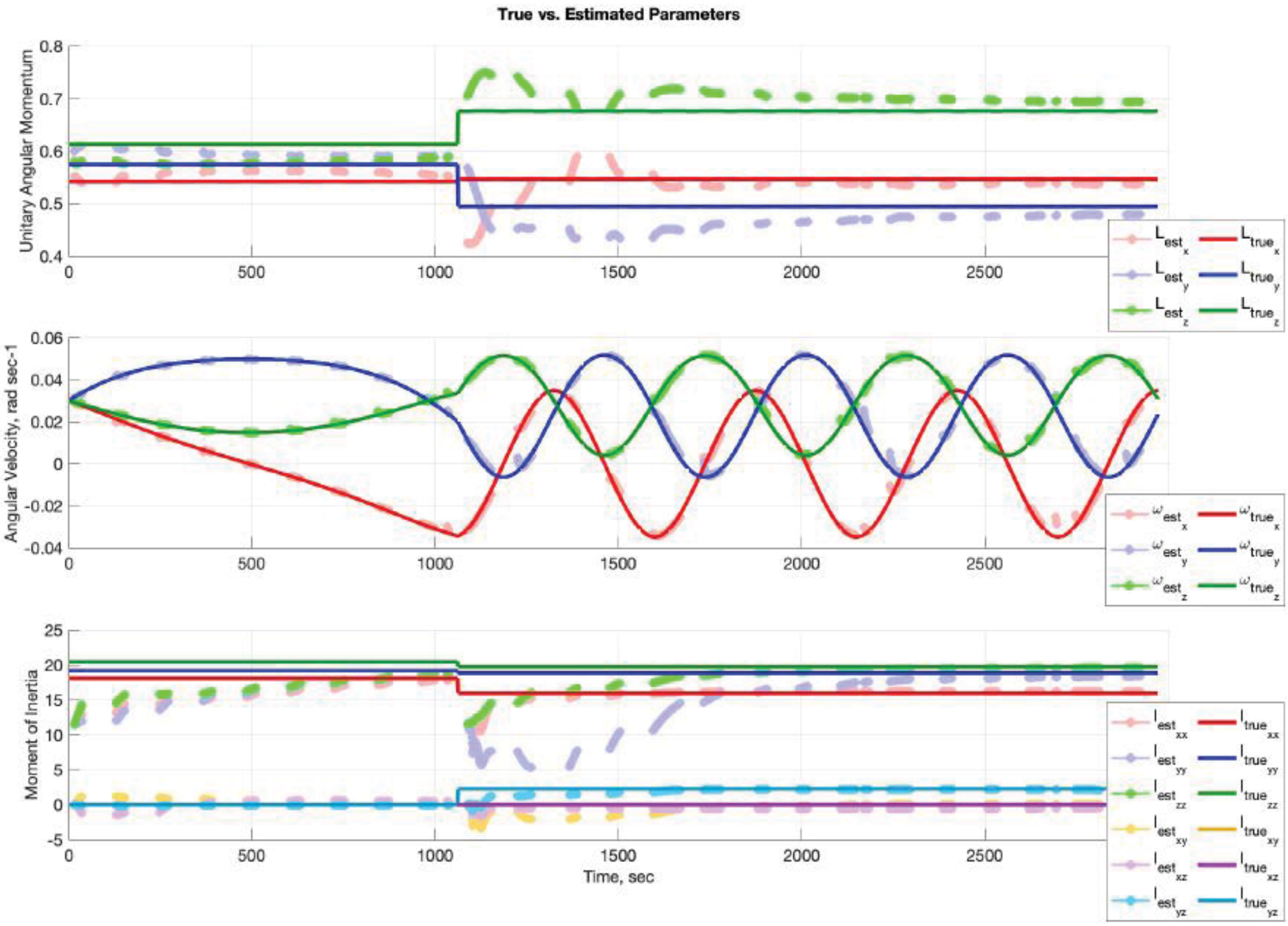

Fig. 3 Real Time Estimation of Angular Momentum and Inertia Tensor

Deorbiting the debris may take some time. Provided the deceleration is performed via a kind of 'Ballute', an inflated drag decelerator, even a micro to nano spacecraft can accomplish deorbiting of the target debris. Also, the debris removal may assume the use of Gun-Nets instead of grabbing/ docking devices, in a contact-less manner.

