Genetic Algorithm, figuring out the optimal solution problem of active removal of space debris

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Keywords: space debris, active removal, Genetic Algorithm, long-term model

Abstract. Space junk, one of the man-made pollution, is destroying the satellite's safety, ultimately making low earth orbit (LEO) unusable. Many countries, such as Japan and U.S., have been proposed many different methods for remediation of the orbital debris environment over the years, including the use of lasers, electro-dynamic or momentum exchange tethers, tugs, and other, more exotic methods. Firstly, this paper picks out five removal methods with the highest feasibility and reliability. These five methods have the ability to clean space junk in different heights near-earth orbit, and in a few years these will become the mainstream methods to make the space cleaning.

Secondly, this paper establishes a model called the Long-term Model which is constructed to figure out the optimal solution problem of active removal of space debris by combining those five methods. Following the three principles drafted by NASA and ESA, 10 hot spots in given orbits should be removed by the combinations of five methods every year in order to reduce the spacecraft's risk. In detail, based on the Genetic Algorithm and taking small disturbance into account, the model has derived the approximate optimal solution by randomization test and iteration so as to figure out the best combination of methods.

1. Introduction

Space junk is mainly including derelict satellites, fragments from upper stage of launch vehicles, satellite explosions or collisions fragments, etc. Even solid rocket motor effluents and tiny flecks could be space junk in orbit about the earth.

A growing number of countries have been proposed many different methods for remediation of the orbital debris environment. After referring to a number of papers as well as consulting with the NASA Orbital Debris Program Office, the article picks out five capturing or removal methods with high feasibility and reliability as the company's alternatives. These five methods have the ability to clean space junk in different heights near-earth orbit, and in a few years these will become the mainstream methods to make the space cleaning. The five methods are laser orbital debris removal (LODR), drag augmentation system (DA), electrodynamic tether system (EDT), towboat to capture debris (TCD), net capturing and removal (NCR).

2. Model Establishment

2.1 The Three Principles

Studies at NASA and ESA show that with a removal sequence planned according to target mass, the environment can be established when on the order of 10 objects are removed from LEO per year. Active removal can be more efficient in terms of the number of collisions prevented versus objects removed when the following principles are applied for the selection of removal targets:

　　1、The selected objects should have a high mass (they have the largest environmental impact in case of collision)

　　2、Should have high collision probabilities (e.g. they should be in densely populated regions)

　　3、Should be in high altitudes (where the orbital lifetime of the resulting fragments is long)

Based on the three targets above, the long-term maintenance service is to clean up 10 hot spots per year using combination of five methods, it's efficient and feasible.

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2.2 The Establishment of the Long-term Model

According to section2.1, long-term debris removal needs only clean up 10 hot pots per year, after permutation and combination, there are 5^{10} different combination schemes, model solution is the process to get the optimal combination scheme by using GA.

2.2.1 Coding

First step is code. Transform variables to binary string, the length of binary string depend on the requiring precision:

$$2^{23} < 5^{10} < 2^{24}$$

Choose 24 bits binary series to code.

Coding 10 targets with number 1~10, coding 5 methods with number 1~5.For example, U = [0000 0000 0000 0000 0000 0000] means using No.1 method(LODR) to remove targets ten times, U = [0000 0000 0000 0000 0000 0001] means using No.1 method nine times and No.2 method (DA) once and so on.

2.2.2Initial Input Selection

Choose 8 individuals randomly to form the initial species:

$$U_1 = [0100\ 0101\ 1011\ 1000\ 1100\ 0110]$$
$$U_2 = [0110\ 1001\ 1001\ 0000\ 1110\ 1000]$$
$$U_3 = [0110\ 0001\ 1001\ 1100\ 1101\ 0010]$$
$$U_4 = [0011\ 1111\ 0011\ 0100\ 0001\ 0110]$$
$$U_5 = [0100\ 1101\ 1010\ 1101\ 1000\ 1100]$$
$$U_6 = [1000\ 0111\ 1000\ 1011\ 1001\ 1010]$$
$$U_7 = [0011\ 0101\ 0011\ 0100\ 1110\ 0110]$$
$$U_8 = [0111\ 0000\ 0001\ 1010\ 1100\ 1001]$$

Those 8 individuals is the initial species of our model.

2.2.3 The evaluation of individual fitness

In 2.2.2, every chromosome U in the initial species represents a combination of methods. The article propose a fitness function to figure out each chromosome U's fitness value, taking Cost and risk into account.

