Optimal mission planning of active space debris removal based on genetic algorithm

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Abstract. With the increasing space activities, the space debris has seriously deteriorated the safe performance of the on-orbit spacecraft and has attracted much attentions. To reduce the rising influence of the space debris and improve the safe performance of the space mission, the three-stage removal strategy for space debris is proposed in this paper. Firstly, the multiple spacecrafts including one main spacecraft and some following spacecraft for space debris removal mission is developed. Then, the fuel, time and the quantity of the following spacecraft are defined as the constraints. Moreover, using the minimum fuel consumption as the optimal object, the mathematical model of the debris removal problem is established. Finally, the genetic algorithm is applied to solve this problem. Compared with the prior space debris removal strategy, the proposed three-stage space debris removal can effectively reduce the fuel consumption. Numerical simulation verifies the effectiveness of the proposed space debris removal scheme.

1. Introduction
Due to the human space activities, space debris becomes the major sources of the space pollutions. The space debris contains the scrapped rocket arrow and satellite body, the jet of the rocket, the discards during the execution of the space mission, the fragments generated by the collision between the space objects and so on. Furthermore, because of the launch of the satellite, the amount of space debris has considerable increase. According to the reports from Space Surveillance Net (SSN), more than 18,000 space targets have been catalogued. Moreover, 90% of the space targets are space debris [1] and the large amount of space debris threatens the safety of the spacecraft in orbit.

For example, Iridium 33 satellite collided with the Russian scrap satellite Cosmos 2251 on February 10, 2009, which seriously influenced the American Iridium constellation. In 1991, Kessler proposed the Kessler Syndrome: Collision of space targets caused a large amount of space debris. Subsequently, the resulting space debris may collide with other spacecraft to lead to the mission failure and produce more debris. Therefore, the number of space debris will continue to increase. Furthermore, when space debris grows to the alert values, even that the humans cannot implement any space activities, space collisions will occur and the amount of space debris will still grow [2]. Based on the related research by NASA and ESA, the fragments should be actively removed every year since
2020. Moreover, the number of space debris need to be controlled and the normal space activities should be guaranteed in the future [3].

At present, the most feasible methods for space debris removal are as follows: the space robot arm capture method [4,5], the space rope net capture method [6], the increasing resistance method [7], and the laser cleaning method [8]. Furthermore, some articles focus on mission planning for debris removal. Braun et al. proposed four debris removal mode and analyzed different types of propulsive systems carried by mission spacecraft. Finally, they obtained the optimal task sequence by exhaustive method [9]. Considering the fuel and time constraints, Madakat optimized the mission planning for LEO debris removal [10]. However, these methods only use the two-stage system of spacecraft: mission satellite and space depot. The mission satellite needs to release the debris to the target orbit and transfer to next debris to continue the mission, resulting in greater fuel consumption. To solve this problem, this article proposed a three-stage debris removing method. The main satellite carries several small propulsive satellites. The small satellites push space debris into lower orbit and the main satellite only need to maneuver among the target debris. Through this way, the space mission could reduce the fuel cost. Finally, considering the limitation of the number of propulsive satellites, time and fuel, the genetic algorithm is applied to design the optimal trajectory. Compared with the prior space debris removal sequence, the optimal three-stage space debris removal sequence can effectively reduce the fuel consumption.

2. The three-stage debris removal mission
The three-stage removal strategy for space debris contains multiple spacecrafts including one main spacecraft and some following spacecrafts. The Main spacecraft is mission satellite and the following spacecrafts is propulsive satellites. Space depot can provide replenishment for mission satellite. The mission spacecraft carries several small propulsive satellites, maneuvering between the target debris, approaching the debris, and releasing the propulsive satellite. The propulsive satellite uses electric propulsion, pushing space debris into lower orbit and burning together with space debris. In the three-stage system, small propulsive satellite burns up after removing one debris and do not need to return. In this way, some fuels will be saved.

Considering that orbital maneuvers between different orbital heights and different orbital planes consume a large impulse, this article select the debris on Sun-synchronous orbit (SSO) with similar altitude and inclination. The space debris and mission satellite run on SSO, and the space depot circles on the orbit 100km below the Sun-synchronous orbit. When the propellant or the spacecraft carried is insufficient, it is necessary for mission satellite to return to the space depot for replenishment.

The entire task process is divided into the following steps
1. Mission satellite transfer to target debris.
2. Mission satellite release propulsive satellite.
3. Propulsive satellite push debris to deorbit.
4. Mission satellite transfer to the next target debris.

