Debris Particle Recovery Using Trawl-Net-Like Small-Satellite Formation Flying

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Abstract

To collect debris particles less than 1 mm in diameter, a novel debris particle recovery method that employs a trawl-net-like small-satellite formation flying mission was designed. This mission was performed using at least four small satellites that played the role of trawl boats. All satellites had the same small eccentricity and semimajor axis but slightly different inclination and right ascension of the ascending node, and rotated around a common central orbit. A simple simulation was conducted and formation flying was confirmed to be feasible. The merit of this method is that it is maintenance-free. If this mission were used at an altitude of approximately 700 km of polar orbit for one week and the orbit rotation radius were 70 m, approximately 27,000 debris particles having diameters larger than 0.1 mm would be recovered if the mission were conducted in 2010, and approximately 56,000 debris particles would be recovered in 2030. The debris density was estimated with NASA's ORDEM 2000. Aerogel is one of the candidate materials for the "trawl net." The area, mass, and volume of the net, the momentum given to the net, the impact force, the average frequency of impact, and maneuverability are discussed.

トロール漁法の網を模したスペースデブリ回収法

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摘要

直径 1 mm 以下のデブリを回収するためにトロール漁法の網を模した小型衛星編隊飛行を提案する。このミッションでは少なくとも 4 機の小型衛星にトロール漁船の役割を持たせることに似なる。これらの小型衛星編隊飛行は同じ軌道長半径と非常に小さい離心率を持ち、相互にわずかに異なる軌道傾斜角と昇交点赤経を持つことで実現でき、それらの平均軌道の周囲を相互に回転する。簡単な計算機シミュレーションで実現性を確認した。この軌道の利点はメインテナンス（マヌーバ）が不要であることである。高度 700 km の極軌道上で、平均軌道に対して半径 70 m の網を適用した場合、1 週間のミッションで 0 直径.1 mm 以上のデブリが 2010 年では 27,000 個、2030 年では 56,000 個回収できる試算を NASA のデブリモデル ORDEM2000 を用いて得た。エアロジェルをトロール網の候補材料の 1 つとして検討した。網の面積、体積、網が受ける運動量、衝撃力、衝突頻度、衝突による運動量補償のためのマヌーバについて検討した。

1. INTRODUCTION

The continuous increase in the number of space debris has become a grave problem. In particular, low earth orbit (LEO) at altitudes less than 1,000 km and geostationary orbit (GEO) are highly crowded with debris, and their presence adversely affects mission performance. The most notable problem posed by space debris is that even particles less than 0.1 mm in diameter may damage shuttle windows, and particles less than 0.2 mm in diameter may pierce spacesuit, impeding extravehicular activity (EVA) [1]. It is also difficult to estimate the motion of debris particles less than 10 cm in diameter before a mission because they are difficult to identify from the ground, in contrast to large debris such as obsolete satellites or the upper stage of rockets, which can be identified and recovered by space robots. For such debris particles, countermeasures, such as the use of shields to prevent severe damage from collisions, have been mainly discussed so far [2, 3]. However, we have to seriously consider ways to remove debris particles for future space missions. To this end, a debris particle recovery method that uses a trawl-net-like small-satellite constellation mission is proposed, as shown in Fig. 1. This mission is performed using at least four small satellites in formation flying, which play the role of trawl boats. All satellites have the same small eccentricity but slightly different inclination and right ascension of the ascending node, and rotate around a common central orbit. A simple simulation was conducted and the constellation was confirmed to be feasible. The merit of this method is that it is maintenance-free. If this mission were used at an altitude of approximately 700 km of polar orbit for one week and the orbit rotation radius were 70 m, approximately 27,000 debris particles having diameters larger than 0.1 mm would be recovered if the mission were conducted in 2010, and approximately 56,000 debris particles would be recovered in 2030. The debris flux was estimated with NASA's ORDEM 2000 [4], and the estimation results are shown in Fig. 2. The small satellites may weigh less than 50 kg if the mission is less than one week. Aerogel is one of the candidate materials for the "trawl net" [5]. Aerogel is a fragile yet lightweight material that has been used to capture debris particles. To construct the net, Kapton film or other fabric is used to absorb the impact of collisions. After the mission, the recovered debris particles, the small satellites, and the net would be burned on re-entry into the atmosphere.