A ballute and a Gun-Net have been assumed to be onboard the servicer spacecraft which attaches them to the target debris. The servicer spacecraft keeps one end of the devices mated with itself. This results in direct contact by the servicer.

The proposed method launches a Gun-Net equipped with an inflatable device from the servicer. This enables the servicer to be free from direct mechanical contact.

D. Benefit: Sustainable and Peaceful Use of Low Earth Orbit

Once the method here is published, in any country, any defense organization notices that destroying reconnaissance satellites never deserves the cost. Clearly, such destructive way results in another threat. Those defense organizations will adopt the method here. And the targeted reconnaissance satellites are malfunctioned easily and safely avoiding recreation of on-orbit debris with little cost.

By employing the proposed method for active debris removal, there would be no need for a large propulsion system onboard, and the debris removal service can be provided even by micro satellites. Such micro satellites can carry multi-projectiles and can provide services to multi target debris during a single flight.

E. Related Technology: Pose & Motion Estimation

Identifying and estimating the attitude motion/dynamics properties are important for debris-removal. Especially in accessing to the debris in spin motion, due to the asymmetric property associated with the unbalanced fuel remaining and with some mechanical destruction, projecting a Gun-Net requires the information on the angular momentum vector direction. The pose estimation corresponds to the static information, while the dynamic estimation is to extract the inertia properties along with the angular velocity.

As long as the shape (not in terms of scale, but of length to width ratio, and so on) is known as to the target body, the dynamic parameters' estimation is possible. This excludes the request to the customers to prepare and carry a prescribed target device before launch.

Unexpected contact of the servicer with the target debris may shift the motion of it to a different state. The motion estimator shall be capable of functioning even in such a case and having the estimator is important. Fig. 3 shows how the estimation of the angular momentum is performed along with the estimation of the inertia properties of the target debris. In embodiment, the strategy of using the pose and motion estimation is essential. In the capturing process, to which direction the Gun-Net should be launched, is a key issue.

F. Inflatable Decelerator Based on Echo-1 & Echo-2 [9]

Echo satellites flew and survived about eight years starting from 1000 km altitude. Referring to the Echo satellites' parameters, here is given a preliminary estimate of a ballute size for deorbiting a 100 kg class satellite. The sphere diameter is concluded as 5 m (in terms of volume it is 65.5 m^3 and the cross-section area is 20 m^2). The aluminized Mylar film thickness is assumed as 5 microns and results in the sphere mass of 534 grams, occupying 0.4 liter volume. If the same liquidized gas is assumed as Echo-1, the gas mass weighs 639 g (3.57 mol).

Both the sphere and liquidized gas are contained within about a 1 liter volume. A 12U-class satellite can carry two sets of ballute devices.

In the case of conventional satellites, the natural orbital decay speed with the ballistic parameter of $\beta = 0.01$ m^2/kg under the solar flux F10.7 of 150SFU: is 15 years starting from the altitude of 600 km. And the propulsive removal consumes the fuel of about 11 kg or more for deorbiting. Also, starting from the altitude of 750 km, the decay period is 100 years, and the propulsive removal consumes about 17 kg or more for deorbiting. On the other hand, with a ballute equipped to the target debris, the natural orbital decay speed with the ballistic parameter of $\beta = 0.20$ m^2/kg under the solar flux F10.7 of 150SFU is only 0.75 years starting from the altitude of 600 km with no fuel consumption. Also, starting from the altitude of 750 km, the decay period is just 5 years also with no fuel consumption. Fuel consumption estimate here assumes 300 sec for the Specific Impulse (Isp), in the case a 100 kg servicer spacecraft provides the deorbiting service to 100 kg dry-mass target debris. In reality, the mass required for the servicer may become much heavier.

Fig. 4 Echo Satellite in 1960s

The aerodynamic decay may make the spacecraft stay around the ISS altitude. And it may lead to a collision risk. However, it is not critical. Around the ISS altitude (400 km), we suppose that such a debris lowering its altitude stays in a 10 km corridor around the ISS altitude, while it is one month for b = 0.01 m^2/kg, it is shortened only to 1.5 days for the case with b = 0.20 m^2/kg. This assures the safety management by monitoring the debris crossing the ISS altitude.