It is essential to notice that the space depot is heavy and its maneuver will consume huge propellant. Therefore, the space depot does not execute maneuver and the mission satellite will transfer to approach space debris.

3. Maneuver strategy between debris

3.1. Two-impulse optimal rendezvous model
Before building maneuver model, several simplifying hypotheses are made:
1. The orbital elements and mass of debris are known.
2. Ignoring the propellant for attitude control during the entire process.
3. Number of propulsive satellites needed for removing any debris is known.
4. Ignoring the effect of perturbations.
This article adopts two-impulse rendezvous maneuvering model under J2000 coordinate frame. Given the location of the two targets of space and the orbital maneuver time, the transfer orbit between the two targets can be obtained by solving the loopy Lambert problem.

In this paper, the method of solving the loopy Lambert problem proposed by Han Chao is used [11].

Define \( t(z) \) as shown in Eq. (1):

\[
t(z) = \frac{1}{\sqrt{\mu}} \left( x'(z) S(z) + A \sqrt{y(z)} \right)
\]

where \( x(z), S(z), y(z) \) is universal variable \( z \), and \( \mu \) is gravitational constant of earth.

Figure 1 shows the relationship between \( t(z) \) and the variation of the universal variable \( z \).

From figure 1, transfer time \( t \) and the universal variable \( z \) has the relationship of approximate periodicity. When given the transfer time \( \Delta t \), there may be one or more corresponding universal variable \( z \). Calculate the \( \Delta v_1, \Delta v_2 \) corresponding to the universal variable, then the impulse required for the orbital transfer can be calculated by Eq. (2)

\[
\Delta v = \Delta v_1 + \Delta v_2
\]

Take the orbit with the smallest speed impulse as the maneuvering transfer orbit, that is, the loopy Lambert transfer orbit with minimum fuel consumption.

However, this method can only calculate the impulse for a given transfer time. When the given transfer time varies, the impulse will change with it. Therefore, there is a certain time to minimize the velocity impulse, and the maneuver time need to be designed. We optimize this problem with particle swarm optimization algorithm (PSO) and obtain the optimal transfer orbit with the smallest impulse, meeting the time constraint. Through priori calculation, the PSO will converge to better results when iterating 6-7 times. In order to speed up the calculation, in this paper, the number of particle groups is set to 20, and the maximum number of iterations is 10. Each Particle swarm optimization calculation takes 0.025s. So far, the required impulse \( \Delta v_i \) and time \( t_i \) from the i-th debris to the j-th debris can be obtained.

3.2. Mission costs

Let \( I_{sp} \) be specific impulse of the mission satellite. The initial mass is \( M_s \). The mass of the carried propellant and propulsion are \( M_f \) and \( M_p \), respectively. \( num \) represents the number of propulsive satellites. The total number of debris to be cleaned is \( n \), and the number of propulsion spacecraft for
each piece of debris is \( \{num_1, num_2, ..., num_j\} \). \( t_i^j, t_j \) and \( t_j \) are maneuver time from the i-th debris to the j-th debris, clearing time for the j-th debris and refueling time respectively. The maneuver from the i-th debris to the j-th debris can be divided into two cases:

a. maneuver to the next target directly

In this situation, fuel and propulsive satellite are enough. Once maneuver between two targets need twice impulse. \( M_i \) represents the left mass of mission satellite after last task. Let \( \Delta v_i^1, \Delta v_i^2 \) be the first and second impulse respectively, By the Tsiolkovsky formula, we can obtain the fuel consumption by Eqs. (3), (4) and (5).

\[
dM_1^j = M_i (1 - \exp(-\frac{\Delta v_i^1}{I_{sp}g})) \quad (3)
\]

\[
dM_2^j = (M_i - dM_1^j) (1 - \exp(-\frac{\Delta v_i^2}{I_{sp}g})) \quad (4)
\]

\[
dM_i^j = dM_1^j + dM_2^j \quad (5)
\]

where \( dM_1^j, dM_2^j \) are fuel consumption of twice impulse respectively. \( dM_i^j \) is the fuel consumption from i-th to j-th debris.

Propulsive satellite is needed for one-time removing mission. The mass change caused by the consumption of propulsive satellite is \( M_p \times num_j \).

