Untrackable Space Debris Active Removal using a Small Satellite

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ABSTRACT

A natural orbital decay of the space debris usually takes very long time. Active space debris removal (ASDR) should be applied to shorten the time. A trackable debris is regarded as a main target because it can be a source of new debris. However, collisions with trackable debris could be forestalled by hazard avoidance maneuvers. This paper rather focused on untrackable and potentially trackable debris, can be imminent threats to spacecraft. This paper proposed a new concept to decelerate space debris for their fast decay. This paper analyzed the most effective direction that debris should be pushed by the active removal. Attitude controls when debris collided and spinning maneuver utilized control moment gyroscopes (CMGs).

1 INTRODUCTION

The number of the space debris has been exponentially increasing. The increased debris have threated operating satellites more harshly. There were several catastrophic events and accidents such as the anti-satellite weapon test in 2007, and the collision between Cosmos 2251 and Iridium 33 in 2009, which generated a number of debris [1]. Such collisions with debris can cause many inconveniences and economic damages to mankind. All takes advantage of benefits from space development should be interested in solving these problems.

Space debris can be categorized as three groups by its size: small (<5mm), medium (5mm-10cm), and large debris (>10cm) in Tab.1. The small and medium debris cannot be trackable from the ground [2]. Spacecraft can avoid possible collisions with large debris by collision avoidance maneuvers in advance, because large debris are trackable. Collisions with small debris can be protected by shields, however, those with medium debris can cause lethal damages to spacecraft.

Table 1 Categorization of space debris in its size [2]

Size	Estimated Population	Trackable	Avoid Strategy
Small	Millions	Impossible	Shielding
Medium	~500,000	Potentially Possible	-
Large	~21,000	Possible	Avoidance maneuver

Several researchers have already studied about active space debris removal (ASDR). There are several space debris removal concepts such as ESA's drag augmentation method, JAXA's electro-dynamic tether method and solar sail propulsion method, and Texas A.M University's slingshot method, which motivated this research [3, 4].

However, previous researchers have focused on removing trackable debris which can be detected from the ground. Some previous concepts required precise rendezvous and complicated control. Although trackable debris are regarded as sources of new debris and so they are valuable to be eliminated, operating satellites can avoid them by collision avoidance maneuvers in advance. Rather, untrackable debris can be more hazard to operating spacecraft as shown in Fig. 1. They cannot be defended by shields and collision avoidance maneuvers due to their untrackable property.

In this paper, a new space debris removal concept aiming at untrackable debris was introduced. The concept was characterized by a spinning operation to decelerate space debris' orbital speed and finally make it decay fast. The purpose of this study was to propose an effective space debris removal concept for untrackable debris and prove its effectiveness and applicability. To control the satellite, control moment gyroscopes (CMGs) was applied, which is an attitude control device generally utilized in agile attitude maneuver. CMGs were utilized for the attitude control of the huge spacecraft such as Skylab, MIR, and ISS. Honeybee Robotics developed a miniature CMG for small spacecraft [5].

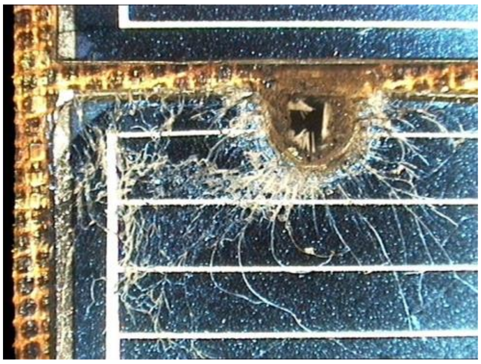

Figure 1 Hubble solar panel damage by space debris. Courtesy of ESA

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2 EFFECT OF ACTIVE SPACE DEBRIS REMOVAL

Before the effectiveness of the proposed algorithm is demonstrated, a natural decay time for the targeted debris was examined. Properties of the targeted debris were shown in Tab. 2. The High-Precision Orbit Propagator (HPOP) in STK 8 was utilized to calculate decay time. It took 1586.4 years to decay from 1000km to 180km altitude. NRLMSISE 2000 was chosen as an atmospheric density model. Schatten solar flux model (SolFlx 1006_Schatten.dat) was applied to reflect solar radiation pressure to decay. A sample space debris was assumed to an aluminium sphere with a 5 cm radius. The mass of the debris can be calculated by density ($2.7g/cm^3$) and volume of the sphere. The debris exists in the space almost permanent. Then, the number of debris may be exponentially increased by incessant collisions as Kessler syndrome. Therefore, ASDR for untrackable debris should be required.

