GTOC9: RESULTS AND METHODS OF TEAM 2 - TSINGHUA UNIVERSITY

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Abstract

This paper summarizes our methods solving GTOC9 problem. This year's problem is very complex and challenging. Traditional tree search methods aren't effective enough for this problem and only impulsive manoeuvre is allowed this time. To overcome these difficulties, a random group search strategy is used to avoid single debris left at last. An estimation method of transfer ΔV and transfer time is used for fast search. Multiple impulsive transfer is optimized by the PSO. The best score of our team is 829.58.

Introduction

It is the year 2060, although human being was already warned by the threaten of space debris about 40 years ago, the Kessler effect [4] still triggered great impacts. Based on this, the GTOC9 problem focuses on a 123 debris removal project to prevent the orbital environment from getting worse [3].

Normally, these problems are solved mainly by two parts, global sequence optimization and local transfer optimization. This year's problem is very complex and challenging, and all the 123 debris must be removed. The traditional tree search strategies can not ensure that the rest dozen of debris are close enough to each other. A good sequence search strategy is needed to find groups of gathered debris and avoid single debris left at last. A big difference from former GTOC problems is that only impulsive maneuver is allowed in this problem. The chemical propulsion does have many advantages and is still irreplaceable in 2060. Multiple impulse optimization is the core of the local optimization.

This paper is organized as follows. The estimation method of transfer ΔV and transfer time is firstly given as the basis of sequence search. Then a random group strategy is presented and the breadth first beam search is used. Then the J_2 perturbed Lambert problem is solved and Particle Swarm Optimization

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(PSO) is used to optimize multiple impulse transfer. Results and conclusion are given at last.

Estimation method of transfer ΔV and transfer time

In the global search process, transfer ΔV and transfer time for every single transfer between two debris are basically needed. However, for fast sequence search, solving optimal impulsive manoeuvres considering J2 perturbation for each transfer is not practical because the computation time will be unbearable long. An estimation method is needed for this problem.

Because that the debris orbits are all quasi-circular orbits and the changes are small, Edelbaums approximation [2] is used here to estimate the transfer ΔV.

$$\begin{aligned} \Delta V_a &= \frac{1}{2}\frac{\Delta a}{a_0}V_0 \\ \Delta V_e &= \frac{1}{2}\Delta e V_0 \\ \Delta V_i &= \Delta i V_0 \\ \Delta V_\Omega &= \sin i_0 \Delta\Omega V_0 \end{aligned} \tag{1}$$

The velocity requirement for phase change is not included here, because the transfer time is considered to be long enough for phasing. The transfer ΔV can be calculated by:

$$\Delta V = \sqrt{(\Delta V_a + \Delta V_e + \Delta V_i)} + \Delta V_\Omega \tag{2}$$

The next step is to determine transfer time. Our strategy is to find the minimum value of RAAN difference between two debris. A transfer time interval [t_{low} t_{upp}] is defined here. For example, the lower bound can be t_{low} = 1 day and the the upper bound can be t_{upp} = 25 days. Giving an allowed ΔV_{max} and the start epoch t_s after 5 days stay in proximity of the debris, the transfer time can be determined by the following procedure:

- Calculate the meet epoch t_{meet} when the RAAN of the two debris are exactly the same. If (t_{meet} - t_s) is within the transfer time interval, then the transfer time is set to be $t_{transfer}$ = t_{meet} - t_s;

- If the meet epoch is beyond the transfer time interval, then calculate transfer ΔV at the boundary of the transfer time interval. Choose the minimum one as the transfer time. For example, if $\Delta V_{low} < \Delta V_{upp}$, then the transfer time is $t_{transfer}$ = t_{low} - t_s.

- If the minimum transfer ΔV is larger than the allowed ΔV_{max}, for example, ΔV_{upp} $>$ ΔV_{low} $>$ ΔV_{max}, then this transfer is considered to be infeasible.

