Coverage of Hotspot Region with Small Satellite Constellation Design and Optimization

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Abstract. In the face of increasingly frequent regional emergency missions, the use of small satellites to obtain spatial information in hotspots has important practical needs. Under the premise of avoiding the short coverage of single satellites and limited access to information, this paper aims at research on the design and optimization of multi-satellite network orbits covered by hotspots regions. Firstly, based on the analysis of satellite coverage characteristics, the satellite coverage model is established, and the coverage calculation and coverage judgment conditions are discussed. Then a genetic algorithm based regional coverage satellite network design and optimization algorithm is proposed, which is designed the coding method, algorithm flow and corresponding constraint test rules in detail. The rationality, feasibility and effectiveness of the algorithm are finally verified by simulation examples. are provided, which provides a useful reference for regional space missions and its certain theoretical significance.

Keywords: Space-to-earth observation · Regional coverage · Orbit design · Network design · Genetic algorithm

1 Introduction

In recent years, the development of space technology, especially the rapid advancement and application of small satellite technology, has provided fast and timely information support for people to cope with and solve regional emergency space missions, such as war conflicts in hot sensitive areas and sudden major natural disasters [1]. Compared with traditional spacecraft, which mainly performs global tasks, large mass, high cost, long design life and long launch period, small satellites can be launched on demand, light in weight, low in cost, short in development time, and relatively simple maintenance on carriers and ground. Therefore, these are more suitable for deployment in low-Earth orbit to complete specific tasks for regional targets [2]. So the research on the design and optimization of small satellite network coverage for regional targets has urgent practical significance and is also the focus of scholars at home and abroad.

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Chao [3] based on an improved grid point simulation method, proposed a corresponding coverage performance index calculation method; Larrimore [4] analyzed the advantages of the constellation of inclined orbit in covering local areas, and designed the pair. The ground area realizes continuous coverage of the oblique orbit satellite constellation; Weng [5] studied the mathematical model of satellite ground cover, constraints and decision algorithms; Vtipil [6] comprehensively compared the existing three repeated ground track designs. In his paper, an initial optimization method for quickly determining the initial value of the solution is proposed, and then the improved optimization design method is proposed. The advantages of the method in solving accuracy and calculation time are also analyzed.

Based on the research results at home and abroad, the current satellite orbit design has not been related to regional coverage tasks, especially the coverage of hotspots, and it is difficult to achieve better regional coverage. Therefore, in the design of satellite orbits, it is necessary to carry out research on coverage characteristics of regional targets and orbital design research for regional coverage, with a focus on improving spatial information acquisition capabilities for regional targets.

In this regard, this paper takes the spatial information support of hotspots as the research background, and studies the design and optimization of small satellite networks for hotspot regional targets, focusing on satellite coverage characteristics analysis, satellite network orbit design and optimization. Based on the analysis of satellite coverage characteristics, the regional complete coverage judgment method is established, and the satellite-to-ground coverage model is established. Also a genetic algorithm-based regional coverage satellite network orbit optimization method is proposed. The simulation method is used to verify the method, proving that it is feasible and effective to cover satellite network optimization calculations for hotspots.

2 Satellite Grounding Characteristics Analysis and Modeling

To study the satellite coverage problem, we must first understand the coverage characteristics of the satellite. Coverage performance metrics are the basic requirement that must be addressed in track design. In this paper, based on the spatial geometric constraint relationship between satellite and ground, the satellite-to-ground coverage model is established, and the coverage performance index is proposed. The coverage analysis is carried out and the coverage judgment conditions are proposed to provide reference for the subsequent orbit design.

2.1 Coverage Problem Description

When the satellite performs the Earth observation mission, it generally carries the sensor as a payload to observe the ground target. The satellite observation area is a cone field of view, and the ground coverage area is a circular area centered on the star point. When entering the coverage area, it means that the satellite can cover the ground target. The satellite sensor sweeps across the surface of the Earth as shown in Fig. 1, which is a strip-like area.

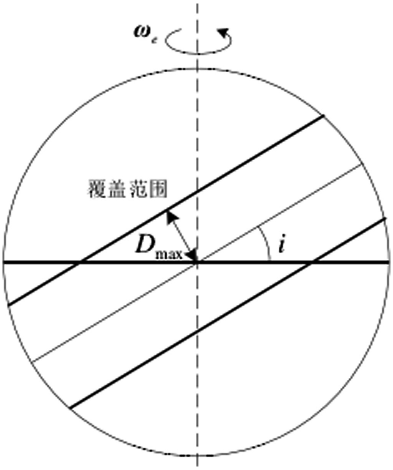

Fig. 1. Schematic diagram of satellite coverage

2.2 Ground Coverage Performance Indicators

The satellite coverage characteristics are an important basis for the satellite to complete related tasks. It is mainly determined by the orbit parameters of the satellite, the performance of the satellite platform itself, and the sensor performance. The satellite coverage characteristics mainly include basic performance indicators and evaluation indicators.

2.2.1 Ground Coverage Performance Indicators

Set in the simulation time T, the satellite covers the target n times. When the target is covered for the i-th time, the coverage start time is $t_{start}(i)$, and the coverage end time is $t_{stop}(i)$. The following coverage performance basic indicators are defined in this design:

(1) Single coverage time

$$T_F(i) = t_{stop}(i) - t_{start}(i)$$

$T_F(i)$ Indicates the duration of a single coverage, in seconds.

