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# The Collision Avoidance Strategy for Geostationary Satellites Considering Orbit Maintenance

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**Abstract**

This study aims to develop an effective strategy for geostationary satellites to avoid collisions with space debris satisfying various operational constraints. Recently, the number of space objects is continuously increasing to threaten operational satellites in the geostationary region. Studies on collision avoidance have been advanced for a long time, but not sufficiently considered orbit maintenance after maneuvering. Not to shorten satellite lifetime by collision avoidance, it is necessary to consider orbit maintenance after maneuvering. Besides, orbit maintenance regularly conducted differs between chemical thruster and electric thruster, so that two different avoidance strategies may be required. This study adopts a Multi-objective Genetic Algorithm to find out an optimal strategy for each thruster under various constraints on the operation. This paper also demonstrates that the optimal collision avoidance maneuvering can achieve both collision avoidance and orbit maintenance with less fuel than regular orbit control.

## 1 Introduction

Recently, the continuous growth of space objects is increasing the collision risk among them. The objects colliding with satellites can demolish their functions or themselves. To avoid colliding objects whose size is greater than 10 cm are always tracked by some institutions such as Combined Space Operations Center (CSpOC).

Researches about collision avoidance maneuvers (CAMs) for satellites have been driven by many scientists for a long time. Bombardelli dealt with the problem of impulsive collision avoidance between two colliding objects in three dimensions assuming elliptical Keplerian orbits [1]. Kim et al. minimized the fuel consumption of CAMs against multi approaching objects within a short period by Genetic algorithm [2]. Lee et al. simulated collision avoidance with an approaching object by East-West (E/W) control maneuver and North-South (N/S) control maneuver keeping a geostationary satellite in a station-keeping slot [3].

They, however, do not sufficiently consider orbit maintenance after collision avoidance for geostationary satellites. According to International Telecommunication Union's rule, they have to be controlled in each allocated station-keeping slot whose size is 0.1 degrees in longitude and latitude direction. The orbits of space objects are influenced and moved by some perturbations such as deviation of Earth's potential, however. Therefore, geostationary satellites execute the E/W control maneuver and the N/S control maneuver to cancel the effects of the perturbations. The E/W control modifies the satellite's longitude and the N/S control amends the satellite's latitude.

In terms of orbit maintenance, it is not desirable for a geostationary satellite to get out of the station-keeping slot just after avoidance even if avoiding ends to succeed with less fuel. It is because another maneuver is promptly needed to keep a satellite in the station-keeping slot and it accelerates fuel consumption rapidly. The lifetime of satellites is equivalent to the amount of fuel. So, not to shorten the operational lifetime of satellites, it is required to decrease fuel consumption at each collision avoidance. Thus, it is important to consider orbit maintenance also after collision avoidance to develop a collision avoidance strategy for geostationary satellites that minimize fuel consumption. Besides, two types of strategies are needed because regular orbit control depends on the propulsion system, chemical propulsion, and electric propulsion. Moreover, those strategies have to take operational constraints, such as velocity increment and collision probability threshold, into account for actual satellite operation.

Therefore, the objective of this paper is to develop an effective CAM method for geostationary satellites to avoid collisions with space debris considering various operational constraints. Actually, the collision risk in geostationary orbit is extremely low nowadays. D. L. Oltrogge et al. say that a collision is likely to occur every 4 years for the entire geostationary active satellite population against a 1 cm space object catalogue, and every 50 years against a 20 cm space object catalogue[4]. Besides, The collision in geostationary region is not catastrophic because relative velocity is low(<1 km/s). However, as said, the number of space objects is increasing, so a new collision avoidance method is needed to consider both avoiding and orbit maintenance for the safety geostationary satellites operating in the future. Section 2 describes the collision avoidance strategy for a chemical thruster and ~~section~~ Section 3 illustrates the one for an electric thruster. Those two strategies are verified by numerical simulations in ~~section~~ Section 4.

## 2 Collision avoidance strategy for chemical thruster

### 2.1 Regular orbit maintenance strategy for chemical thruster in Geostationary Orbit

The chemical propulsion thruster equipped on many satellites for a long time. It thrusts high temperature and pressure gas by burning chemical fuel. This system can change the satellite's orbit during a very short period because of its strong thrust. A geostationary satellite with this propulsion conducts an E/W control maneuver each about two weeks and an N/S control maneuver about once a month.

Figure 2.1 shows orbit control to cancel perturbations in E/W direction that geostationary satellites regularly conduct where $\lambda$ is longitude, $\lambda_0$ is spacecraft nominal longitude, and $\Delta\lambda$ is 0.05 deg, error tolerance of longitude. At first, a satellite drifts from point A to point B and finally reaches point C due to perturbations. When the satellite moves from point A to point B, the longitude drift rate is $\dot{\lambda} > 0$ and from point B to point C, $\dot{\lambda} < 0$. At point C, the satellite conducts an E/W control maneuver and change $\dot{\lambda}$ to positive, then the satellite tracks the black line again.

Figure 2.2 illustrates an example of the regular N/S control strategy for geostationary satellites where $\Omega$ is the right ascension of the ascending node and $i$ is inclination. When a satellite drifts from point A to point B, an N/S control maneuver is conducted at point B where the inclination change rate is $\mathrm{d}i/\mathrm{dt} > 0$. Then the ascending node is transferred to the descending node and $\mathrm{d}i/\mathrm{dt}$ is changed to negative. After the maneuver, a satellite follows the black line from point C to point D.