Search strategy

Sequence search is the basis for obtaining the optimal solution. The orbit plane of debris is changing all the time because of the J2 perturbation. The inclination keeps constant in this problem. The precession rate of RAAN is constant. Different debris has different precession rate of RAAN, so two debris may meet each other at a specific epoch, which is the best chance for the transfer between these two debris. The removed debris in one mission must be close to each other in terms of RAAN. The problem is then converted to help the debris find the right companion at the right time. But it's always very hard to make the right choice.

It's very common that without a good strategy, the rest of the debris will be far away from each other. In this case, for one of the rest debris, the suitable companion debris is already 'chosen' by former debris. However, the former debris may have many other choices, so the problem is how to assign the debris so that each debris can find their suitable companion. According to the strategy described in the last section, the debris will select the optimal debris as target. But this local optimal solution is not global optimal solution. It's necessary to avoid some of the local optimal solutions.

The traditional search method such as depth first search with pruning or improved breadth first search named beam search is not effective enough to solve this problem. Some strategies need to be given here to avoid single debris left.

A random strategy is used here. Before the search process in each mission, the debris will be randomly and evenly divided into each group. In one mission, the number of removed debris in the same group can not be more than an limitation, such as 3, and the limitation is different for different mission. For example, before the first mission, the debris will be randomly divided into 10 groups with 12 debris in each 7 groups and 13 debris in each 3 groups. In the search process, the maximum number of selected debris in each group is 3, which means even if there are lots of local optimal solutions in one group, they can't be all selected. The number of group is different for different missions. For example, the numbers of group for the first six missions are 10,8,8,6,4,2, and the last missions won't be grouped. This random strategy need a huge number of simulations to work. The parallel technology is used here to accelerate the search process. We start simulations on the computer and then pray to get a good solution, so we call this method 'Random Gift'. Every time we check the result, just like opening a gift pack to see if there is a surprise.

In one mission, the start time is discrete and beam search is used. The search will start from each rest debris at each discrete time epoch. The heuristic cost of beam search is total ΔV. It's noticed that in the beam process, two sequences with the same length may have all the same debris but their orders are different. If the last debris and the last arrival time are the same, then these two sequences will be seen as one sequence when extend the next level in beam search. This will greatly reduce the amount of calculation. The search will stop when the total ΔV is beyond the maximum limitation or there is no suitable debris. The allowed ΔV_{max} and the total ΔV limitation will increase with the increase of the mission number. The sequence of most debris number and the minimum total ΔV is saved as this mission's plan.

With this random search strategy, a 12 missions result is acquired. After this, the acquired sequence can still be improved by optimizing the arrival epoch. Take the arrival epoch determined in last section as the initial value and then PSO is used to optimize the arrival epoch. The object function is the total ΔV. Some adjustment, such as take one or two debris from a long sequence into some other short sequence, can also improve the score.

Impulsive manoeuvres optimization

Different from former GTOC problems, impulsive manoeuvres, and only impulsive manoeuvres is allowed in this year's problem.

The J_2 perturbed Lambert problem needs to be solved firstly. Using the two body Lambert problem's solution as the initial value, the J_2 perturbed Lambert problem's solution can be solved by shooting method. If the transfer time is very long, shooting method can't converge sometimes. A J_2 homotopy method is used here. In the homotopy process, the problem is changed from a two body Lambert problem to a J_2 perturbed Lambert problem. The value of J_2 is changed form 0 to the actual value.

The PSO is used to optimize the multiple impulse transfer. In one impulse, the four variable parameters are the epoch t, velocity magnitude v, and two velocity direction angle α and β. The $\Delta \boldsymbol{v}$ of last transfer is acquired by solving J2-Lambert problem, so the constraints are satisfied. In the PSO process, mean orbital elements are used to avoid integration [1]. Given the osculate orbital elements of spacecraft at t_0, mean orbital elements can be transformed, and mean orbital elements at t_f can be analytic propagated, then osculate orbital elements at t_f are acquired. Approximate orbital elements of spacecraft are fast calculated through this analytic mean method and the accuracy is ensured. The equations of multiple impulse transfer is given as this:

$$\begin{aligned}
&\boldsymbol{v}_i^+ = \boldsymbol{v}_i^- + \Delta \boldsymbol{v}_i \\
&\left(\boldsymbol{r}_{i+1}, \boldsymbol{v}_{i+1}^-\right) = f\left(\boldsymbol{r}_i, \boldsymbol{v}_i^+, t_i, t_{i+1}\right) \\
&i = 1, 2, \cdots, n-2 \\
&\left(\Delta \boldsymbol{v}_{n-1}, \Delta \boldsymbol{v}_n\right) = \mathrm{J_2Lam}\left(\boldsymbol{r}_{n-1}, \boldsymbol{r}_n, t_{n-1}, t_n\right)
\end{aligned} \quad (3)$$

