Intelligent planning method for large-scale low-orbit constellation supplementary network

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Abstract. Large LEO constellations have become increasingly prominent in the aerospace field. When some satellites in the constellation fail, the traditional SOC (Streets-of-Coverage) constellation coverage analysis method can no longer evaluate the coverage of the constellation accurately. A method for calculating the space coverage performance of the large constellation with an incomplete configuration using a single-satellite space coverage stacking method is deduced. The constellation TT&C (Telemetry Tracking and Command) planning method based on spatial coverage assessment is proposed. The genetic algorithm is taken to illustrate the general steps of the intelligent planning of constellation complementary network, and the intelligent planning model design for multiple constellation TT&C restriction and covering the optimal target is realized.

1. Introduction

In recent years, the low-orbit satellite constellation of China has achieved rapid development. As of December 2020, there are 6 low-orbit constellation plans that have been released in China. It is estimated that the total number of China satellites in orbit will be about thousands after all these constellations are launched and networked. As the current satellite's autonomous control capabilities are not efficient enough, the TT&C of these low-orbit constellations mainly rely on ground-based TT&C systems, which places high requirements on the planning capabilities of the constellation TT&C system.

In the low-orbit constellation TT&C process, the multiple continuous coverage of the constellation is the main basis for the ground TT&C system. In 1961, Luders R D. et al. studied the satellite network for continuous regional coverage [1]. In 1978, D.C. BESTE discussed the global constellation design method for continuous coverage systematically [2]. In 1999, Cheng Fengzhou et al. discussed the space coverage of the Walker constellation and pointed out the orbit-related factors of the constellation coverage performance [3]. Since then, due to the development of hybrid constellations, people have gradually begun to study the coverage of multiple hybrid constellations including the Walker constellations. In 1994, Lang T. J. discussed the optimal low-orbit constellation design model to achieve global coverage [4]. In 1999, Yuri Ulybyshev discussed the continuous coverage of near-polar orbit satellites [5]. After 2010, Liang and Fu et al. analyzed and numerically simulated the coverage capability in the low-orbit satellite constellation system design [6][7]. In 2013, O.C. Eke Vincent et al. discussed the ground coverage of the global communication constellation [8]. In 2017, Chen et al. applied the SOC method to complete the LEO constellation design [9] and Su Weilian et al. systematically discussed the
communication coverage problem based on cubic stars [10]. In 2018, Meng et al. deduced the space coverage optimization method of orbiting satellites [11].

With the rapid development of intelligent optimization and artificial intelligence technology, the intelligent technology was gradually introduced into the design process of various constellations after 2000. In 2007, Zeng Yujiang designed constellation with intelligent algorithms [12] [13]. In 2013, Eric Frayssinhes et al. design a data collection service system with non-continuous regional coverage (in the United States and its neighboring areas and Europe) and optimized the GPS system by genetic algorithms [14]. In 2016, Mezianetani I et al. analyzed the continuous area coverage of small satellite constellations by the multi-objective genetic algorithm [15].

In the TT&C process of large-scale low-orbit constellations, the planning of supplementary networks for incompletely configured constellations is one of the core issues of constellation TT&C planning. Within the perspective of historical research, although the research on constellation coverage calculation methods is relatively various, the existing constellation coverage calculation methods are mainly oriented to the field of constellation design, and there are very few discussions on coverage performance loss and network supplement planning methods in the case of partial satellite failures in the constellation. It is very difficult to calculate the coverage performance of the incomplete constellation and plan the constellation network supplementary.

An intelligent supplementary network planning method based on space coverage assessment for the TT&C requirements of large-scale low-orbit constellations is proposed in this manuscript. The objective function, restriction conditions and optimization method of the intelligent planning algorithm is illustrated. The general steps of constellation supplementary network intelligent planning are explained using genetic algorithm as an example. The intelligent planning model design for large-scale low-orbit constellation supplementary network is completed.