An efficient space debris removal satellite is required to be repeatable and persistent. Because it is quite expensive to develop the satellite and send it into space (approximately $60,000 per 1kg), the satellite should remove debris as many as possible. Many previous concepts tried to remove debris by using limited materials or by committing suicide itself with debris. The proposed concept tried to physically promote debris' faster decay. Thus, it can repeatedly eliminate many debris. Moreover, the proposed concept is for the space debris removal mission from 900km until its natural decay. The lifetime of the proposed debris removal satellite is approximately 160 years long (estimated by a lifetime estimator in STK 8). Therefore, the proposed concept was designed to operate repeatedly and long-lasting in space.

The proposed algorithm is categorized as a contact removal method, which is a method that debris cleaner satellite directly contact debris to eliminate; physically pushes space debris into the lower altitude. The relative motion of the pushed debris and removal satellite should be analyzed. First, to determine the direction that debris will be pushed, simple simulations were performed to analyze the effectiveness of the concept by examining a decrease in decay time. The pushed debris is decelerated and which meant a decrement in orbiting energy, the trajectory of debris was changed. Exposed by lower altitude with a higher air density, the debris will be decayed faster.

Space debris was pushed to four directions, a radial, anti-velocity, along velocity, and nadir direction. For each direction, orbital decay time were examined. Astrogator in STK8 was used as a propagator for the simulations. The simulations were performed to find the most efficient direction where debris to be pushed for fast decay. Thus, several properties of the space debris and its orbit were properly chosen. A 5kg debris started its decay from 500km altitude to 180km. The initial orbit was chosen as a 500km circular orbit with a 28.5° inclination angle and 0° of right ascension of ascending node (RAAN). It has 1 m^2 cross-sectional area for atmospheric drag, solar radiation pressure, and radiation pressure. It was assumed that the debris were pushed and the decrement of debris orbital velocity (ΔV) was 0.01km/s. The trajectory of the debris is described in Fig. 2 Moreover, four directions are marked as arrows with numbers from one to four, radial, anti-velocity, along-velocity, and nadir direction in order.

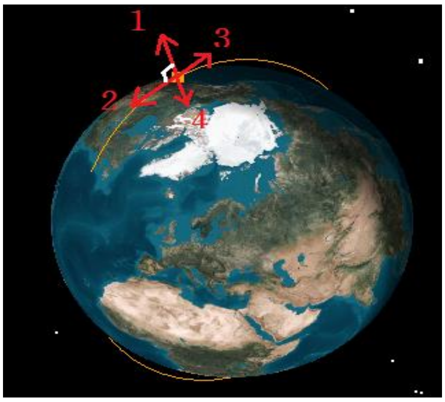

Figure 2 Direction of additional thrust exerted on debris

Table 2 Orbital decay time depends on pushing direction

Direction	Decay time (days)	Increment of decay time (%)
Natural decay	44.58	0
1. Radial	44.08	-1.12
2. Anti-velocity	**32.17**	**-27.83**
3. Along-velocity	58.42	32.05
4. Nadir	44.83	0.56

Tab. 2 represents the natural orbital decay time and decay time changes upon pushing direction. The decay time of debris was most efficiently decreased as 27.83 percent compared to natural decay time when the debris was pushed in the opposite direction of its orbital velocity vector. Therefore, the proposed space debris removal concept was designed to push debris in the anti-velocity vector direction. It seemed that pushed debris was released in the opposite direction in the relative motion. In fact, it maintained its original velocity vector but decelerated with respect to the inertial frame.