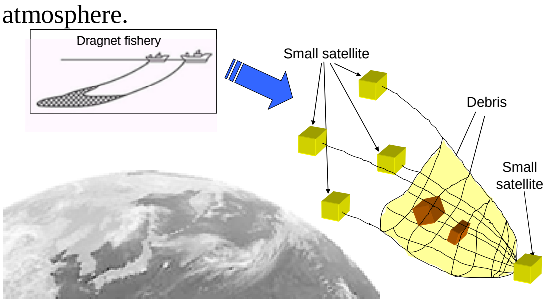

Fig. 1 Outline of debris particle recovery mission using trawl-net-like small-satellite constellation.

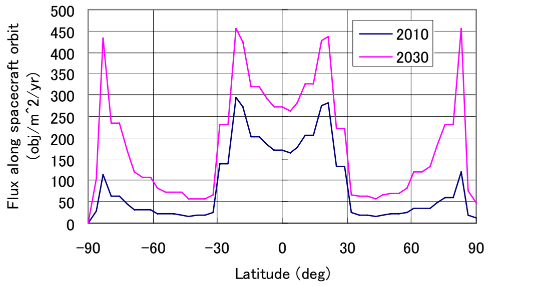

Fig. 2 Debris flux at 700 km altitude orbit in 2010 and 2030 estimated with ORDEM 2000.

2. ORBIT DESIGN

The basic idea of formation flying of polar orbit is the combination of four elliptic orbits whose semi-major axes and eccentricities are the same, but the argument of perigee (AP) is separated by 90 degrees from each other. They have slightly different inclinations and right ascensions of the ascending node (RAAN). The four satellites rotate around a certain orbit. The idea is shown in Fig. 3.

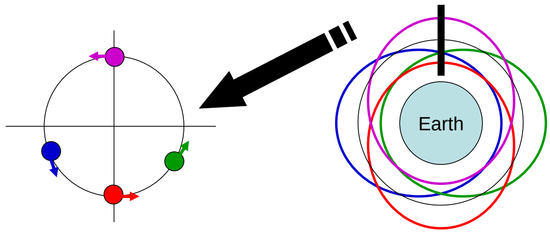

Fig. 3 Conceptual orbit design.

Based on this idea, the following orbits are considered (semi-major axes and eccentricities are common). The size of the net can be designed in any way; however, the feasible size for a test mission is assumed here (the radius of aperture is approximately 70 m).

Semi-major axis: 7419319.8 m

Eccentricity: 0.00001

(1) Inclination: 90.00057 deg.
RAAN: 0.0 deg.
AP: 0.0 deg.
True anomaly: 0.0 deg.

(2) Inclination: 89.99943 deg.
RAAN: 0.0 deg.
AP: 180.0 deg.
True anomaly: -90.0 deg.

(3) Inclination: 90.0 deg.
RAAN: 0.00057 deg.
AP: 90.0 deg.
True anomaly: -90.0 deg.

(4) Inclination: 90.0000 deg.
RAAN: -0.00057 deg.
AP: -90.0 deg.
True anomaly: 180.0 deg.

The first 1000-second motions of these satellites around their mean position are shown in Fig. 4. In the calculation, no perturbations such as J2 or air drag are considered. The satellites rotate around their mean position with approximately 70 m radius.

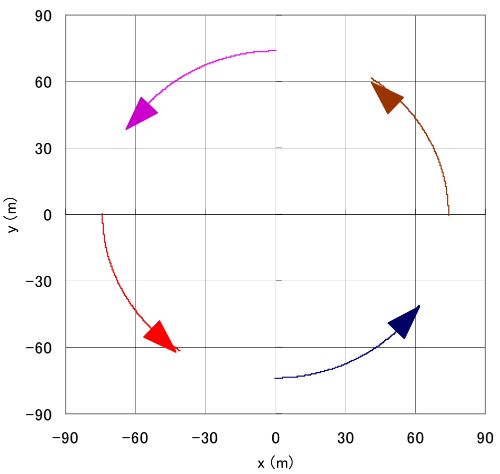

Fig. 4 Motion of satellites in orbit.

3. NET DESIGN

To design the net, the following items are defined.