Assuming that the method i's (i ∈ 1,2,3,4,5) Cost is c_i, Risk is p_i and the times to choose method i among 10 is n_i

$$\sum_{i=1}^{5} n_i = 10$$

The fitness function:

$$eval(U_i) = f(c_i, p_i) = \sum_{j=1}^{10} (\alpha c_i n_i + \beta p_i n_i)$$

In this formula, α=0.6(the contribution value of cost)
        β=0.4(the contribution value of risk)

Calculate the individual fitness of the initial species in 4.3.2

$eval(U_1) = 17.370896$ $eval(U_2) = 26.408399$
$eval(U_3) = 9.8394732$ $eval(U_4) = 15.234124$
$eval(U_5) = 18.341234$ $eval(U_6) = 11.857285$
$eval(U_7) = 16.234232$ $eval(U_8) = 26.324282$

It's obvious that U_2 is the one with highest fitness. Consequently, U_2 is the best chromosome and its value is defined as $eval(U)_{max}$.

2.2.4 The mating of new species

The mating of new species is conducted in accordance with the fitness of last generation. Here's the steps:

1、Calculate the fitness value of the chromosome U_k

$$eval(U_k) = f(c_k, p_k)$$

In this formula, k=1,2,3,……

2、Calculate the sum of the species fitness value

$$F = \sum_{k=1}^{\text{pop\_size}} eval\,(U_k)$$

3、Calculate the probability of each chromosome to be copied

$$P_k = \frac{\text{eval}(U_k)}{F}$$

4、Calculate the sum probability of each chromosome to be copied

$$Q_k = \sum_{j=1}^{k} P_k$$

5、Use random number generator to produce 4 random numbers in 0 ~ 1 and pick out the chromosome to mate according to the location where the number falls into.

6、Make pairs of 4 chromosomes. For example, select the U_8 and U_4 as the father generation. Use random number generator to produce a number in 0~23(since the length of the chromosomes is 24). If the number is 3, then the two father generation chromosomes exchange their part behind the position 3(the 4th of the binary series) with each other. Therefore, two new chromosomes are generated.

$$U_4 = \begin{bmatrix} 001 & \underline{11111\ 0011\ 0100\ 0001\ 0110} \end{bmatrix}$$
$$U_8 = \begin{bmatrix} 011 & 1\ 0000\ 0001\ 1010\ 1100\ 1001 \end{bmatrix}$$

After mating

$$U_4^{\,*} = \begin{bmatrix} 001 & 1\ 0000\ 0001\ 1010\ 1100\ 1001 \end{bmatrix}$$
$$U_8^{\,*} = \begin{bmatrix} 011 & \underline{1\ 1111\ 0011\ 0100\ 0001\ 0110} \end{bmatrix}$$

7、When the mating finishes, combine the new chromosomes with the initial species so that to form the new species.

2.2.5 The variation of new species

Referring to the Roulette Selection Operator, spin the roulette 2 times (8 chromosomes in species) and each time the variation will take place in one chromosome. The operator the model adopts is one-point crossover which means that when the crossover occurred, we choose a cross point at random and the part behind the cross point will change so that to generate two new chromosomes. We take U_1 as an example.

$$U_1 = [0100\ 0101\ 1011\ 1000\ 1100\ 0110]$$

After one-point crossover

$$U_1 = [0100\ 0101\ 10\uparrow 11\ 1000\ 1100\ 0110]$$
$$U_1{}' = [0100\ 0101\ 10\uparrow 00\ 0111\ 0011\ 1001]$$

Repeat the process of 2.2.2 and figure out the one with highest fitness, then compare it with the former $eval(U)_{max}$ and update the $eval(U)_{max}$.

The first generation process of genetic algorithm has completed so far, a new round will begin from 2.2.2 and the rest could be concluded in this way.

2.3 Long-term Model Implementation

Referring to the model established in 2.2, the article iterates 300 times and figures out the chromosome code U_{best} of the maximum value of the objective function at the 301 times.

$$U_{\text{best}} = [0000\ 0011\ 1111\ 1010\ 1001\ 1111]$$

The fitness value:

$$eval(U_{\text{best}}) = 38.818208$$

The true value of chromosome after serial decoding:

$$3866440$$

After calculating, the value represents that we plan to use LODR for the previous 3 times , then using DA for 4 times, the last three times using LODR again.

3. Summary

1. Instead of being trapped in local optimum, the article locates the global optimum by considering disturbance in the implementation process.

2.It's believed that the result is feasible and credible since the result has three different parts rather than using the same method to make the cleaning as we predicted and the differences may result from the risk factor.

3. The individual fitness function is reasonable so that it can be modified and extended in the future.

From what has been discussed above, there is an optimal solution exists. The paper could draw a conclusion that this solution is feasible and also has strong attraction in economic aspect.

References

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