3 PROPOSED CONCEPT

The space debris removal satellite consists of three parts. The first part is a body which contains several basic components of a satellite such as an electric power system (EPS), onboard computer (OBC), attitude determination system(ADS), GPS, and control moment gyroscopes (CMGs) as an attitude control system. The second part is a blade which is used to catch space debris and its side is for a place where solar panels are placed to produce the electricity. There is a spongy material on the front side of the blade for an inelastic collision with debris. The third part is a tip of the blade which obstructs the caught debris from getting out of the blade due to a centrifugal force. The debris will be released through the unfolded tip of the blade when the debris is accelerated enough.

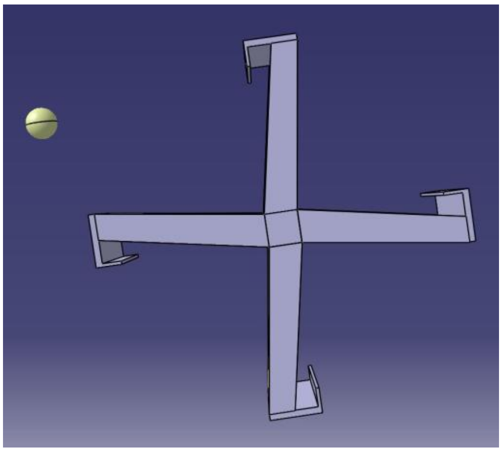

Figure 3 Description of spinning windmill satellite

The proposed space debris removal concept aimed at conditionally trackable debris (<10cm) from 700km to 900km in altitude, with inclination of 99 ° (sun synchronous orbit). The proposed concept can be divided into four steps: (1) approach, (2) capture, (3) spinning, and (4) release, which are described in Fig. 7. The proposed concept was introduced under three assumptions. First, it is a perfectly inelastic collision when debris collided with a blade of the satellite. Thus, debris sticks to a satellite's surface without bounce. Second, the caught debris roll along the inclined surface of the satellite and will be confined between a blade tip and hook. Third, the debris is released at the lowest point toward the anti-velocity direction exactly.

3.1 APPROACH

The space debris removal satellite approaches to debris. While rendezvous with debris, the satellite gradually increases its angular velocity by CMGs. Here, the angular velocity should be controlled to keep debris between two blades. If the angular velocity is too fast to catch, debris will be hit by the blade. Therefore, the satellite maintains a slow angular velocity until a sensor detects a contact between debris and blade.

3.2 CAPTURE

The satellite captures the debris, which is not a capture literally, but an inelastic collision between a blade of the satellite and debris. On the blade, a buffer that absorbs the impact from debris to the satellite was installed on a contact surface to protect the satellite. A centre of mass is moved toward the debris when the satellite caught debris. The centre of mass moved toward debris and it can be obtained in Eq. (1).

$$\vec{\boldsymbol{L}}_{cm2} = \frac{m_d}{M_{sat} + m_d}\hat{\boldsymbol{l}}_d \tag{1}$$

where M_{sat}, M_{cen}, and M_b are mass of the total satellite, a body, and blade, respectively. The vector $\hat{\boldsymbol{l}}_d$ is an unit vector to debris. The total mass, M_{sat} can be obtained by adding mass of five objects, $M_{sat} = M_{cen} + 4M_b$. Because a collision between debris and a spongy blade is an inelastic collision under the assumption, only conservation of linear and angular momentum is valid. From the conservation of linear momentum relation,

$$(M_{sat} + m_d)\vec{\boldsymbol{V}}_2 = M_{sat}\vec{\boldsymbol{V}}_1 + m_d\vec{\boldsymbol{V}}_d \tag{2}$$

From the conservation of angular momentum relation,

$$\boldsymbol{J_1 w_1} + m_d\left(\vec{\boldsymbol{l}}_b \times \Delta\vec{\boldsymbol{V}}_d\right) = \boldsymbol{J_2 w_2} \tag{3}$$

where $\boldsymbol{J}$ is a moment of inertia matrix of the satellite, $\boldsymbol{w}$ is an angular moment vector and subscriptions 1 and 2 stand for before and after the collision, respectively. A vector $\Delta\vec{\boldsymbol{V}}_d$ is a relative velocity of debris with respect to the satellite's centre of mass, $\vec{\boldsymbol{V}}_d - \vec{\boldsymbol{V}}_1$