Considering orbit maintenance and fuel consumption, it is desired to implement an E/W maneuver at point C in Figure **2.1** and an N/S maneuver at point B in Figure **2.2**, the board of a station-keeping slot. However, CAM could be needed before these timings when other space objects approach a satellite. In that case, the satellite orbit is possibly changed to an undesired shape by CAM. Figure 2.3 and Figure 2.4 indicate examples of undesired maneuvers in terms of orbit maintenance which are conducted until the next orbit maintenance maneuver (OMM). In Figure 2.3, CAM No.1 drawn by the red line makes a satellite go over the board of a station-keeping slot and CAM No.2 makes a satellite go back to west longitude tolerance earlier. Thus, a satellite should not implement maneuvers when $\dot{\lambda} > 0$. On the other hand, in Figure 2.4, CAM No.1 decreases satellite's inclination while $\mathrm{d}i/\mathrm{dt} < 0$

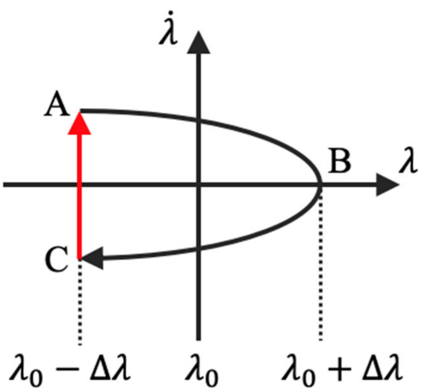

Figure 2.1 Regular E/W control strategy

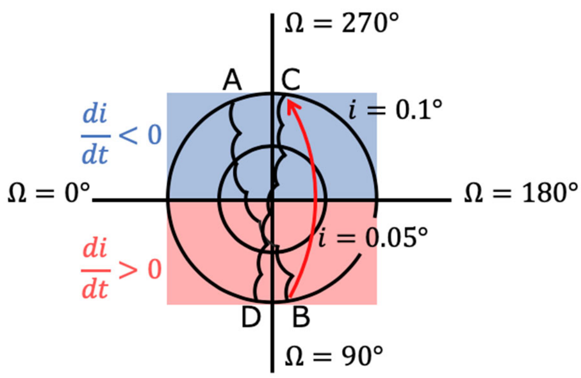

Figure 2.2 Regular N/S control strategy

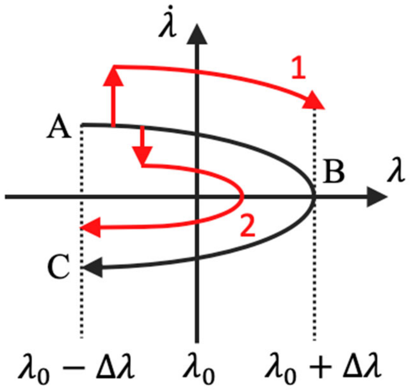


Figure 2.3 Undesired E/W control maneuver

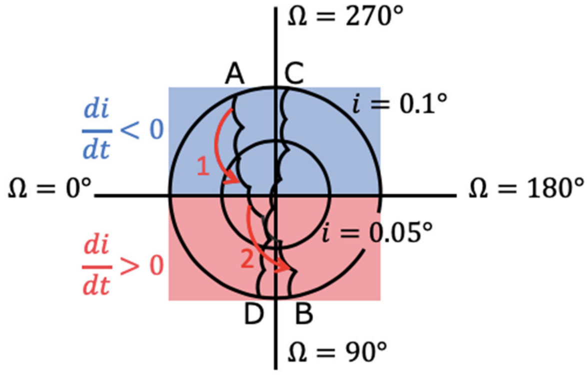


Figure 2.4 Undisired N/S control maneuver

and CAM No.2 increases satellite's inclination while $di/dt > 0$. These maneuvers are inadequate in terms of orbit maintenance because they make the period until the next N/S control maneuver shorter. Therefore, maneuvers should be conducted to increase inclination when $di/dt < 0$ or decrease when $di/dt > 0$. In this paper, these points are considered to optimize CAM. The detail is introduced in the ~~below~~ following sections.

### 2.2 Critical points in CAM optimization for chemical thruster

The following four points are important to optimize CAM for geostationary satellites with a chemical propulsion system, considering the regular orbit maintenance strategy introduced in the previous section.

Point 1: Maneuver simultaneously achieves collision avoidance and orbit maintenance

As described in 2.1, geostationary satellites equipped with chemical propulsion thruster have to execute E/W control and N/S control with a constant interval. Thus, it is more effective to avoid approaching objects and modify the orbit by one maneuver because it can save fuel. In other words, a satellite avoids dangerous objects by E/W control maneuvers or N/S control maneuvers. Some geostationary satellites do not conduct N/S control maneuvers to save fuel because the fuel consumption in an N/S control maneuver is much larger than an E/W control maneuver. However, in this study, a satellite executes both E/W control maneuver and N/S control maneuver, and they are verified in numerical simulations.

Point 2: A satellite avoids as many approaching objects as possible at a single avoidance maneuver

The reason is almost the same as point 1; if a satellite separately implements CAM against each approaching object, it rapidly accelerates fuel consumption. Besides, the avoidance aims to make maximum collision probability against approaching objects less than the threshold. This study assumes it to be $1.0 \times 10^{-6}$. This value is from actual geostationary satellite operations.