The whole mass decrement of mission satellite is shown in Eq. (6):

\[
\Delta M_i^j = dM_i^j + M_p \times num_j \quad (6)
\]

The time for one debris is got by Eq. (7)

\[
T_j = t_i^j + t_j \quad (7)
\]

where \( t_i^j \) and \( t_j \) are maneuver time from the i-th debris to the j-th debris and clearing time for the j-th debris respectively.

b. maneuver to the space depot for replenishment

In this situation, fuel or propulsive satellite is not enough. According to the orbit model, the optimal transfer orbit can be calculated through PSO, that is, the maneuver impulse to space depot and impulse from depot to the next debris. Record the four maneuver impulses as \( \Delta v_s^1, \Delta v_s^2, \Delta v_s^3, \Delta v_s^4 \) in accordance with the time. When maneuvering to space depot, the mass of mission satellite returns to the original state. \( P \) represents space depot, the fuel consumption can be calculated by Eqs (8) ~ (12).

\[
dM_1 = M_i (1 - \exp(-\frac{\Delta v_s^1}{I_{sp}g})) \quad (8)
\]

\[
dM_2 = (M_i - dM_1) (1 - \exp(-\frac{\Delta v_s^2}{I_{sp}g})) \quad (9)
\]

\[
dM_3 = M_s (1 - \exp(-\frac{\Delta v_s^3}{I_{sp}g})) \quad (10)
\]

\[
dM_4 = (M_s - dM_3) (1 - \exp(-\frac{\Delta v_s^4}{I_{sp}g})) \quad (11)
\]

\[
dM_i^j = dM_1^j + dM_2^j + dM_3^j + dM_4^j \quad (12)
\]

where \( dM_1^j, dM_2^j, dM_3^j, dM_4^j \) are fuel consumption of four impulse respectively. \( dM_i^j \) is the fuel consumption from i-th to j-th debris.

The whole mass decrement of mission satellite is shown in Eq. (13):
\[ \Delta M_j = dM_j + M_p \times \text{num}_j \] (13)

Fuel to be filled at space depot is shown in Eq. (14):
\[ M_s = M_j - M_r \] (14)

where \( M_r \) is the remaining fuel of mission satellite.

The time for one debris is got by Eq. (15)
\[ T_j = t'_r + t_f + t'_r + t_j \] (15)

where \( t_f \) and \( t_j \) are refueling time and clearing time for the j-th debris respectively. \( t'_r \) and \( t'_r \) are transfer time from i-th debris to space depot and from space depot to j-th debris respectively.

4. Optimization model

The number of space debris to be cleaned is \( n \), and they are numbered 1-\( n \) in order. The target of the task is all the \( n \) debris are completely removed. The order of removing the depot can be represented by an array of the \( n \) numbers. For example, \( N = [3,4,1,2] \) means that the 3rd, 4th, 1st, and 2nd debris are cleaned in order. All the possible paths are the full arrangement of the \( n \) numbers. The optimal array or the optimal path can be found after calculating the fuel consumption in each arrangement. Set the initial position of the mission satellite the same as the first debris.

4.1. Calculation process

When a sequence of \( N \), that is, the order of debris removal is given, from the first debris, the mission spacecraft execute the orbital maneuver in sequence to remove debris. After removing the first debris, the fuel consumption and propulsive spacecraft consumed by orbital maneuvers and debris removal can be obtained according to the maneuver strategy. When the next target is to be removed, a judgment is needed: if the mission satellite carries insufficient propulsive satellites or the remaining fuel is insufficient to transfer to the next target, it will maneuver to the space depot for replenishment. The maneuver impulse and time consumption for the mission satellite transfer from debris to debris or space depot can be determined by the orbital model. Through such process, the fuel and time consumption for the given mission sequence can be obtained.

The calculation process can be summarized as the following steps:

- **Step1**: Remove the first debris.
- **Step2**: Judge whether fuel or propulsive satellite is enough.
- **Step3**: If the condition of step 2 is met, remove the next space debris.
- **Step4**: If the condition of step 2 is not met, maneuver to space depot for replenishment and remove the next space debris.

In all the steps, the particle swarm optimization algorithm is needed to find the optimal transfer orbit.

4.2. Constrains

In this problem of mission planning, some constrains need to be satisfied.

Let \( t_{\text{max}} \) be the maximum transfer time for each piece of debris. Therefore, the transfer time need to satisfy \( t' \leq t_{\text{max}} \). Total mission time need not to be limited as each process of the task is constrained.