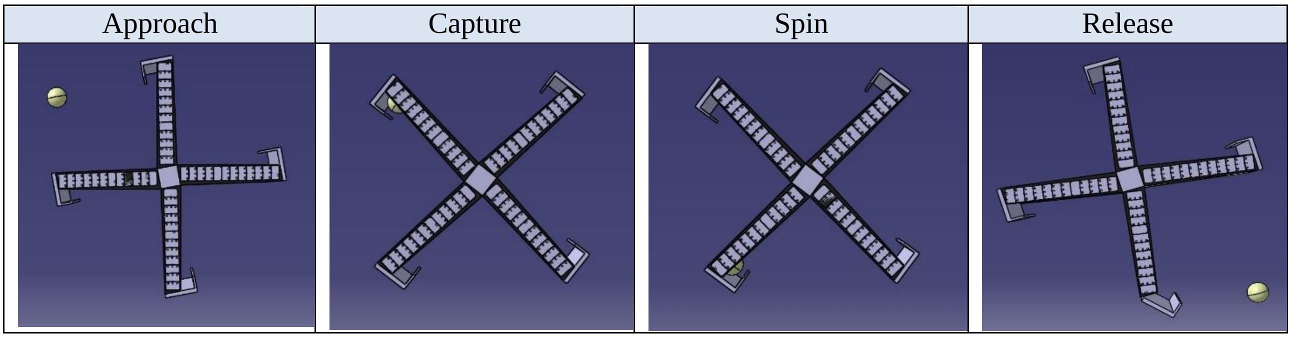

Figure 4 Proposed space debris removal sequences

The angular momentum of the debris before the collision can be obtained by the cross product of two vectors, $\vec{\boldsymbol{l}}_b$ is a vector of blade tip. Finally, the mass of captured debris can be calculated by using Eq. (1~3). A shift in centre of mass and changes in moment of inertia of the system can be negligible if a relative velocity of debris with respect to the debris removal satellite is not quite high.

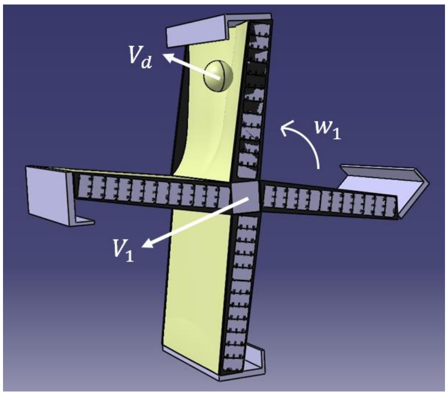

Figure 5 Description of capturing moment

3.3 SPINNING

The satellite starts to accelerate its rotation by using CMGs. The captured debris moved to the tip of the blade by the centrifugal force as a result of the satellite's rotation. The captured debris was stuck at the tip of the blade and a small hook by gradually increasing angular velocity. The hook was installed with a hinge on the tip of the blade. A surface of the blade was specially designed to make debris smoothly roll to the tip.

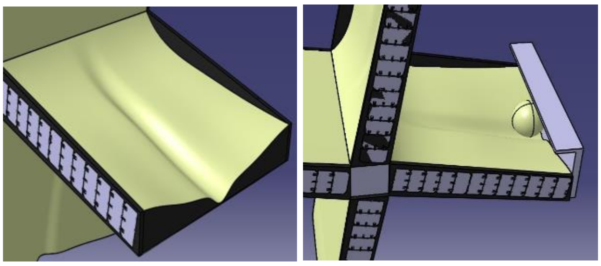

Figure 6 Spongy surface of the blade

3.4 RELEASE

The debris was released from the satellite when the debris was accelerated enough angular velocity. The hinge is opened the hook when the blade with the debris is heading for the opposite direction to the satellite's velocity vector. Then, the debris is released to the opposite direction.