An inflatable decelerator like a Ballute has been proposed as a means for debris removal (Global Aerospace). And a membrane decelerator has been proposed, too (Analytical Mechanics Associates). However, all the scenarios so far have assumed that those decelerators are directly mated to the target debris. And the servicer spacecraft cannot avoid mechanical contacts. The idea here enables the servicer spacecraft to avoid the direct contact.

G. Capturing Device: Gun-Net

The use of a Gun-Net is an easy solution to capture a target debris. The servicer spacecraft is free from the direct handling of the target. Despite the easiness, using the device has not become popular for the service of debris removal. It is because the removal or the deorbiting has been assumed by the propulsion means like the ESA's concept. To exhibit the propulsion capability, the thrust must penetrate to or have a secured arm length management with respect to the center of mass for the mated configuration with the target debris. Gun-Net capture may not be suitable for such firmly restrained configuration.

In the present method, the debris removal servicer has only to cast a Gun-Net to the target. The Gun-Net should be equipped with the spherical decelerator that is activated a certain period after the Gun-Net is projected. These sequences never require direct handling of the target. It is done in a contactless way. The Gun-Net does not need to cover the entire size of the target debris. Some target debris may have long solar panels. The Gun-Net has only to capture the debris hub portion only, since the method does not request the management of the center of mass once the debris is captured. The Gun-Net should have Auto-Closure function.

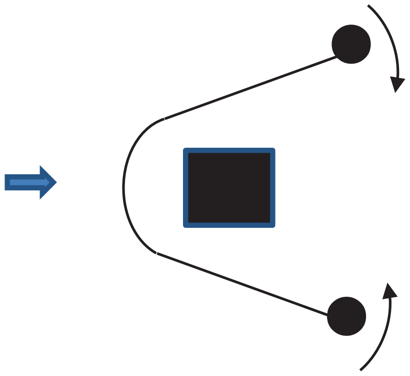

Fig. 5 Auto-latch Net Capture

Theoretically, tip masses have the angular momentum with respect to the target body and will automatically wind up around the body. The strings should have the latchets that prevent the strings from unwinding back (Fig. 5). Shooting speed of the Gun-Net should be taken depending on the spin rate of the target.

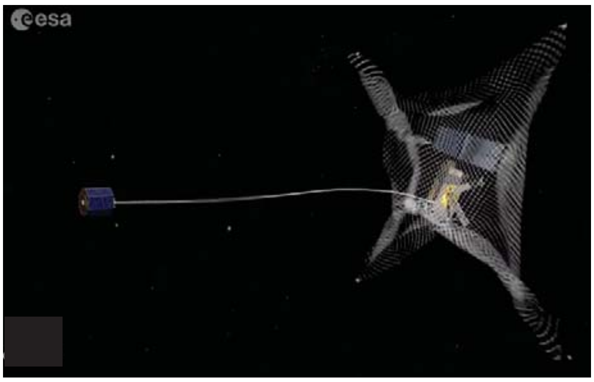

Fig. 6 Capture Device Idea at ESA [11]

For the purpose of capturing the target debris, uncooperative targets, there are studies [5], [11] with experiments and even with the flight demonstration. However, all the scenarios so far assumed at least one end of the net is mated via a tether with the servicer spacecraft that is to be decelerated by some means including propulsion system (Fig. 6). Therefore, the mechanical contact with huge force and torque is unavoidable.

H. Combined Scheme and Strategic Demonstration Mission

As the present method shows, the use of torpedo-like projectiles solves the difficulty, if the projectiles launch Gun-Nets and inflate Ballutes from them. It does not require any sophisticated robot function or any mechanical contact at all. The scheme is featured by the use of third body other than the first body of the servicer and the second body of the target debris.

The servicer spacecraft uses its own propulsion unit to approach the target satellite. Meeting the target satellite is a key in the debris sweeper flight. Typical contemporary launch vehicle injects the debris sweeper spacecraft accurately. The eccentricity, in other words, the altitude management of 20 km requires approximately 10 m/s delta-V. Compensating the typical inclination dispersion, the out of plane dispersion, of 0.1 deg requests approximately 10 m/s delta-V. The altitude alteration of 20 km controls the longitude of the ascending node almost 0.01 deg/day. And its typical dispersion of 0.2 deg is compensated during 20 days by the above mentioned 10 m/s. This infers the delta-V required to perform the approach to one target debris is about 30 m/s. This is paid by 10% mass of propellant of the servicer spacecraft for each debris removal even by low Isp cold gas jet thrusters.