Nomenclature

M (kg)	mass of net
ρ_n (kg/m^3)	density of net
S (m^2)	area of net
V_n (m^3)	volume of net
r (m)	radius of net
d (m)	thickness of net
m (kg)	mass of debris particle
ρ_p (kg/m^3)	density of debris particle
D (m)	diameter of debris particle
V_p (m^3)	volume of debris particle
v (m/s)	relative velocity between debris particle and net
T (m)	track length of debris particle
t (s)	time to stop debris particle in net
a (m/s^2)	deceleration of debris particle during capture in net
M_p (kg m/s)	momentum given by debris particle to net
F_p (N)	force given by debris particle to net
f_y (obj/m^2/yr)	flux along spacecraft orbit
f_s (obj/s)	flux captured by our mission

As the candidate material for the net, special (multi-layered) foils [2] or fibers [3] have been suggested. However, they are too massive for our application. We choose aerogel, whose density ρ_n is 30 kg/m^3. Figure 5 shows a photograph of the candidate aerogel. According to ref. [6], the ratios of track length to diameter (T/D) of most debris particles are less than 100, which mean that if the diameter of debris particle D is 1×10^{-4} m, the required thickness of net d is 1×10^{-2} m.

(1) Net area and mass

We assume that the net is shaped like a disc. Then, the area S, volume V_n, and mass M of the net are defined as follows.

$$S = \pi r^2, \quad (1)$$

$$V_n = S\, d \quad (2)$$

$$M = \rho_n V \quad (3)$$

Since the orbit is designed as motion in a radius of 70 m, net radius r is assumed to be 70 m. From (1), the area is

$$S = \pi \times 70\ (\mathrm{m}) \times 70\ (\mathrm{m}) = 15{,}4\ 00\ (\mathrm{m}^2).$$

From (2), the volume is

V_n = 15,400 (m^2) × 0.01 (m)= 154 (m^3),
and from (3), the mass is

M = 154 (m^3) × 30 (kg/m) = 4,618 (kg).

Fig. 5 Areogel.

(2) Momentum given to the net

Volume V_p, mass m, and momentum M_p of the debris particle are calculated as follows, assuming that the debris particle is spherical.

$$V_p = (4/3)\,\pi\,(D/2)^3 \tag{4}$$

$$m = \rho_p V_p \tag{5}$$

$$M_p = m\,v. \tag{6}$$

As the typical diameter of debris particle D, 2×10^{-4} m is assumed, and as density of debris particle, ρ_p = 2.7 (g/cm^3) = 2.7×10^3 (kg/m^3), which is equal to the density of aluminum, is assumed. The typical relative velocity between debris particle and the net is assumed to be 8×10^3 m/s. Then, from (4), (5), and (6),

$V_p = (4/3)\,\pi\,(2 \times 10^{-4}/2)^3 = 4.19 \times 10^{-12}$ (m^3),

$m = 2.7 \times 10^3 \times 4.19 \times 10^{-12} = 1.13 \times 10^{-8}$ (kg),

$M_p = 1.13 \times 10^{-8} \times 8 \times 10^3 = 9.0 \times 10^{-5}$ (kg m/s).

(3) Impact force

If debris particle having velocity v and requiring time t to move a distance D is stopped, the relationship between them is expressed as follows. Here, deceleration a is assumed to be constant.

$$D = (1/2)\,a\,t^2 \tag{7}$$

$$v = a\,t \tag{8}$$

From (7) and (8),

$$D = (1/2)\,v\,t. \tag{9}$$

From (9), in our case,

t = 2 D / v = $2 \times 1 \times 10^{-2} / 8{,}000 = 2.5 \times 10^{-6}$ (s).

The impact force at capture is calculated based on the impulse-momentum theorem.

$$F\,t = M_p \tag{10}$$

From (10), the impact force is

$F = 9.0 \times 10^{-5} / 2.5 \times 10^{-6} = 36.0$ (N).

As the impact force is quite large, the net should be strong enough to withstand any effects of the impact. Two net structures are considered: the first one is aerogel supported by a film such as Kapton from the back, and the second one is aerogel wrapped with cloth. These will be discussed later.

(4) Average frequency of impact

Since one year is 3.15×10^7 (s), debris flux captured by our mission is described as follows.

$f_s = f_y S / 3.15 \times 10^7$.

From Fig. 2, in the case of 2010, if we assume that flux f_y is 90.5 objects per m^2 per year, then,

$f_s = 90.5 \times 15{,}4\,00$ (m^2) $/ 3.15 \times 10^7 = 0.044$.

This means that in our mission, debris particles larger than 100 μm in diameter will be captured every 22.6 seconds, and if the mission continues for one week, the number of captured debris particles will be 27,000.

In the case of 2030, if we assume that flux f_y is 190 objects per m^2 per year, then, the number of captured debris particles will be approximately 56,000.