2. Intelligent optimization method of TT&C service scheduling based on space coverage evaluation

2.1. Coverage calculation issue for large-scale low-orbit constellation supplementary network

In a large-scale low-orbit constellation, the network supplementary TT&C needs to be performed in the system when some constellation satellites malfunction. Due to the limitation of system resources, when \(N\) satellites fail, they need to be prioritized according to the optimal constellation space coverage, the top-level resource scheduling and allocation for the TT&C system will be performed and the constellation supplementary network TT&C process will be completed based on the priority order. The constellation satellite TT&C planning problem \(Q\) based on the optimal coverage of the constellation is described by the following equation

\[
Q = \langle P, I, C, T \rangle
\]

Where \(P = \{\text{Sat}_1, \ldots, \text{Sat}_n\}\) is the satellite collection sequence should be control through planning and \(n \leq N\); \(P_0\) is the initial collection and \(P_f\) is the final collection that satisfies various restrictions and can achieve the goal. \(I\) is the initial state of the planning issue. \(C\) are the planning issue restrictions. \(T\) are the goals of the planning issue.

2.2. Intelligent planning objective function

Satellite space coverage refers to the surface of the earth that can be observed by satellite instruments at a certain moment or during a long period of time. Common coverage performance includes coverage percentage, maximum coverage gap, average coverage gap, time average gap, and average response time. The ground coverage is related to the satellite orbit parameters, such as the right ascension of the ascending node of the satellite orbit, orbital inclination, orbital height [3].

The SOC methods are traditionally used for coverage analysis in Walker constellations and similar constellations. The general theory is: the coverage of multiple satellites on a single orbital plane of a
Walker constellation is regarded as an annular zone covering the surface of the earth. Multiple satellites are equally spaced on the same orbital plane. The set of circles with multiple sub-satellite points as the center and radius \( \theta \) is the coverage area of multiple satellites on a single orbital plane of the constellation. If the number of satellites in the constellation is large, multiple coverage of the ground can be formed. The width of the \( j \)-layer coverage zone is expressed as \( 2c_j \), at any point in the \( j \)-layer coverage zone, \( j \) satellites can be observed at the same time. The relationship between the width \( c_j \) of the \( j \)-layer coverage zone, the radius \( \theta \) of the coverage circle and the number of satellites \( n \) in a single orbit is [9]:

\[
\cos \theta = \cos c_j \cos(\frac{j\pi}{n})
\] (2)

The restrictions for multiple coverage of the constellation is discussed in literature [3]. For single coverage, the restrictions are:

\[
\sin c \geq \sin \phi_i \cos i - \cos \phi_i \cos(\frac{\pi}{p}) \sin i
\] (3)

\[
\sin c = (\cos \phi_i) \cos([m-1] \frac{\pi}{p}) \sin i - (\sin \phi_i) \cos i
\] (4)

\[
\sin c \geq \frac{\sin([m-1] \frac{\pi}{p}) \sin(\frac{\pi}{p}) \sin i \cos i}{(\cos^2 i + \cos^2([m-1] \frac{\pi}{p}) \cos^2(\frac{\pi}{p}) \sin^2 i)^{1/2}}
\] (5)

Constraints in the case of 2-4 layer constellation coverage are also listed in literature [3].

In equations (3)-(5), \( i \) is the inclination of the orbital plane of the constellation, \( \phi_i \) is the lowest latitude threshold and \( \phi_u \) is the highest latitude threshold. \( c \) is the half-width of the coverage band, and \( p \) is the number of orbital planes in the constellation.

The premises of using the SOC method for constellation coverage analysis are [9]:

1) All the altitude and inclination in the constellation satellite orbits are same;
2) The number of satellites in each orbital plane of the constellation is the same;
3) Satellites are evenly distributed on each orbital plane of the constellation.

For the existing large-scale low-orbit constellations of China, conditions 1), 2), and 3) can all be satisfied when all satellites in the constellation are operating normally. Therefore, it is appropriate to analyzed by the SOC method under these circumstances.