TABLE I
12U SWEEPER SPACECRAFT

	Mass (kg)	Vol.(U)
Ballute (each)	3.4 (1.7 each) Balloon: 0.55 Gas: 0.65 Mechanics 0.5	2
Gun-Net (each)	3.4 (1.7 each)	2
RCS: Pro-pulsion	5.2 (incl. 3.7 kg fuel for 2 flights)	2
Satellite Bus	6	6
Total	18.5	12

Table I summarizes the typical 12U class debris removal servicer. It carries two sets of torpedo-like projectiles that occupies approximately 4U (2x2U) volumes. The servicer carries the modest cold gas thruster whose propellant is a liquidized gas. The Isp assumed here is very modest and is 30 sec. The total mass of the 12U servicer is about 18.5 kg.

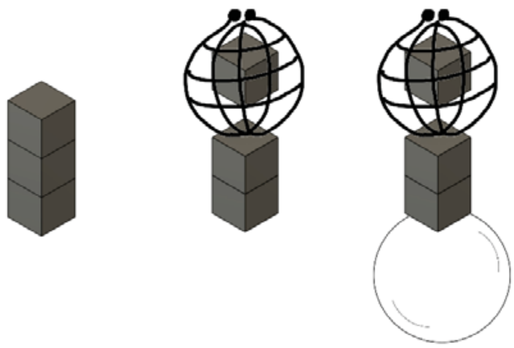

Fig. 7 A 3U-class Self-Demonstrator

It should be noted here that the target debris is assumed to weigh 100 kg dry mass. The ballute size is governed by the cross-section area of the ballute. The size of the demonstration spacecraft well fits for the startups and also fits for the universities.

The first demonstration can be performed by a smaller 3U class satellite. Despite that small size, it can carry 2U class torpedo-like projectiles that are also assumed for the 12U debris sweepers. The demonstration does not need to have an artificial target debris. The hub 1U size module may play the double roles of the servicer and the target debris. The demonstrator itself is decelerated by the ballute and deorbits by itself. It is a very simple and affordable demonstration even the universities can perform.

I. Drag Decelerators and Capturing Devices

The method is described referring to the use of the Gun-Net and the ballute for simplicity. However, the core part of the method is the use of the torpedo-like third body equipped with both the drag decelerator and the capturing devices. The type of drag decelerator and the type of capturing device never affect the core notion of the method.

The drag decelerator does not have to be ballutes but can be membranes, films and kites. Any deployable, inflatable or extendible device is included in and fits for the method. Especially the gas required for inflation weighs heavy. The ballute does not have to be a simple balloon, but can be multilayered or extendible with inflatable ribs to save the mass of the gas. The gas that hardens quickly is also a choice. The gas may be made of the material that hardens with ultra-violet ray or with temperature rise owing to the sun light. The material of the balloon can be self-hardening without the gas. Any kind of drag decelerator fits for the method. Also, any choice of the capturing devices fits for the method. It does not have to be a net to be projected; any tethers with certain hooks at the end also meet the method. Adhesives, magnets, wraps and the like can be used, as long as they are projected in a contactless manner from the servicer spacecraft.

III. Concluding Remarks

The core of this method is in introducing the third body launched from the servicing robot, which can be an unsophisticated and disposable device equipped with the dual capabilities, deceleration and capturing. The third body is launched from a distance farer than the size of the target debris. The core characteristics is not in the combination of two existing devices. And the idea can hardly be inspired by ordinary researchers and engineers. Without the third body, such a straightforward combination of them cannot provide the solutions to the problems discussed above.

The method here realizes the peaceful and sustainable use of low Earth orbits space. Shooting the enemy satellites has continued by now, and threatens the safe use of the low Earth orbit space. However, once the method presented above is disclosed, any country will be aware of the method. The method prevents any country from performing shooting the satellites kinematically, mechanically or in a destructive manner. It contributes to enhancing the sustainable use of low Earth orbit space.

Australia is the country that ratified the Moon treaty. It is a member state at the Committee on the Peaceful Uses of Outer Space, the United Nation (UN COPUOS). Australia should lead the debris removal activity.

The proposed method was already applied for and filed in the Patent Cooperation Treaty (PCT) system.

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