(5) Maneuverability

The average momentum that the net receives from debris per second in the case of 2010 is

M_p / 22.6 = 9.0×10^{-5} (kg m/s) / 22.6 (s) = 4.0×10^{-6}.

This means that the thruster for maneuver requires approximately 4.0×10^{-6} (N) during the mission. This requirement seems reasonable even if small satellites weighing less than 50 kg is used for this mission.

(6) Reinforcement method

Since aerogel is fragile, some reinforcement is required. Two methods are discussed below.

<u>Attachment to Kapton film</u>

As shown in Fig. 6, aerogel is attached to polyimide film (brand name: Kapton film). The selection of adhesive agent is important: high-viscosity alpha-cyanoacrylate (brand name: Krazy Glue) is a promising candidate for a one-week mission. However, since the net material used in this method is exposed to space, other small debris particles would be generated.

Wrapping with cloth

As shown in Fig. 7, aerogel is wrapped with cloth that is used as the outermost material of spacesuit. Usually, the cloth is made of white Ortho-Fabric, which is a blend of Gore-Tex, Kevlar, and Nomex [7]. In this case, it would not be a problem if fragile aerogel were broken into pieces inside the cloth, or if small debris particles were generated. However, the cloth would make the mass large.

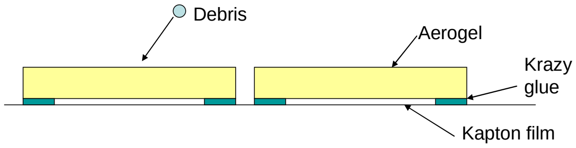

Fig. 6 Attachment to Kapton film.

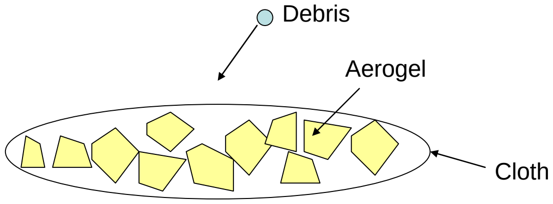

Fig. 7 Wrapping with cloth.

Vacuum Test

To confirm the properties of aerogel in vacuum, aerogel attached to Kapton film with Krazy glue was left inside a vacuum chamber for one week. White turbidity was observed, which was caused by the capillary phenomenon of Krazy glue (Fig. 8); however, the physical properties of aerogel remained unchanged. The pressure of the vacuum chamber is shown in Fig. 9. Since aerogel is porous, it took three days to achieve vacuum condition of the order of 10^{-7} Torr. Nevertheless, we did not encounter any problems when using aerogel for one week under a vacuum environment.

Fig. 8 White turbidity of aerogel.

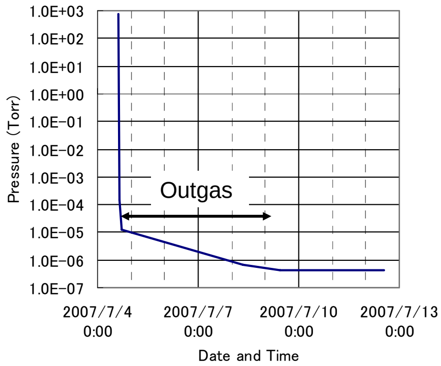

Fig. 9 Pressure of vacuum chamber.

4. DISPOSAL

After the mission, the net and the small satellites would burn up during reentry into the atmosphere. The net shape at reentry is shown in Fig. 10.

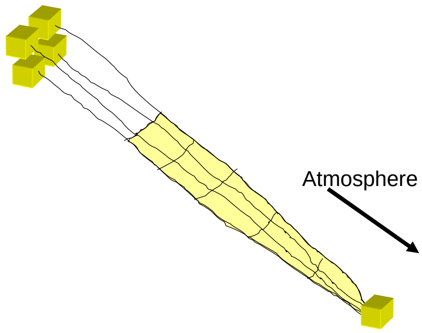

Fig. 10 Reentry and disposal.

5. CONCLUSIONS

This study is summarized below.

(1) To collect debris particles less than 10 cm in diameter (actually less than 1 mm), a novel debris particle recovery method that uses a trawl-net-like small-satellite constellation mission was proposed.

(2) As the candidate for formation flying orbit, a combination of four elliptic orbits was considered and the net aperture radius of approximately 70 m was feasible.

(3) As net material, aerogel was considered and its feasibility was discussed.

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