Point 3: CAM optimization aims to minimize total fuel consumption at CAM and next OMM

Figure 2.5 shows the reason why considering the next OMM is needed. If CAM is conducted at point D to avoid approaching objects, the next OMM will be executed at point F. In that case, the total velocity increments of the first CAM and the next OMM is less than the sum of two regular OMMs. Thus, the magnitude of the next OMM depends on the magnitude of the first CAM.

Point 4: CAM optimization also aims to maximize the station-keeping period

This is because a longer station-keeping period can decrease the number of OMM.

These four points are considered in CAM optimization. However, the period from point E to point F is shorter than the period from point A to point C in Figure 2.5. Considering point 3, there is a trade-

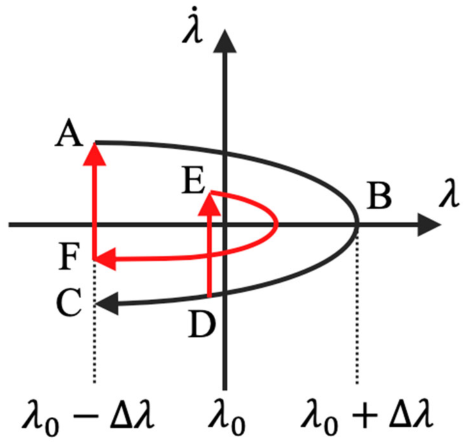

Figure 2.5 An example of CAM and next OMM

off relationship between velocity increment and station-keeping period. Therefore, it is needed to deal with a multi-objective optimization problem to find optimal CAMs. This study uses a Multi-Objective Genetic Algorithm (MOGA) to solve it.

### 2.3 CAM optimization for chemical thruster by MOGA

In this study, CAM optimization is implemented by NSGA-II which is one of MOGA [5]. The reason why it was chosen is that it can maintain a better spread of solutions and converge better than other Multi-Objective Evolutionary Algorithms (MOEAs), and it has been successfully applied to many multi-objective optimization problems [6].

Genes are maneuver time and magnitude in the tangential direction and normal direction on orbit. As described in 2.1, maneuver by chemical thruster is assumed to be impulsive in the optimization. The number of genes depends on how to avoid approaching objects. For example, the avoidance is done by a single N/S control maneuver, the number of genes is three: the maneuver time $t_{\mathrm{man}}$, the tangential velocity increment $\Delta v_{\mathrm{T}}$, and the normal velocity increment $\Delta v_{\mathrm{W}}$. Geostationary satellites have a slight inclination, and tangential and normal velocity increments are needed to control them in N/S direction.

There are some constraints in the optimization. Firstly, the maneuver time must be before the closest approach (CA). Secondly, the magnitude of maneuver is less than the one of the regular OMM, 0.08 m/s against an E/W control and 3.4 m/s against an N/S control because 1.9 m/s is required for annual E/W control and from 41 to 51 m/s is needed for annual N/S control [7][8]. Thirdly, a threshold of maximum collision probability $P_{\max}$ against approaching objects is less than $1.0 \times 10^{-6}$. It is calculated by Alfano-Negron Close Approach Software (ANCAS) and Chan's method [9][10]. Finally, station-keeping period $T$ is more than 14 days in case of avoidance by E/W control or 30 days in case of avoidance by N/S control. In conclusion,

(1) $2 < t_{\mathrm{man}} < \text{Closest approach time } t_{\mathrm{CA}}$
(2) $|\Delta v_{\mathrm{T}}| \leq 0.08 \text{ [m/s]}$
(3) $|\Delta v_{\mathrm{W}}| \leq 3.4 \text{[m/s]}$
(4) $P_{\max} < 1.0 \times 10^{-6}$
(5) $T > 14 \text{ or } 30 \text{ [days]}$

Objective functions in this optimization are equations 2-1 and this optimization aims to minimize them. $\Delta \boldsymbol{v}_{\mathrm{total}}$ is the total velocity increment at CAMs. These functions do not depend on the number of approaching objects. Thus, this optimization can cope with various avoidance situations.

$$f_1 = 1/T$$
$$f_2 = |\Delta \boldsymbol{v}_{\mathrm{total}}| \qquad (2-1)$$

There are two types of population: an archive population and an explored population. The former is a population to take over and preserve the previous population. The latter is created by copying the archive population and it is for exploring new solutions by operating their genes. The number of its individuals is equal to the archive population. the crossover method is Simulated Binary Crossover (SBX) [11] and the mutation method is Power Mutation (PM) [12]. In these operations, genes are operated not to break the above constraints. the method to select the best solution in the final population is the following steps. At first, the individuals which satisfy all constraints are picked up. Then, the one that is closest to the origin on the plane of the objective function is determined as the best individual.

Figure 2.6 shows the sequence to optimize CAM. First of all, genes are created at random and they are assigned to each individual. Those individuals compose the initial population. Second of all, the archived population and explored population is created. Third of all, ANCAS is adapted to each individual with genes, and fitness functions are calculated based on the result of ANCAS. Forth of all, non-dominated sorting and crowded sort are implemented to evaluate individuals. After that, if the iteration number reaches the final population, optimization is finished and the genes with the best individual are determined as an optimal solution. If not, crowded tournament selection is conducted to create a newly explored population and gene operation adapts to the population. Then, the calculation goes back to the second step.