And the objective function is:

$$J = \sum |\Delta v| \quad (4)$$

At last, take the parameters acquired from the PSO as the initial value, and the final shooting process using the accurate equations of motion for the spacecraft [3] will give the accurate impulsive manoeuvres.

Results

The best score of our team is 829.58. The number of missions in our final submission is 12, and in each mission the number of debris is: 17, 14, 14, 10, 12, 8, 8, 9, 9, 7, 7, 8. The RAAN change in each mission is shown from Figure 1 to Figure 12. It can be seen that RAAN changes in a linear way. In the last missions, some of the RAAN difference between two neighboring debris are a little big. This is because the allowed ΔV_{max} is big in the last missions

The larger the difference of the precession rate of RAAN is, the easier these two debris meet each other. Take our first mission and last mission as an example, as shown in Figure 13 and Figure 14. The debris is ordered by their precession rate of RAAN. The x label is debris number, the y label is the precession rate of RAAN, and the red asterisk is the removed debris in this mission.

Conclusion

A random strategy is used in sequence search to avoid single debris left. This strategy is effective and after a huge number of simulations, the best result is 12 missions. Compared with the 10 missions result submitted by the winner, this strategy needs still to be improved. PSO is a good method solving multiple impulse transfer, but the calculation speed and stability needs also to be improved. Look forward to the next GTOC.

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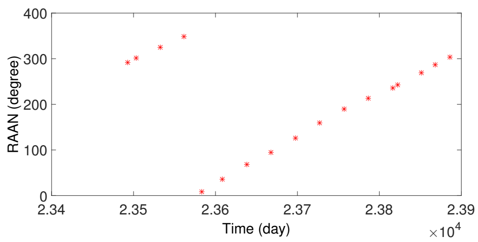

