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Evaluation of a satellite constellation for active debris removal

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A R T I C L E I N F O

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A B S T R A C T

This paper analyzes an example of a three-dimensional constellation of debris removal satellites and proposes an effective constellation using a delta-*V* analysis that discusses the advisability of rendezvousing satellites with space debris. Lambert's Equation was used to establish a means of analysis to construct a constellation of debris removal satellites, which has a limit of delta-*V* injection by evaluating the amount of space debris that can be rendezvoused by a certain number of removal satellite. Consequently, we determine a constellation of up to 38 removal satellites for debris removal, where the number of space debris rendezvoused by a single removal satellite is not more than 25, removing up to 584 pieces of debris total. Even if we prepare 38 removal satellites in their respective orbits, it is impossible to remove all of the space debris. Although many removal satellites, over 100 for example, can remove most of the space debris, this method is economically disproportionate. However, we can also see the removal satellites are distributed nearly evenly. Accordingly, we propose a practical two-stage strategy. The first stage is to implement emergent debris removal with the 38 removal satellites. When we find a very high probability of collision between a working satellite and space debris, one of the removal satellites in the constellation previously constructed in orbit initiates a maneuver of emergent debris removal. The second stage is a long-term space debris removal strategy to suppress the increase of space debris derived from collisions among the pieces of space debris. The constellation analyzed in this paper, which consists of the first 38 removal satellites, can remove half of the over 1000 dangerous space debris among others, and then the constellation increases the number of the following removal satellites in steps. At any rate, an adequate orbital configuration and constellation form is very important for both space debris removal and economic efficiency. Though the size of constellation of debris removal satellites would be small originally, such a constellation of satellites should be one of the initial constellations of removal satellites to ensure the safety of the future orbital environment.

1. Introduction

Since the beginning of our space utilization in 1950s, the number of on-orbit artificial objects has been increasing. North American Aerospace Defense Command (NORAD) is now observing 14,997 objects and discloses their orbit elements, with 11,626 of these objects being debris, e.g., broken satellites and launcher fairings [1].

In 2000, the Inter-Agency Space Debris Coordination Committee (IADC) adopted the guidelines for the reduction of space debris by which we are exerting effort to suppress the creation of new space debris. However, it is estimated that space debris will continue to increase, even if we never launch any new objects to orbit, and National Aeronautics and Space Administration (NASA) predicts 8 incidents of collision between on-orbit objects should

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Nomenclature

a	semi-major axis of elliptical orbit
ΔV	velocity increment
e	eccentricity of orbit
f	true anomaly of junction point
f_0	true anomaly of debris unusually defined in Fig. 6
f_i	true anomaly of satellite
m_0	initial satellite mass including propellant
m_f	satellite dry mass
p_i	semi-latus rectum of orbit
$\mathbf{r}$	position vector of debris in the coordinate system
$\mathbf{r_d}$	position vector of debris in geocentric-equatorial coordinate system
$\mathbf{r_i}$	position vector in orbit
r_i	length of the position vector
t_f	transfer time of satellite
t_p	transfer time for phase shift
W_i	orbital velocity vector
θ	transfer angle
ϕ	relative inclination of satellite and debris
ϕ_s	inclination of satellite in geocentric-equatorial coordinate system
Ψ	argument of perigee unusually defined in Fig. 6
ω_1	magnitude of angular velocity of initial orbit
ω_2	magnitude of angular velocity of target orbit
Ω	the right ascension of the ascending node (RAAN) unusually defined in Fig. 6
Ω_0	RAAN of debris unusually defined in Fig. 6
Ω_s	RAAN of satellite in geocentric-equatorial coordinate system

occur, even if the 25-year-rule is executed. In short, safety is not ensured only by the mitigation of space debris. Here, debris removal is essential in parallel, and it is said that 5 large space debris removal actions per year and 150 removals in all can maintain the present level of space debris.

There is a great deal of anthropogenically derived space debris especially at an orbital altitude of less than 2000 km, primarily between 800 and 900 km [2]. The first-ever incident involving space debris, the collision between IRIDIUM33 and COSMOS2251 in 2009, and the debris derived from 1 ton of their total mass was scattered in orbit. At that time, IRIDIUM33 was capable of its own orbit transfer, but it was not instructed to control its orbit, while COSMOS2251 malfunctioned because it was estimated that the minimum distance between them should have been 584 m. This incident indicated that the collision forecast and control operations of satellites are practically very difficult.

We are still unable to forecast the collision between on-orbit objects with a prevision of a couple of days before; as a result, we should launch debris-removal satellites into orbit and focus their operation in the cases in which the probability of collision is very high. Such active debris removal by a constellation or a cooperation among a variety of debris removal satellites involves the following steps, as shown in Fig. 1: we keep a set of debris removal satellites with the capability of orbital transfer by using a propulsion system or tether systems in orbit, and we then assign one of these debris removal satellites to rendezvous with a piece of space debris that is forecasted to collide with another object, reducing the probability of collision in orbit. This system is called Zero-Debris Space Construction in Low Earth Orbit. Note that a given set of debris removal satellites should always keep at a specified distribution in a waiting orbit, and that an end-of-life removal satellite should be replaced by a substitute removal satellite. With this concept, we count the removal satellites as a single satellite even if we substitute an end-of-life removal satellite for another, as long as they allocate the same or similar position in the distribution.

The authors have even analyzed an example of a constellation of debris removal satellites, and indicated that 8 satellites in a constellation at the orbital altitude of 1000 km, as shown in Fig. 2, having a comparatively inexpensive propulsion with a specific impulse of 120 s and propellant of 20% of their weight can reach any debris of a comparable weight with the satellites lying in the same plain at the orbital altitude of 500–1500 km within 10,800 s, for example [3]. Such an analysis can quantitatively estimate how many satellites are required and where they should be positioned.

Supposing that a debris removal satellite was engaged in rendezvousing repeatedly to its reachable space debris as represented in Fig. 1, in this paper, we analyzed an example of a three-dimensional constellation of debris removal satellites, and we evaluated an effective constellation by delta-V analysis, which discussed the feasibility of rendezvous of the satellites to space debris using Lambert's equation.

2. Orbital transfer problem between two points

To analyze a constellation of debris removal satellites, it is necessary to confirm the feasibility and practicality of rendezvous of the removal satellites to space debris, which is the orbital transfer problem between two points with two impulses, as shown in Fig. 3.

The orbital transfer problem involves the following equations:

$$c = |\mathbf{r_2} - \mathbf{r_1}| \tag{1}$$

$$s = \frac{c + r_1 + r_2}{2} \tag{2}$$

$$a \geq a_m = \frac{s}{2} \tag{3}$$

$$\theta = \cos^{-1} \frac{\mathbf{r_1} \cdot \mathbf{r_2}}{r_1 r_2} \tag{4}$$

where the indices 1 and 2 represent the positions of the first impulse injection (the initial point of a satellite in its