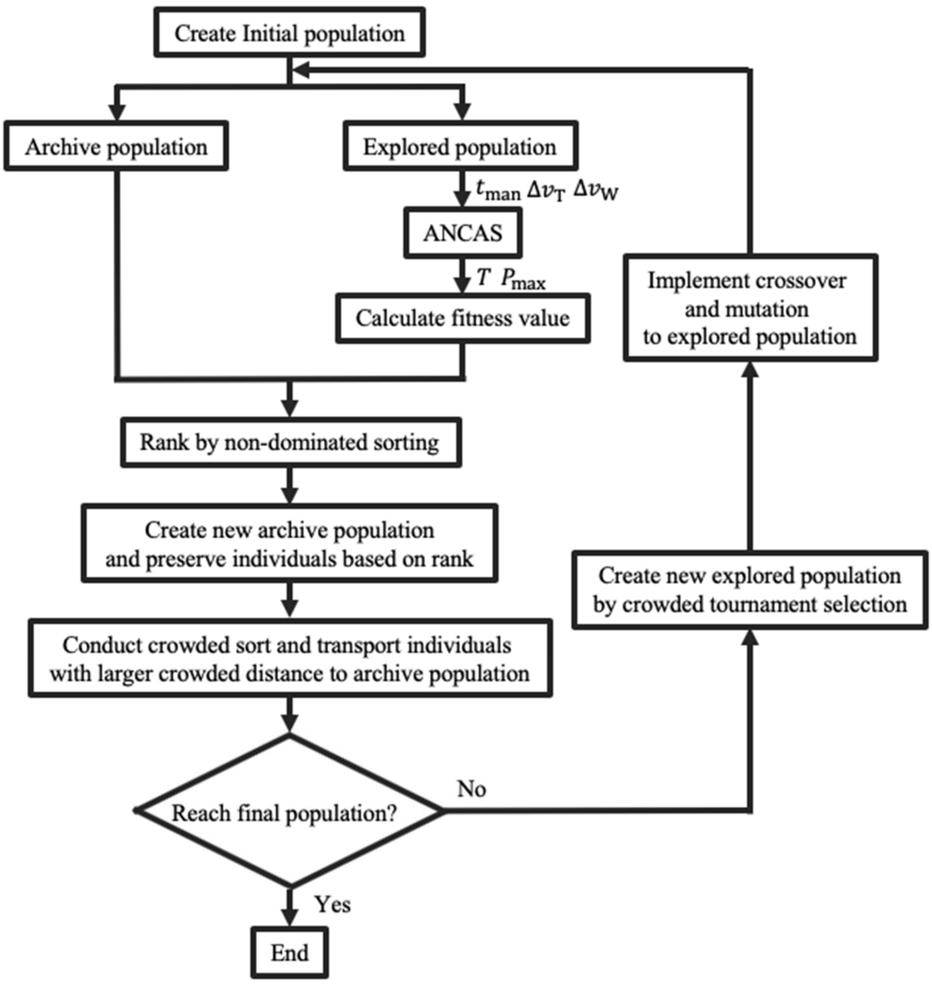


Figure 2.6 Optimization algorithm

## 2.4 Collision avoidance strategy for chemical thruster

A satellite can implement CAMs once 14 days or 30 days under the constraint that OMM has to achieve collision avoidance simultaneously. Thus, a satellite has to avoid potential approaching objects no matter how imprecise the collision prediction is. These days, collisions between tracked space objects in geostationary orbit (GEO) can be predicted about two weeks before. After collision alert, few days are required to judge whether CAM is truly needed or not. So, a satellite should avoid dangerous objects based on a few days before analysis. Considering them, the collision avoidance strategy is proposed as the following steps, as shown in Fig. 2.7.

Step 1: Receiving collision alert

After receiving an alert, few days is needed for satellite operators to judge that CAM is truly needed or not by observation and analysis. If CAM is really required, go to the next step.

Step 2: Planning avoidance based on the number of approaching objects

Two avoidance patterns, 1-to-1 avoidance or 1-to-multi avoidance, could be considered here. The optimization method explained in 2.3 is used in this step. When multiple objects approach a satellite, 1-to-multi avoidance is planned and executed. Only in the case of 1-to-1 avoidance, go to the next step.

Step 3: Confirming whether an optimal maneuver is adequate or not

It is undesired for a satellite to approach other space objects surrounding it by optimized CAMs. Thus, safety confirmation is needed before implementing optimized CAMs by analyzing the drift rate of other objects. Drift rate $\dot{\lambda}$ is calculated by equation 2-2 and 2-3 [13] where $a_{\mathrm{sat}}$ is the satellite's semi-major axis and $\Delta a$ is the difference between $a_{\mathrm{sat}}$ and nominal semi-major axis on GEO.

$$\dot{\lambda}\ [^\circ/\mathrm{day}] \approx -0.0128\Delta a\ \ [^\circ/\mathrm{day}] \qquad (2-2)$$

$$\Delta a = a_{\mathrm{sat}} - 42164\ \ [\mathrm{km}] \qquad (2-3)$$

If $\dot{\lambda}$ of other objects reaches almost the same longitude as a satellite during station-keeping, the optimized maneuver is inadequate, and re-planning as 1-to-multi avoidance including the other objects is required.