Figure 1: RAAN change in 1st mission

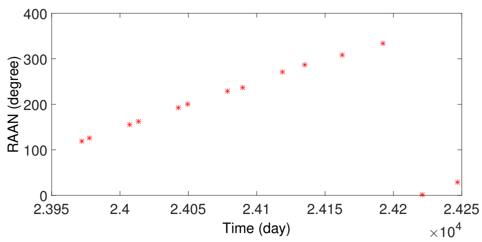

Figure 2: RAAN change in 2nd mission

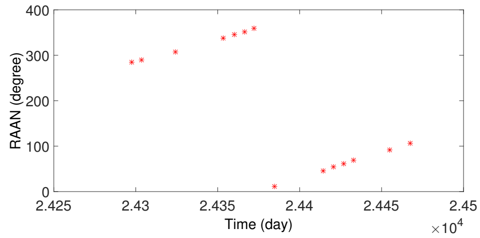

Figure 3: RAAN change in 3rd mission

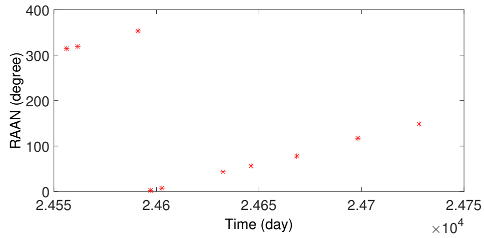

Figure 4: RAAN change in 4th mission

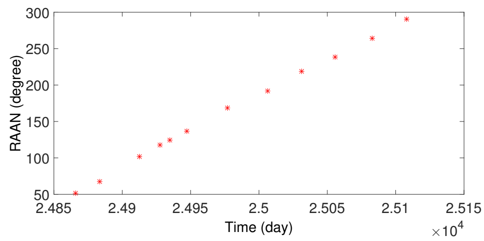

Figure 5: RAAN change in 5th mission

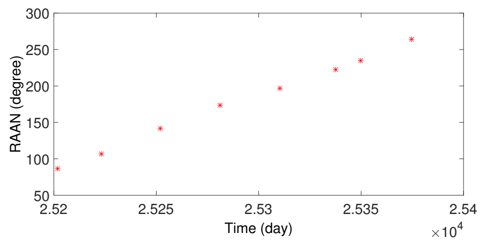

Figure 6: RAAN change in 6th mission

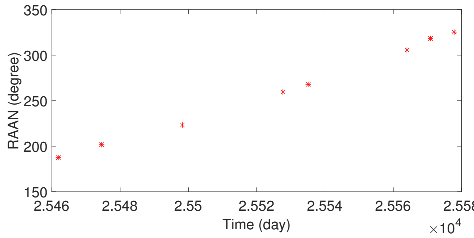

Figure 7: RAAN change in 7th mission

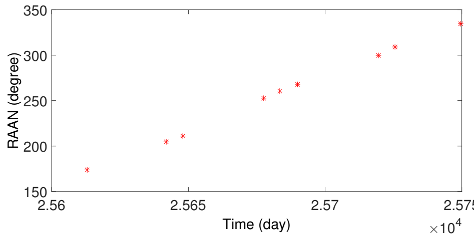

Figure 8: RAAN change in 8th mission

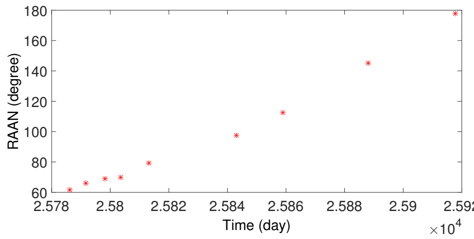

Figure 9: RAAN change in 9th mission

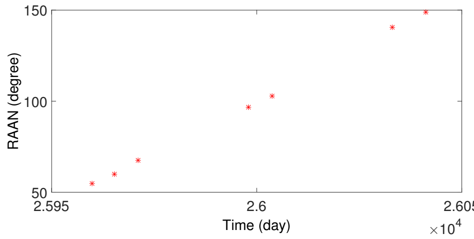

Figure 10: RAAN change in 10th mission

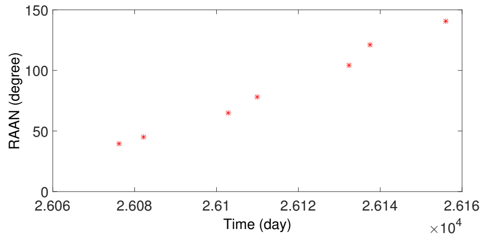

Figure 11: RAAN change in 11th mission

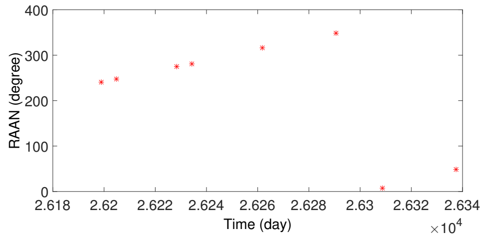

Figure 12: RAAN change in 12th mission

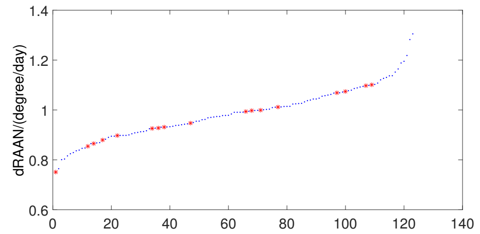

Figure 13: Removed debris in 1st mission

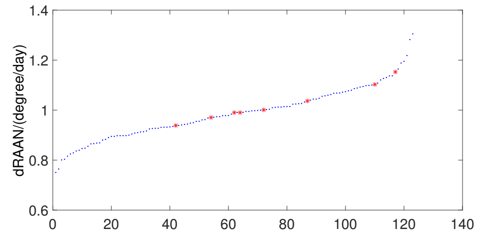

Figure 14: Removed debris in 12th mission