Let \( M_r \) be the remaining fuel in mission satellite. The constraint of propulsion in fuel consumption is less than surplus fuel, that is \( dM_j \leq M_r \). The third constraint is the limit of propulsive satellite. Mission satellite must carry enough propulsive satellites to remove debris, that is \( \text{num}_j \leq \text{num} \cdot \text{num} \) represents the remaining amount of propulsive satellite.

Take fitness function \( \phi(N) \) as the whole fuel consumption and the target of optimization is to find \( N \) with minimum fitness function. The optimization model of space debris removal is shown as Eq.(16):
5. Genetic algorithm design

It can be analyzed that the problem to be solved in this paper is a TSP problem in fact. When there are more debris to be removed, the problem of “combination explosion” will occur, which greatly increases the amount of calculation. In the method of solving the TSP problem, the genetic algorithm has great advantages in solving this problem. This paper uses genetic algorithm to solve this problem.

Step1. Code

In this paper, positive integer coding is used. The chromosomal gene represents the order of debris removal. For example, there are 7 debris to be removed, then the chromosomes [6, 5, 7, 2, 3, 1, 4] indicate that these targets are removed in order.

Step2. Select

The random sampling method is selected for selection. The fitness function is \( \phi(N) \), which represents the fuel consumption.

Step3. Crossover

The crossover method is selecting a position in chromosomal gene randomly, and crossing over the parental gene after the selected position. If the chromosome after the crossover has a repeated gene, the repeated gene is replaced with other gene. E.g.

select a position in chromosomal gene randomly

\[
\text{FatherN1} = [3, 6, 8, 7, 4, |5, 1, 2] \quad \text{FatherN2} = [6, 8, 7, 1, 2, |4, 3, 5]
\]

Crossover and generate offspring

\[
\text{SonN1} = [3, 6, 8, 7, 4, |4, 3, 5] \quad \text{SonN2} = [6, 8, 7, 1, 2, |5, 1, 2]
\]

Two repeat genes appear in the two offspring, replace them with other genes

\[
\text{SonN1} = [3, 6, 8, 7, 4, |1, 3, 2] \quad \text{SonN2} = [6, 8, 7, 1, 2, |5, 3, 4]
\]

Step4. Mutation

The mutation operation is selecting two points on the chromosome randomly and exchanging the genes represented by the two points.

6. Simulation and analysis

All the spacecrafts run on near-circular orbit. Select 9 pieces of space debris on SSO at the height of 850 km. Orbital inclination is 98.8212 and RAAN is 70. Space depot runs on the same orbital plane 100km under the debris orbit. The true anomaly of debris is shown in table1.

| Serial number | Space debris1 | Space debris2 | Space debris3 | Space debris4 | Space debris5 | Space debris6 | Space debris7 | Space debris8 | Space debris9 |
|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| True Anomaly  | 15            | 46            | 94            | 138           | 162           | 217           | 239           | 277           | 334           |
The mass of the mission satellite is 1000 kg, the propellant carried is 300 kg, the specific impulse is $I_p = 3000 \text{s}$, and gravity constant is $g = 9.8 \text{ m/s}^2$. The number of propulsive satellites is 5, and each mass is 100 kg. The number of propulsive satellites required for removing each piece of debris is $num = [2, 2, 3, 1, 1, 3, 2, 1, 2]$. Time needed for debris cleaning is $t_c = 1000 \text{s}$. The refueling time is $t_f = 8000 \text{s}$. The maneuver time constraint is less than four orbital periods.

Before optimization, the fuel and time consumption are calculated in the condition that the mission schedule is not planned. Set the debris removal path $N = [1, 2, 3, 4, 5, 6, 7, 8, 9]$. The results are as follows, mission satellite need replenishment for 3 times and the fuel and time consumption of the entire task is 624.28 kg and 352830 s respectively.

$$N = [1, 2, 3, 4, 5, 6, 7, 8, 9]$$
$$dM = 624.28 \text{ kg}$$
$$dt = 352830 \text{ s}$$
$$n = 3$$

Optimize the debris removal path using genetic algorithm. The GA population size is 20, and number of generations is 100. The optimal result is obtained by calculation.

![Figure 2. GA convergence curve.](image2)

![Figure 3. Optimal mission satellite removing path.](image3)

Figure 2 shows iterative process of genetic algorithm. The result is convergent after 25 generations. As shown in figure 3, the optimal debris removal path $N = [5, 6, 7, 8, 9, 2, 3, 4, 1]$. The minimum fuel
consumption during the refueling process is 402.14 kg. 280.02kg of fuel is supplied by space depot. Mission satellite needs to be replenished three times. Total task time is 316330s. It can be seen from the experimental results that the optimal fuel consumption will reduce by 35.6%(222.14kg) compared to the initial removal path, and the total mission time reduces by 10.3%.