4 DE-TUMBLING CONTROL BY CMGs

There are five operation modes to control the proposed concept: (1) power generation mode, (2) attitude change mode, (3) de-tumbling mode, (4) spin accelerating mode and (5) stabilizing mode. Among five operation modes, an attitude control for the de-tumbling mode was analyzed. When the debris is captured by a blade of the satellite, a sensor detects the contact and the satellite initiates a de-tumbling mode to stop debris from tumbling. The debris' linear momentum is transferred to angular momentum of the satellite. It was assumed that angular momentum of the debris is negligible compared to that of the satellite. To analyze CMG operations, a mathematical modelling of the rigid satellite dynamics with CMGs was considered [6]. In Ref. [3], four SGCMGs were mounted on pyramid. A mathematical modelling of satellite dynamics with CMGs can be expressed in Eq. (5) [6].

$$\dot{\boldsymbol{H}}_s + w \times \boldsymbol{H}_s = \boldsymbol{T}_{ext} \tag{5}$$

where $\boldsymbol{H}_s$ is the angular momentum vector of the total debris removal satellite including CMGs in Eq. (6) [6], $\boldsymbol{w}$ is an angular velocity vector of a spacecraft. The total angular momentum can be obtained by adding angular momentum of the CMGs and satellite.

$$\boldsymbol{H}_s = J\boldsymbol{w} + \boldsymbol{h} \tag{6}$$

The external torque, $\boldsymbol{T}_{ext}$ can be obtained by calculating the time derivative of angular momentum.

$$\boldsymbol{T}_{ext} = \frac{d\boldsymbol{L}}{dt} = \frac{J_2 w_2 - J_1 w_1}{\Delta t} = \frac{m_d(\vec{\boldsymbol{l}}_b \times \Delta\vec{\boldsymbol{V}}_d)}{\Delta t} \tag{7}$$

An indirect singularity-avoidance steering law in a feedback control form was applied for demonstrating the de-tumbling mode [6]. To consider the most severe case, it was assumed the debris collided at the corner of the blade. It was assumed that it took 0.5s to inelastic collision between debris and spongy surface of the satellite. The debris can collide with any points of the surface in Fig. 6. To consider the most severe condition, it was assumed that the debris is collided at the corner of the blade and it is composed of Tungsten ($\rho = 19.3 \text{g}/cm^3$), which has the highest density among debris' composition [7]. The external torque vector is [-5.055, -5.055, 10.11] Nm by using simulation parameters in Tab. 3. Then, initial angular velocity of the satellite due to the external torque can be obtained as [-2.47, -2.47, 3.68] rad/s.

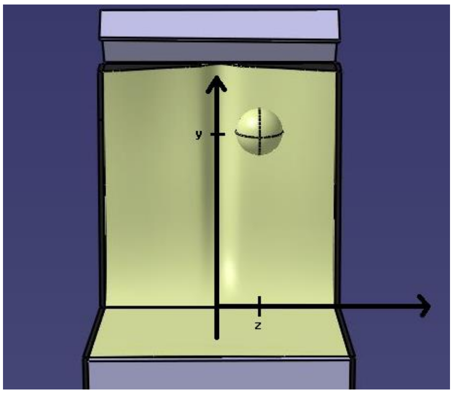

Figure 7 Description of the debris capture

Table 3 Simulation parameters for de-tumbling mode

Simulation parameters	**Values**
Moment of inertia matrix	[2.04, 2.04, 2.74] kgm^2
Debris size (sphere, Tungsten)	10cm in diameter
Blade length & width	50cm
Relative velocity	[-1,-1,-1] m/s
Duration of collision	0.5s
CMGs parameters	**Value**
CMG angular momentum [5]	56mN · m ·s
Pyramid skew angle [6]	54.73°
Gimbal max angular velocity	$\left\|\dot{\delta}\right\| < 2$ rad/s
Quaternion feedback gains	$K_p = [4, 2, 1]$
Angular velocity feedback gains	$K_d = [-2, -3, -5]$

For initial and final conditions of the angular velocity and quaternion were determined as, w_0 = [-2.47, -2.47, 3.68], w_f = [0, 0, 2], q_0 = [0, 0, 0, 1]; q_f = [0, 0, 1, 0]. Fig. 8~10 shows histories for Euler angles, control torque input, and gimbal angles. With severe simulation conditions, the satellite stabilized and achieved targeted attitude and angular velocity by CMGs in 20 seconds. In Fig. 10, gimbal angles overcame singular points and finally converged. After the de-tumbling mode, the debris removal satellite will accelerate its angular velocity in z-axis (main axis) and release debris. Assume the satellite can decelerate debris' orbiting speed by 100m/s, it can reduce its decay time to nine months. However, it should be developed more cutting-edge CMGs to accelerate the proposed spinning satellite's angular velocity to make captured debris to get much faster releasing velocity.

