CS-512

ARTIFICIAL INTELLIGENCE

TERM PAPER

INDIAN INSTITUTE OF TECHNOLOGY ROPAR

SOLVING THE PROBLEM OF SPACE DEBRIS

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May 1, 2022

1. Introduction

For more than a decade, the Space Debris problem has become a major problem for space researchers. As of data of 2019, there are about 900,000 pieces of debris of size between 1 and 10 cm and there are more than 128 million debris of size less than 1 cm traveling at the rate of 20 times the speed of the bullet.

With the growing space sector of countries, the space environment is becoming crowded. The major problem is when these space items are used up then also they remain in the orbit which is called space debris. These space debris can be collided with the satellites incurring heavy losses to upcoming space programs. The issue here is to deal with a plan that can take these sub satellites efficiently to all the identified debris in the range with the minimization of energy (fuel) and the time. This problem can be modeled as a traveling salesman problem.

The method used for debris removal is Active Debris Removal (ADR) which involves a parent satellite with some small satellites in it. Whenever the parent satellite detects debris then it releases the sub satellites from it which can trap the debris using different de-orbit devices equipped in them and move the debris to lower orbit.

2. Background and Related work

The problem of calculating an efficient route for satellites to remove space debris can be formulated as a travelling salesman problem. The travelling salesman problem is defined as finding the shortest route in which a salesman will travel all the cities listed and come back to the original position, similarly the satellite with some fuel will travel to different debris in space and after moving them to lower earth orbit it will come back to the main space station. The work done by (1) involves use of two orbital distance techniques, Hörmann orbital rendezvous and Double elliptical maneuver and a novel approach of Route-Break chromosome pairing with the genetic algorithm to find the minimum cost of satellites to remove the space debris in an efficient way. The route-break chromosome pairing is performed in following eight steps:

1. Reproduce
2. Flip only route chromosome
3. Swap only route chromosome
4. Slide only route chromosome
5. Reproduce-Modify breaks
6. Flip-Modify breaks
7. Swap-Modify breaks
8. Slide-Modify breaks

This method provides advantage of better fitness because offspring have a better chance of inheriting individuals with high fitness from parent, also there is a reduction of search time. Apart from advantages this paper (1) include the limitation of satellite calculation, the number of satellites are taken statically which will unevenly distribute the number of debris on each satellite. We have proposed a method that will calculate the minimum number of satellites required for efficient path of space debris calculation also it will try to evenly distribute debris to each satellite.

3. Methodology

In this paper, we are dealing with the multi-satellite platform, in which there is parent satellite that carries several sub-satellites to remove debris from space. These satellites are equipped with space sensors to identify space objects and have orbital maneuvers that can circumvent other satellites and debris. These satellites need to visit all the identified debris sets within their finite energy. So the main problem here is to plan an efficient strategy to reduce the weighted sum of time and energy to traverse all the identified debris in one mission. Also we are also finding the number of sub-satellites required to remove all of the debris. We propose to model the debris planning problem as an multiple traveler salesman problem (MTSP).

Contributions of the paper:

1. The debris are considered as the cities to be visited and the sub-satellites are the travelers to traverse all the unidentified debris sets. Path that utilizes the minimum fuel is found.

2. Number of sub satellites required to remove all the debris is found.

3. A new crossover technique (2) is used in the proposed genetic algorithm.

3.1. Proposed Method

3.1.1 Preliminaries

A main satellite is carrying several number of sub-satellites, each of these sub-satellites remove a certain number of space debris and come back to the main satellite. The goal is to find the minimum number of satellites to remove all the space debris based on the ordering of the debris to remove.

The fuel consumption will depend on the satellite's orbital strategy, which is related to the satellite orbit speed increment. For dynamically changing distances, the Cost of fuel is described as a linear function of change in velocity and change in time.

$$F(x,y)=\alpha\Delta V + \beta\Delta T, \text{ where } \alpha + \beta = 1$$

α and β are energy and time impact factor and F is fuel consumed from orbit x to orbit y.