However, in the case of single or multiple satellite failures in a certain orbital plane, the number of satellites in each orbital plane is not equal, and the satellites in the orbital plane where the malfunctioning satellite is located have been unevenly distributed. The condition 2) and 3) are no longer satisfied, so the SOC method cannot continue to be used for coverage performance analysis. At the same time, since the overall number and unit space density of large-scale low-orbit constellations far exceed those of traditional constellations, the multiplicity of ground coverage is generally much greater than 1. Therefore, for the analysis of the impact of constellation coverage performance when some satellite failures in a large-scale low-orbit constellation, it is necessary to calculate the reduction in the coverage of the satellite failures under the ideal operating state of the constellation except calculating the global single coverage of the constellation. In this case, the numerical analysis method of single-satellite coverage overlap can be used.

Literature [16] proposed a simplified method to analyze the coverage performance of the constellation. When analyzing the coverage of the low orbit constellation, the coverage of the constellation satellites is abstracted from the real spherical circle to the inscribed regular hexagon of the spherical circle, and the same orbital plane and adjacent orbital planes are completed by the method of splicing multiple regular hexagons. In this case, the radius \( \theta \) of the spherical circle covered by a satellite with height \( h \) from the earth's surface is:

\[
\theta = \arccos\left(\frac{r_e \cos \epsilon}{r_e + h} - \epsilon\right)
\] (6)
Where $r_e$ is the radius of the earth and $\varepsilon$ is the lowest elevation angle of the satellite.

According to the law of cosines of spherical triangles, the half of the inner angle $\Phi$ of the inscribed spherical hexagon is:

$$\Phi = \arccos\left(\frac{\cos \theta(1 - \cos \varphi)}{\sin \theta \sin \varphi}\right)$$

(7)

Where, $\theta$ is the radius of the spherical circle, $\varphi$ is the side length of the hexagon inscribed by the spherical circle. The area $A_s$ of the spherical regular hexagon covered by a single satellite is:

$$A_s = 12\Phi - 4\pi$$

(8)

For the coverage performance analysis of a large scale low-orbit constellation with incomplete configuration, the following methods can be used to complete the impact calculation of the constellation coverage performance:

1) According to the number of orbital planes, the number of satellites in a single orbit, the radius of the coverage circle, the half-width of the coverage band, the minimum latitude threshold, the maximum latitude threshold and other parameters, the maximum coverage multiple of the constellation under ideal operating conditions is calculated by the SOC method;

2) In the event that some satellites fail, simplify the coverage of a single satellite to a regular hexagon inscribed on a spherical circle, and calculate the overall coverage performance and multiplicity of the constellation under incomplete configuration one by one;

3) Calculate the number of reductions in constellation coverage multiple and the loss of coverage performance based on the results of 1) and 2);

4) Sort the number of constellation coverage multiple reductions and coverage performance losses, and select the corresponding faulty satellites from large to small. This sequence is the satellite control priority for optimal space coverage.

Suppose the $SAT$ is the set of faulty satellites, the goal of the system planning is: When $P = \{Sat_1, \cdots, Sat_n\}$, the space coverage of the satellite constellation after repairing the network is the optimal, that is, the loss of the constellation coverage performance is the largest when the satellites in $P$ is malfunction. The objective function $T$ is as follows:

$$T = \max \sum E_i X_i, i \in N$$

(9)

Where, $E_i$ is the loss of constellation space coverage performance caused by satellite $i$ failure. $X_i$ represent whether the satellite is selected for TT&C. If it is necessary for TT&C, then $X_i = 1$, otherwise $X_i = 0$. Goal $T$ ensure that the constellation satellites planned for TT&C will maximize the overall coverage performance of the constellation.

2.3. Intelligent planning restrictions

The mathematical expressions of the key restrictions $C$ of the system include four types: time window restriction of TT&C, continuous TT&C time window restriction, storage resource restriction, computing power restriction, and satellite unique observation restriction, denoted as $C_1, C_2, C_3$ and $C_4$. Its mathematical expression is:

$$\forall i \in I, if X_i = 1, then t_i \in [S_{ij}, E_{ij}] and t_i + D_i \leq E_{ij}$$

(10)

$$\forall i_2 \in I, \forall i_2 \in I, if i_2 - i_1 = 1, then t_{i_1} + t_{D_{i_1}} + t_{M_{i_1}} \leq t_{i_2} and t_{i_1} + D_{i_1} \leq t_{M_{i_1}}$$