**Table 2.** optimal results for debris removal.

| Removing sequence | Impulse(m/s) | Fuel consumption(kg) | Transfer time(s) |
|-------------------|--------------|----------------------|------------------|
| SD5               | 0            | 0                    | 1000             |
| SD6               | 192.9        | 57.16                | 24467            |
| SD7               | 102.7+164.4  | 18.64+54.38          | 38549+30132      |
| SD8               | 103.1        | 23.16                | 30882            |
| SD9               | 158.1        | 28.76                | 30586            |
| SD2               | 250.2+53.81  | 26.15+18.14          | 38644+3910       |
| SD3               | 167.7        | 43.84                | 24710            |
| SD4               | 65.22+80.37  | 9.808+26.97          | 37500+19900      |
| SD1               | 333.8        | 95.15                | 33350            |
| **Total**         | **402.14**   | **316330**           |                  |

Table 2 shows the detailed consumption of the whole mission. The plus sign indicates mission satellite maneuver to space depot for replenishment. From the figure, fuel consumption is large when satellite need replenishment. The optimal removing sequence of the mission satellite is in the order of sequentially adding a true anomaly angular position. When the service spacecraft returns to the space depot, the order of removing is no longer in full compliance with this law. Under the constraint of propulsive satellite, mission satellite needs to maneuver to space depot more often, increasing fuel consumption of the mission. Transfer time is close to the critical value as longer maneuvering time bring smaller impulse.

7. Conclusion

In this paper, the active space debris removal mission planning is studied and the three-stage system is proposed to solve this problem. Firstly, the multiple spacecraft including one main spacecraft and some following spacecraft for space debris removal mission are developed. Then, the fuel, time, and the quantity of the following spacecraft are defined as the constraints. Moreover, using the minimum fuel consumption as the optimal object, the mathematical model of the debris removal problem is established. Finally, the genetic algorithm is applied to solve this problem. Compared with the prior space debris removal sequence, the optimal three-stage space debris removal sequence can effectively reduce the fuel consumption. Numerical simulation verifies the effectiveness of the proposed space debris removal scheme. Furthermore, the debris removal mission planning strategy can also be applied to refueling problem. However, this developed strategy ignores the influence of perturbation. In the future, the influence of the perturbation and the safe constraints should be studied.

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References

[1] The NASA Orbital Debris Office. Orbital Debris Quarterly News [J]. Orbital Debris Quarterly News, 2018, 22(1).
[2] Klinkrad H. Space Debris – Models and Risk Analysis[M]. Springer, 2006
[3] Liou J C, Johnson N L, Hill N M. Controlling the growth of future LEO debris populations with active debris removal[J]. Acta Astronautica, 2010, 66(5):648-653.
[4] Bosse A B, Henshaw C G, Pipitone F, et al. SUMO: spacecraft for the universal modification of orbits[J]. Proceedings of SPIE - The International Society for Optical Engineering, 2004, 5419.

[5] Obermark J, Henshaw C G. SUMO/FREND: vision system for autonomous satellite grapple[J]. Proceedings of SPIE - The International Society for Optical Engineering, 2007, 6555:65550Y-65550Y-11.

[6] Kawamoto S, Makida T, Sasaki F, et al. Precise numerical simulations of electrodynamic tethers for an active debris removal system[J]. Acta Astronautica, 2006, 59(1):139-148.

[7] Toyoda K, Reiso S, Cho M. Experimental investigation of space debris removal method using electrostatic force in space plasma[C]// Aiaa Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, 2013.

[8] Rubenchik A M, Barty C P, Beach R J, et al. Laser Systems for Orbital Debris Removal[J]. 2010, 1278(1278):347-353.

[9] Braun V, Lüpken A, Flegel S, et al. Active debris removal of multiple priority targets[J]. Advances in Space Research, 2013, 51(9):1638-1648.

[10] Madakat D, Morio JRO, Vanderpooten D. Biobjective planning of an active debris removal mission[J]. Acta Astronautica, 2013, 84:182-188

[11] Chao H. Research on Algorithm of Loopy Lambert Transfer in Space Rendezvous[J]. Chinese Space Science & Technology, 2004.