Two different orbit transfer strategy are used depending on the ratio of the target orbital radius to the original orbital radius. When $r_2/r_1 < 11.94$, Hormann Orbital Transfer is most economical (3).

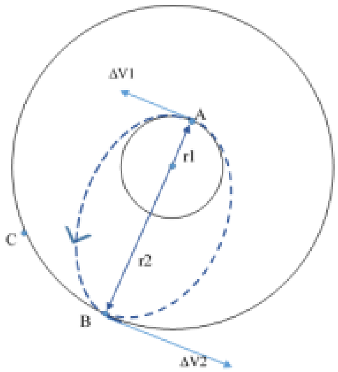

Figure 1: Hormann Orbital Transfer

As is shown in Figure 1, the initial position of the spacecraft is at point A, and the target is at point B. The speed changes for hormann transfer orbit:

The first change (at point A) :

$$\Delta V_1 = \sqrt{\frac{\mu}{r_1}}\left(\sqrt{\frac{2r_2}{r_1 + r_2}} - 1\right)$$

The second change (at point B) :

$$\Delta V_2 = \sqrt{\frac{\mu}{r_2}}\left(\sqrt{\frac{2r_1}{r_1 + r_2}} - 1\right)$$

where μ is the standard gravity parameter for a central object.

The energy consumed by a Hormann transfer is =>

$$V_h = |\Delta V_1| + |\Delta V_2|$$

The time for rendezvous can be obtained by Kepler's third law :

$$t_H = \pi\sqrt{\frac{r_1 + r_2}{8\mu}}$$

When $r_2/r_1 > 15.58$, Double Elliptical is most economical.

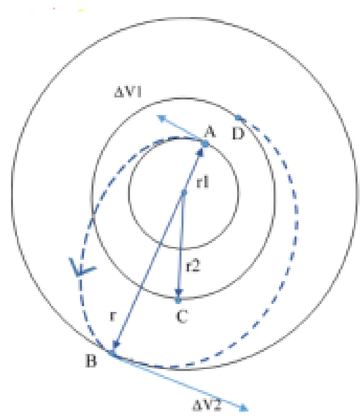

Figure 2: Double Elliptical Transfer

The speed changes for Double Elliptical transfer orbit:

The first change (at point A) :

$$\Delta V_1 = \sqrt{\frac{\mu}{r_1}}\left(\sqrt{\frac{2r_2}{r_1 + r_2}} - 1\right)$$

The second change (at point B) :

$$\Delta V_2 = \sqrt{\frac{\mu}{r}}\left(\sqrt{\frac{2r_2}{r_2 + 2}} - \sqrt{\frac{2r_1}{r_1 + r}}\right)$$

The third change (at point D) :

$$\Delta V_3 = \sqrt{\frac{\mu}{r_3}}\left(\sqrt{\frac{2r}{r + r_2}} - 1\right)$$

The time of rendezvous is :

$$t_D = \pi\left(\sqrt{(r + r_1)^3} + \frac{\sqrt{(r_2 + r)^3}}{2\sqrt{2\mu}}\right)$$

The energy consumed by Double Elliptical Transfer:

$$V_d = |\Delta V_1| + |\Delta V_2| + |\Delta V_3|$$

3.1.2 Genetic Algorithm

Initial population : An initial population of multiple chromosomes is created. Each chromosome represents the ordering in which the space debris will be removed. Each gene in a chromosome represent the debris that is going to be removed next.

Fitness function : A fitness function able us to determine how fit an individual is. Fitness Function gives a fitness score to each of the individual. Selection of individuals depend on this fitness score. Fitness function here is described as a linear function of change in velocity and change in time.

Selection : The selection will be based on tournament selection which is a strategy used for selecting fittest candidates based on their fitness scores from current generation in genetic algorithm. In a M-way tournament selection, M fittest candidates are selected based on a tournament among them.