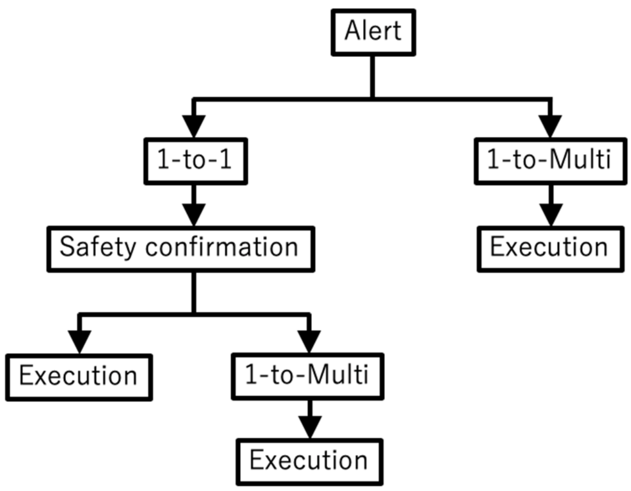


Figure 2.7 Collision avoidance strategy

## 3 Collision avoidance strategy for electric thruster

### 3.1 Regular orbit maintenance strategy for electric thruster in GEO

The electric propulsion system for satellites has been developed since the 1960s [14]. There are some species of that, for example, ion thruster, and all of them have low thrust, higher specific impulse (from 500 to 10000 sec), low acceleration, and faster fuel thrust velocity than chemical propulsion system [15][16]. So, electric propulsion can save fuel than chemical propulsion. Over 200 geostationary satellites have this propulsion system these days.

A satellite with electric propulsion cannot instantly change its orbit because of its low thrust. Then, geostationary satellites equipped with electric propulsion conduct orbit control as routine work by maneuvering almost every day. Here is an example of an orbit maintenance strategy at Space Systems/Loral [17].

Dairy strategy

A satellite implements N/S control maneuver twice a day at ascending node and descending node. Each maneuver duration is from 45 min to 50 min. E/W control maneuver is conducted if it is needed after N/S control. The maneuver plan is uploaded to an onboard computer each week.

Weekly strategy

A satellite executes maneuver about five days a week. N/S control is also implemented twice every day at ascending node and descending node. Each maneuver time is from 65 to 70 min. A satellite controls its longitude at an interval of N/S control. The maneuver plan is updated at the end of the week.

### 3.2 Critical points in CAM optimization for electric thruster

The four points in 2.2 are also important in this section to optimize CAM. Besides, the other six points are added here.

Point 5: Thrust is from 0.08 N to 0.2 N

This assumption derives from the general specification of electric propulsion thruster for geostationary satellites.

Point 6: A satellite cannot change the magnitude of thrust during a maneuver

This is because it could occur electric efficiency at the satellite system to decrease. So, a satellite can only on-off control at stable thrust, and maneuver is dealt with as rectangle input in simulation.

Point 7: The interval of maneuver at a thruster is more than 12 hours

Continuous thrust with quite short intervals gives the thruster a big burden.

Point 8: Maneuvers are planned once a week

This is according to 3.1. Then, including point 7, the second maneuver start time $t_{\mathrm{start}_2}$ is $0.5 < t_{\mathrm{start}_2} < 6.5$ because the maximum number of maneuvers before CA is two in this study.

Point 9: Timing of N/S control maneuver does not depend on satellite's node

A satellite can implement N/S control maneuvers, whenever. It drives from the results in the simulation for chemical propulsion in 4.2.

Point 10: Collision avoidance is achieved by only N/S control maneuver

This point aims to cancel the effect of perturbations by fewer maneuvers. According to [18], the drift of geostationary objects can be represented in equation 3-1. $E_6$ is longitude drift rate, $E_1$ is the difference between satellite's mean motion and Earth's angular velocity, $\eta = \sqrt{1-e^2}$, $\nu$ is true anomaly, $n$ is mean motion, $r$ is orbit radius, $p = a(1-e^2)$, $u_{\mathrm{r}}$, $u_{\mathrm{t}}$, $u_{\mathrm{n}}$ are perturbation acceleration in radius, tangential, normal direction, respectively. This equation shows that satellite drift motion drives from perturbation acceleration in three directions. So, to cancel them by fewer maneuvers, velocity increment in as many directions as is needed. Maneuver generally increases tangential and normal velocity, so N/S control maneuver is adequate in this case.

$$\frac{\mathrm{d}E_6}{\mathrm{d}t} = E_1 - \left(\frac{e\eta\cos\nu}{(1+\eta)na}\right)u_\mathrm{r} + \frac{e\eta\left(1+\frac{r}{p}\right)\sin\nu}{(1+\eta)na}u_\mathrm{t} - \frac{r\tan\left(\frac{i}{2}\right)\sin(\omega+\nu)}{na^2}\left(1 + \frac{e}{(1+\eta)\eta}\right)u_\mathrm{n} \qquad (3-1)$$

### 3.3 CAM optimization for electric thruster by MOGA

The CAM optimization algorithm is almost the same as 2.3. Only different points follow below. Genes are maneuver start time $t_{\mathrm{start}}$, maneuver duration $t_{\mathrm{end}}$, tangential maneuver thrust $\Delta F_\mathrm{T}$ and normal maneuver thrust $\Delta F_\mathrm{W}$ . In the simulation, $\Delta F_\mathrm{T}$ and $\Delta F_\mathrm{W}$ are changed to acceleration in the tangential and normal direction, $\Delta a_\mathrm{T}$ and $\Delta a_\mathrm{W}$ by equation 3-2. Then, these accelerations are added to Cowell's ~~equation~~ formulation~~shown~~ _ ~~below~~ in equation 3-3 [9]. $m_{\mathrm{sat}}$ is assumed to be 3000 kg. $x$, $y$, $z$ are satellite's position and $\dot{x}$, $\dot{y}$, $\dot{z}$ are satellite's velocity, $\mu$ is Earth's gravitational constant, $F_\mathrm{r}$, $F_\mathrm{s}$, $F_\mathrm{w}$ are perturbation acceleration.