(11)

$$\forall i \in I, DS_i \leq DS_{free}$$

(12)

$$\forall i \in I, DC_i \leq DC_{free}$$

(13)
Formula (10) is the time window restriction $C_1$ of TT&C. The TT&C task $i$ of a satellite must start after a certain visible window starts and finish before the end of this visible window. Equation (11) is the continuous TT&C time window restriction $C_2$. For two consecutive TT&C of the same satellite, the second TT&C can only be performed after the first TT&C task is completed and the control result calibration is completed, and the start time of the control result calibration must be after the end of the current TT&C task. That is, the TT&C plan of a certain satellite not only be determined according to its current spatial position and contribution to the space coverage of the constellation, but also be determined the time window of its own TT&C sequence. Where, $t_i$ is the start time of the TT&C task $i$, $D_{t_1}$ is the time used for the first TT&C task $1$, and $t_{M_i}$ represents the time of the control results calibration in the first TT&C task $i$, and $t_2$ is the start time of the TT&C task $2$, $t_2 - t_1 = 1$ represents the TT&C task $i_1$ and the TT&C task $i_2$ are two consecutive task. Equation (12) is the storage resource restriction $C_3$, $DS_i$ is the system storage space capacity that the TT&C task $i$ will occupy, and $DS_{free}$ is the currently available storage capacity. Equation (13) is the calculation ability restriction $C_4$, $DC_i$ is the system calculation ability that the TT&C task $i$ will occupy, and $DC_{free}$ is the currently available calculation ability.

2.4. Intelligent planning optimization method

As shown in section 2.2, the constellation TT&C planning issue based on the optimal coverage of the constellation is a non-linear issue. Therefore, the issue cannot be solved by the traditional linear programming method, but must be solved by an intelligent optimization algorithm. Through intelligent optimization algorithms, the optimal solution $P_f$ of $\{Sat_1, \ldots, Sat_n\}$ in the complete set of faulty satellites $SAT$ is obtained.

Constellation satellite TT&C planning issue $Q$ can be solved by the intelligent optimization methods include immune optimization algorithms, particle swarm optimization algorithms, genetic algorithms, and neural networks. After completing planning based on multiple optimization algorithms, the optimal algorithm results according to the objective function can be selected.

The genetic algorithm be selected to solve the issue as an example to illustrate the solution process of the constellation satellite TT&C planning issue $Q$. The solution process is:

1) A constellation planning issue is coded according to the genetic algorithm coding method to generate the initial population;

2) Add the restriction conditions $C_1$, $C_2$, $C_3$, $C_4$ and perform conflict check on each bit of the chromosome. Tasks that fail the conflict check is abandoned, that is, the value of chromosome is 0;

3) Calculate the fitness value of each individual and the best individual with the highest fitness value is obtained;

4) Compare the planning goals $T$, if the end conditions are met, stop the algorithm and go to 5); otherwise, select individuals to enter the mating pool according to the selection mechanism, complete mutation and crossover operations to generate new individuals, and update the population to obtain the next generation population, return to 2);

5) Obtain the best individual after evolution and output the final planned satellite combination for this TT&C.

3. Conclusion

The manuscript aims at the issue that traditional SOC coverage analysis methods are difficult to evaluate the coverage performance of incomplete large-scale low-orbit constellations. The space coverage of
incomplete constellations with equivalent single-satellite coverage is proposed. A constellation TT&C intelligent planning method based on space coverage evaluation is proposed. Finally, a constellation TT&C service scheduling algorithm for multiple constellation TT&C restriction and coverage optimization goals is realized.

It should be noted that many intelligent optimization methods is available for constellation satellite TT&C planning. Due to space limitations, the comparison of the planning time and planning results of different constellation parameters for each method has not been studied in this article. At the same time, neural network-based constellation TT&C planning is rarely seen in published papers. In the future, if neural network methods are introduced into constellation TT&C planning, it will be possible to quickly implement constellation TT&C planning with multiple constellation satellite parameters based on historical data analysis. These issues are important directions for the follow-up research of this article.

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