Cross-Over : The crossover used in the proposed method is discussed in paper (2) which include the following steps :
Step 1: Randomly select two parents and randomly select two crossover points, let's say position a and position b. Therefore the chromosome is now divided in three parts.
Step 2: Offspring 1 will be formed by including the genes of parent 1 from initial position to position a. Similarly offspring 2 will be formed by including the genes of parent 2 from initial position to position a.
Step 3: Now the cost of parent 1 and parent 2 between positions a and b are calculated and compared whichever is lowest will be added to both the offspring.
Step 4: Now offspring 1 will finally include the genes of parent from position b to end. Similarly offspring 2 will include the genes of parent 2 from position b to end.
Step 5: Now the duplicate genes are removed from both the offspring.
Step 6: Now missing genes are found and to insert them we have to compare with first and last gene to have minimum cost.

Mutation : Mutation is a small change performed randomly in the chromosome to get a new solution which is used to maintain diversity in the genetic population. Mutation helps in maintaining diversity within the population and prevents from falling in local minima.

3.1.3 Finding number of satellites

The small satellite leaves the main satellite in search for a debris. After moving one debris to the lower earth orbit it should have enough fuel to go back to the main satellite. So once the fuel has been filled in the satellite, it will always conserve enough fuel to go back to the main satellite also it will try to cover maximum amount of debris for removal. Firstly, the fuel tank of a satellite has been filled to give it initial propulsion. After that at every debris position the remaining fuel is calculated such that it will have enough fuel to reach the main satellite. If the fuel remaining is not enough to go to other debris then a new satellite will be launched from the main satellite.

4. Experimentation

To test the genetic algorithm we have conducted our experiments on multiple travelling salesman problem (MTSP) datasets. The simulation experiments are carried via Python-3 on 8GB ram, i5 11th gen processor.
Datasets used :
1. EIL51 : EIL51 is a dataset of 51 coordinates that can be interpretted as a debris position. The dataset is available at here.
2. SP11 : The data is an artificial integer distance matrix for 11 objects. The dataset is available at here.
3. UK12 : This dataset includes the travel times between 12 cities in the United Kingdom. The dataset is available at here.
4. SGB128 : This dataset contains 128 cities in the continental US and lower Canada are considered. The dataset is available at here.

Some of the assumptions that we have assumed:
1. We have assumed our main satellite at origin (0,0) in every dataset.
2. The fuel capacity in a satellite is defined and fuel is filled only at initially.
3. Velocity of propulsions is already considered in orbital manoeuvres.

5. Results and Discussions

Following are the results obtained :

Dataset	Population Size	Costs Per Satellite	Number Of Satellites	Fuel per Satellite
EIL51	80	4319	3	5000000
EIL51	120	3046	5	3000000
EIL51	160	1043	10	1000000
SGB128	160	18593	10	19000000
UK12	160	2874	3	3000000
SP11	160	755	3	750000

Results obtained in paper (2):

Dataset	Population Size	Costs Per Satellite	Number Of Satellites
EIL51	80	477	3
EIL51	120	532	5
EIL51	160	727	10
SGB128	160	38789	10
UK12	160	2295	3
SP11	160	135	3

When the population size is changing from 80 to 160 in EIL51 dataset then the final cost per satellite shows a drastic change moving from 4319 to 1043. We were able to improve the results of SGB128 dataset by almost half in comparison to the approach followed in paper (1). The results of UK12 and SP11 were comparable to the paper (1).

6. Conclusion

Proposed method is efficient both in terms of minimizing cost of fuel as well as in minimizing the number of satellites required to move the debris to lower earth orbit. When the satellites will leave the main satellite they will try to to get an equal distribution of distance to debris also keeping enough fuel to come back to main satellite. Future work can be done in the direction of making this environment dynamic so that every other satellite should not have to wait for previous satellite to come back instead all satellites should estimate the work on arrival.

References

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