$$\Delta a_\mathrm{T} = \frac{\Delta F_\mathrm{T}}{m_{\mathrm{sat}}} \qquad \Delta a_\mathrm{W} = \frac{\Delta F_\mathrm{W}}{m_{\mathrm{sat}}} \qquad (3-2)$$

$$\frac{d}{dt}\begin{Bmatrix} x \\ y \\ z \\ \dot{x} \\ \dot{y} \\ \dot{z} \end{Bmatrix} = \begin{Bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \\ -\mu\frac{x}{r^3} + F_\mathrm{r} \\ -\mu\frac{y}{r^3} + F_\mathrm{s} + \Delta a_\mathrm{T} \\ -\mu\frac{z}{r^3} + F_\mathrm{w} + \Delta a_\mathrm{W} \end{Bmatrix} \qquad (3-3)$$

The first and fourth constraints are the same as 2.3. Updated ones are the following.

(2)′ $0.08\ [\mathrm{N}] < \Delta F_\mathrm{T} < 0.2\ [\mathrm{N}]$

(3)′ $0.08\ [\mathrm{N}] < \Delta F_\mathrm{W} < 0.2\ [\mathrm{N}]$

(5)′ $T > 8$ days

(6) In the case that second CAM is conducted before CA, $0.5 < t_{\mathrm{start}_2} < 6.5$.

(7) Required thrust per day at regular orbit control $\Delta F_{\mathrm{routine}} >$ total maneuver thrust per day

Constraint (7) is also represented by equation 3-4.

$$\Delta F_{\mathrm{routine}} = \frac{0.08[N] \times \frac{1}{24}[\mathrm{day}] \times (2 \times T)}{T[\mathrm{day}]} > \frac{\Delta F_{\mathrm{man}}[N] \times t_{\mathrm{end}}[\mathrm{day}]}{T[\mathrm{day}]} \qquad (3-4)$$

The second fitness function is only updated as equation 3-5.

$$f_2 = t_{\mathrm{end}}\sqrt{\Delta F_{\mathrm{T}}^{2} + \Delta F_{\mathrm{W}}^{2}} \qquad (3-5)$$

### 3.4 Collision avoidance strategy for electric thruster

A satellite with electric propulsion thruster changes its orbit every day. It means that long-term collision prediction does not work differently from a satellite equipped with a chemical propulsion system. Therefore, it is not needed to avoid not invading objects to satellite's station-keeping slot. Considering that, the collision avoidance strategy for geostationary satellites with electric propulsion thruster is ~~below~~shown in Fig. 3.1.

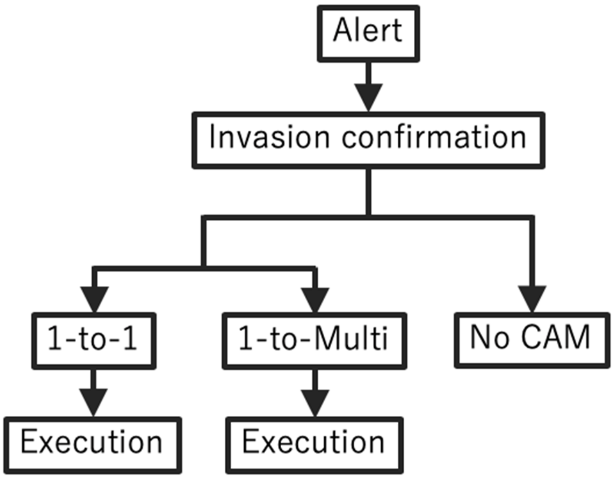


Figure 3.1 Collision avoidance strategy

Step 1: Receiving collision alert

Step 2: Confirming whether approaching objects go through the station-keeping slot or not

Their drift rate can help this analysis. If they penetrate the station-keeping slot, collision avoidance planning is started. If not, CAM is not implemented.

Step 3: Planning maneuver

The plan aims to avoid all invading objects.

## 4 Numerical simulation

### 4.1 Simulation conditions for chemical propulsion maneuver

The parameters in the collision probability calculation are shown in Table 4.1. The value of error ellipse radius derives from the position error (<1 km) of orbit determination by using two-line elements [19]. Collision probability is calculated in two dimensions here. If it is calculated in three dimensions, the error of velocity becomes smaller. Thus, collision analysis is quite strict in this simulation.

Table 4.1 Parameters in the collision probability calculation

| | |
|---|---|
| Satellite radius [km] | 0.0073 |
| Error ellipse radius [km] | 1.0 |

A satellite and approaching objects are created in this study. Their orbit elements and predicted CA before avoidance in each simulation are Table 4.2. Moreover, the number of maneuvers before predicted CA has two patterns in each avoidance, once or twice.

1-to-1 avoidance simulation

In Table 4.2, $a$ is semi-major axis, $e$ is eccentricity, $\omega$ is argument of perigee, $M$ is mean anomaly and $N_{\mathrm{man}}$ is the number of maneuvers before predicted CA. In Table **4.3**, $P_{\mathrm{max}}$ is not 1, though the closest distance is smaller than a satellite radius. It is because the closest distance is calculated with the error of space objects position.