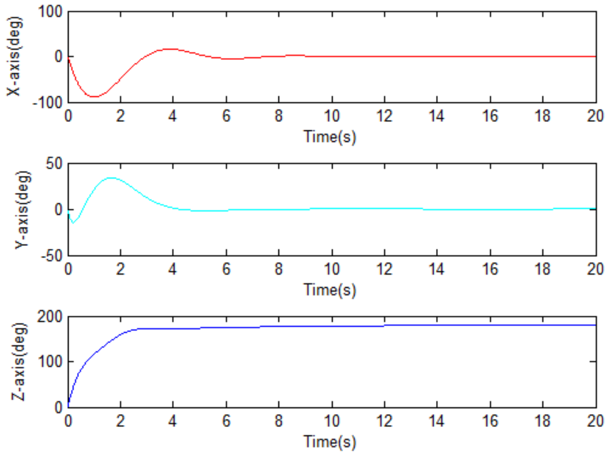

Figure 8 Euler angle history

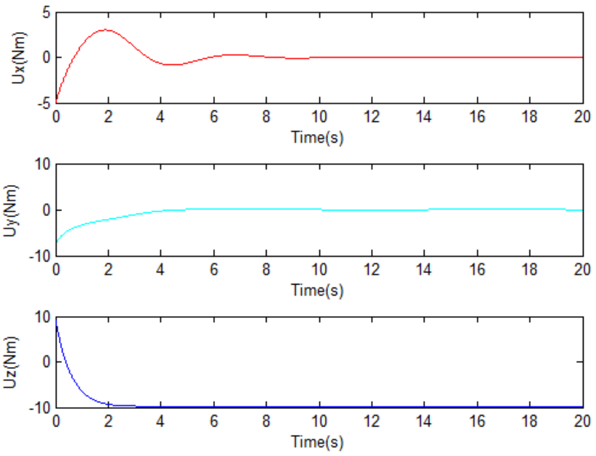

Figure 9 Control torque input history

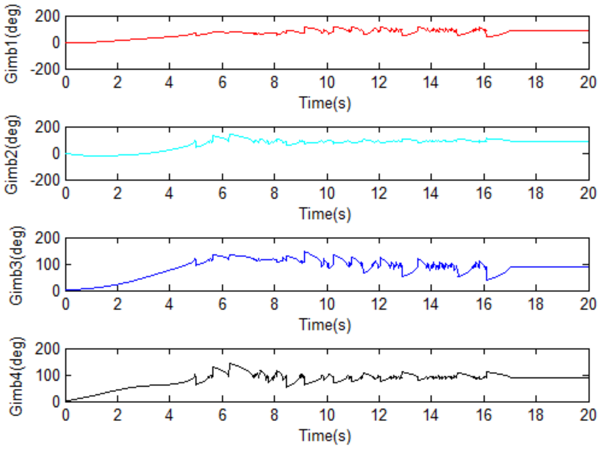

Figure 10 Gimbal angle history

5 CONCLUSION

In this paper, a new concept for removing untrackable (less than 10cm) space debris was introduced. The targeted trajectory is in 1000km altitude and 83 deg. Inclination. It utilized the spinning windmill to decelerate the debris' original orbiting speed. Moreover, we analyzed the most effective direction that debris should be pushed by the active removal. It was most effective when the debris was pushed the opposite direction of its original velocity. It could decrease its natural decay time by 27% in 500km altitude. Moreover, stabilization of the removal satellite by CMGs was analyzed. CMGs are appropriate to agile attitude control and it has developed for small satellite these days. The simulation has shown that small CMGs can stabilize the proposed concept from the sudden disturbance in 20s, but it lacked of ability to accelerate debris' releasing speed for faster decay. Therefore, it should be upgraded to efficiently decelerate the space debris' orbiting speed by scaling the size of the satellite or decelerating concept for future works. In addition, more realistic analysis will be supported such as analysis for EPS and more details about capturing process.

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