Table 4.2 Orbit elements of a satellite and approaching object (1-to-1)

| | Satellite | Object 1 |
|---|---|---|
| Epoch [UTC] | 2018 11/20 08:21:45 | |
| $a$ [km] | 42164.2 | 42164.5 |
| $e$ | 0.00024 | 0.00023 |
| $i$ [deg] | 0.0392 | 0.0392 |
| $\Omega$ [deg] | 354.2 | 354.2 |
| $\omega$ [deg] | 199.8 | 200.6 |
| $M$ [deg] | 125.6 | 124.9 |
| $\lambda_0$ [deg] | 134.95 | - |

Table 4.3 Predicted CA before avoidance (1-to-1)

| | |
|---|---|
| Epoch [UTC] | 2018 11/27 10:26:15 |
| Closest distance [km] | 0.005 |
| $P_{\mathrm{max}}$ | $2.6 \times 10^{-5}$ |

Table 4.4 Parameters of MOGA (1-to-1)

| | by E/W control | | by N/S control | |
|---|---|---|---|---|
| $N_{\mathrm{man}}$ | 1 | 2 | 1 | 2 |
| Individual | 100 | 100 | 100 | 100 |
| Population | 200 | 500 | 1000 | 200 |
| Crossover possibility | 1.0 | 1.0 | 1.0 | 1.0 |
| Mutation possibility | 1.0 | 1.0 | 1.0 | 1.0 |

1-to-2 avoidance simulation

In this simulation, 1-to-multi avoidance is assumed to be 1-to-2 avoidance as a first step. There are two patterns in 1-to-2 avoidance simulation. The one is conducted after safety confirmation following 1-to-1 avoidance planning. The other is implemented just after receiving an alert. In this study, the first case is called pattern 1 and the other case is called pattern 2. In both patterns, the satellite and first approaching objects are the same as 1-to-1 avoidance simulation.

Table 4.5 Second approaching objects (1-to-2, pattern 1)

| | by E/W control | by N/S control |
|---|---|---|
| Epoch [UTC] | 2018 11/20 08:21:45 | |
| $a$ [km] | 42163.0 | 42162.2 |
| $e$ | 0.00027 | 0.00027 |
| $i$ [deg] | 0.0392 | 0.0392 |
| $\Omega$ [deg] | 354.3 | 354.2 |
| $\omega$ [deg] | 202.6 | 195.4 |
| $M$ [deg] | 122.7 | 129.9 |

Table 4.6 Second approaching object (1-to-2, pattern 2)

| | |
|---|---|
| Epoch [UTC] | 2018 11/20 08:21:45 |
| $a$ [km] | 42164.4 |
| $e$ | 0.00024 |
| $i$ [deg] | 0.0392 |
| $\Omega$ [deg] | 354.2 |

| | |
|---|---|
| $\omega$ [deg] | 200.1 |
| $M$ [deg] | 125.3 |

Table 4.7 Predicted CA before avoidance (1-to-2, pattern 1)

| | by E/W control | by N/S control |
|---|---|---|
| Epoch [UTC] | 2018 12/4 2:36:21 | 2018 12/10 11:17:41 |
| Closest distance [km] | 0.048 | 0.25 |
| $P_{\max}$ | $2.6 \times 10^{-5}$ | $2.6 \times 10^{-5}$ |

Table 4.8 Predicted CA before avoidance (1-to-2, pattern 2)

| | |
|---|---|
| Epoch [UTC] | 2018 11/28 17:06:32 |
| Closest distance [km] | 0.17 |
| $P_{\max}$ | $2.6 \times 10^{-5}$ |

Table 4.9 Parameters of MOGA (1-to-2)

| | by E/W control | | by N/S control | |
|---|---|---|---|---|
| $N_{\text{man}}$ | 1 | 2 | 1 | 2 |
| Individual | 100 | 100 | 100 | 100 |
| Population | 200 | 200 | 200 | 200 |
| Crossover possibility | 1.0 | 1.0 | 1.0 | 1.0 |
| Mutation possibility | 1.0 | 1.0 | 1.0 | 1.0 |

## 4.2 Simulation results for chemical propulsion maneuver

Figure 4.1 shows the results of avoidance by E/W control maneuver and Figure 4.2 indicates the results of avoidance by N/S control maneuver. Red bars mean optimized velocity increment per day during station-keeping and blue bars mean succeeded station-keeping period. Each figure has better results in terms of the number of maneuvers in each simulation, 1-to-1, pattern 1 of 1-to-2 written as "1-to-2(1)", pattern 2 of 1-to-2 written as "1-to-2(2)", and word in () under simulation cases mean the number of maneuvers before CA. The counterparts of velocity increment and station-keeping period in regular orbit control are at the right side in two graphs as "routine work". As a result, all optimal solutions are not only better than routine work in terms of velocity increment and station-keeping period but also fulfilled all constraints. Table 4.10 shows $P_{\max}$ in each simulation. Some of them seem to be almost the same value as the threshold of $P_{\max}$ $1.0 \times 10^{-6}$. However, as described in 4.1, collision justification is strict in this study, so it is no big issue here. Thus, the collision avoidance strategy developed in this study for a satellite equipped chemical propulsion thruster can simultaneously achieve collision avoidance and orbit control with less fuel than regular orbit maintenance operation.

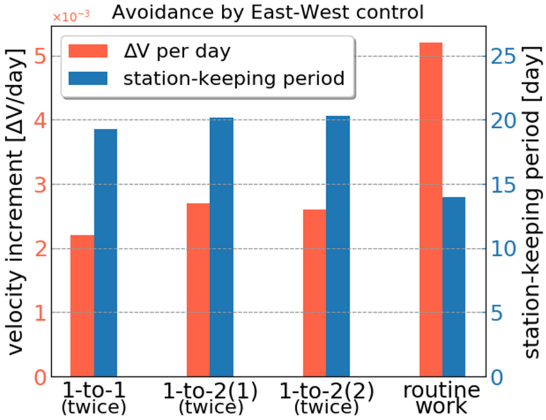

Figure 4.1 Result of avoidance by E/W control

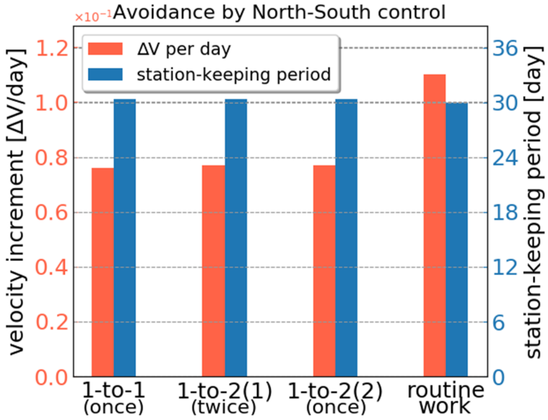

Figure 4.2 Result of avoidance by N/S control

Table 4.10 $\boldsymbol{P_{\max}}$ in each simulation

| | 1-to-1 (E/W, twice) | 1-to-2(1) (E/W, twice) | 1-to-2(2) (E/W, twice) | 1-to-1 (N/S, once) | 1-to-2(1) (N/S, twice) | 1-to-2(2) (N/S, once) |
|---|---|---|---|---|---|---|
| $P_{\max}$ | $9.9 \times 10^{-7}$ | $9.9 \times 10^{-7}$ | $9.9 \times 10^{-7}$ | $6.7 \times 10^{-7}$ | $9.8 \times 10^{-7}$ | $9.9 \times 10^{-7}$ |

### 4.3 Simulation condition for electric propulsion maneuver

A satellite is the same as 4.1. The first approaching object is the same as in Table 4.2 and the second one is the same as in Table 4.6. The parameters of MOGA are ~~below~~specified in Table 4.11.

Table 4.11 Parameters of MOGA

| $N_{\text{man}}$ | 1 | 2 |
|---|---|---|
| Individual | 100 | 100 |
| Population | 200 | 200 |
| Crossover possibility | 1.0 | 1.0 |
| Mutation possibility | 1.0 | 1.0 |

### 4.4 Simulation results for electric propulsion maneuver

Figure 4.3 shows the result of avoidance by electric propulsion and Table 4.12 indicates $P_{\max}$ in each simulation. Red bars in Figure 4.3 mean optimized thrust per day. All results satisfied constraints perfectly. Required thrusts are much less than the counterpart of routine work and succeeded station-keeping periods are longer than one of routine work. Besides, the more maneuvers are conducted before CA, the less fuel is consumed. Therefore, this strategy enables geostationary satellites to fulfill collision avoidance and orbit control with less fuel than regular orbit maintenance.

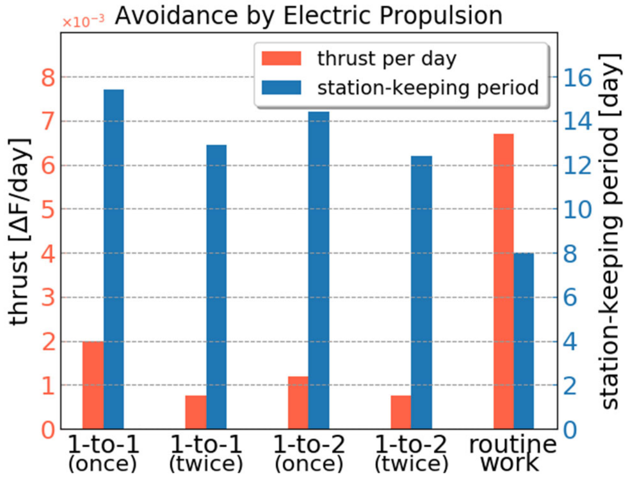

Figure 4.3 Result of avoidance by electric propulsion

Table 4.12 $\boldsymbol{P}_{\mathbf{max}}$ in each simulation

| | 1-to-1 (once) | 1-to-1 (twice) | 1-to-2 (once) | 1-to-2 (twice) |
|---|---|---|---|---|
| $P_{\max}$ | $1.0 \times 10^{-7}$ | $4.2 \times 10^{-7}$ | $2.4 \times 10^{-8}$ | $9.4 \times 10^{-7}$ |

## 5 Conclusion

This study proposed two collision avoidance strategies for two types of geostationary satellites with chemical propulsion or electric propulsion, by considering regular orbit control. These strategies need to minimize fuel consumption and maximize the station-keeping period simultaneously because considering orbit control after collision avoidance is indispensable not to shorten satellite lifetime. These two optimizations have a trade-off relationship between themselves, however. Therefore, MOGA is adopted to optimize CAMs start time, duration, velocity increment, and thrust, satisfying various constraints from the actual operation and the specifications of two types of thrusters. Besides, considering avoidance situations based on the number of dangerous objects achieves to establish appropriate avoidance strategies with optimal CAMs. As verified in simulations, these strategies enable a geostationary satellite to avoid up to two approaching objects keeping itself in a station-keeping slot with less fuel compared to regular orbit control. Therefore, those strategies can help geostationary satellites evacuate from increasing dangerous objects and not shorten their lifetime by excess maneuvers. It must lead to the safety satellite operations in the future.

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