(2) Interval

$$T_G(i) = t_{start}(i+1) - t_{stop}(i)$$

$T_G(i)$ Indicates the interval between the start of the i + 1th overlay and the end of the i-th overlay.

(3) Revisiting time

$$T_C(i) = t_{start}(i+1) - t_{start}(i)$$

$T_C(i)$ Indicates the time interval at which the satellite continuously covers the target start time twice.

2.2.2 Ground Coverage Performance Indicators

Based on the above basic concepts, the following satellites are used to evaluate the coverage performance of the target area:

(1) Total coverage time

$$T_{Ftotal} = \sum_{i=1}^{n} T_F(i)$$

The total coverage time represents the total coverage time of the satellite to the target in a given time, and is the basic indicator of the satellite coverage time characteristics.

(2) Average coverage time

$$T_{Fmean} = \frac{1}{n} T_{Ftotal}$$

The average coverage time is the average of each coverage time, which represents the average of the satellite's single-to-ground coverage time, and the average level of satellite-to-ground coverage.

(3) Maximum coverage time

$$T_{F\max} = \max\{T_F(i)\}$$

The maximum coverage time is the maximum of a single coverage time, reflecting the ability of the satellite to cover the ground. The larger the maximum coverage time, the more sufficient the coverage time is, and the more favorable it is to complete the reconnaissance observation and other tasks.

(4) Minimum coverage time

$$T_{F\min} = \min\{T_F(i)\}$$

The minimum coverage time is the minimum of a single coverage time, reflecting the worst case scenario of satellite coverage. The smaller the minimum coverage time, the shorter the coverage time, and the more difficult it is to complete the reconnaissance observation of the target.

(5) Average revisit time

$$T_{Cmean} = \frac{1}{n} \sum_{i=1}^{n} T_c(i)$$

The average revisit time is the average of the satellite's single revisit time, indicating the ability of the satellite to continuously cover the ground. The smaller the average revisit time, the stronger the ability of the satellite to continuously cover the ground.

For regional targets, it is also necessary to consider the relevant time characteristics of a complete coverage. Suppose that in the kth complete coverage, the definition of the coverage start time is, and the end time is, then the following time coverage characteristic indicators are proposed:

(6) Time required for complete coverage of the area

$$T_{stop}(k) - T_{start}(k)$$

(7) Regional full coverage revisit time

$$T_{start}(k+1) - T_{stop}(k)$$

The spatial coverage characteristic mainly refers to the distance between the satellite and the target when the satellite covers the ground target. Since the target is not necessarily in the orbital plane every time the satellite covers the target, even if the target is in the orbital plane, the satellite is not always above the target, so the distance from the satellite to the target is generally greater than the orbital altitude of the satellite. For satellites with orbital parameters and sensor parameters, the distance between the satellite and the ground target will affect the resolution of the satellite to the target, and the resolution is an important performance parameter of the remote sensing satellite. The spatial coverage characteristics mainly include: the average distance between the satellite and the target; the maximum distance between the satellite and the target; the minimum distance between the satellite and the target.

2.3 Coverage Calculation Process

Set the S′ latitude and longitude of the satellite star point at a certain time (λ_s, φ_s), the latitude and longitude of the target point (λ_0, φ_0), and calculate the geocentric angle of the target point and the sub-satellite point ψ. If so $\psi < \beta$, the target is in the instantaneous coverage area of the spacecraft, otherwise, it is not in the coverage area. If the initial time t_0 is given, the appropriate step size Δt is selected. By judging whether the target is within the satellite coverage area after each step of time advancement, the start time t_1 and the end time t_2 of the satellite coverage target can be obtained, and the difference T_F between the two can be obtained. The coverage time of the satellite to the target. The specific judgment process is shown in Fig. 2.

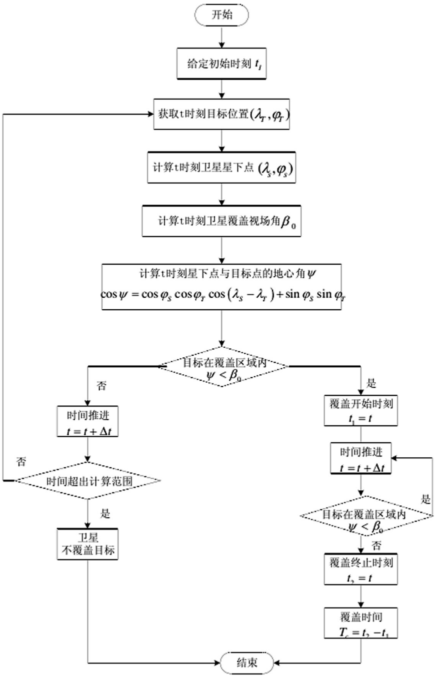

Fig. 2. Calculation process of the coverage time of the ground

3 Design and Optimization of Satellite Area Coverage Network Based on Genetic Algorithm

The problem of regional coverage satellite network optimization is a multi-parameter optimization problem under complex constraints [7]. The problem is to meet the requirements of coverage, coverage time performance and space performance under the premise of system tasks. Excellent networking parameters.

3.1 Network Track Design Optimization Variables

For the hot spot coverage observation problem, the satellite orbital height, orbital inclination, ascending node and the near-earth angle can affect the coverage performance of the network orbit to a certain extent. Therefore, in the orbit optimization process, the orbital parameters of each satellite in the networking system, namely the orbital height, the orbital inclination, the ascending point, the ascension, the initial latitude and the angle, are used as design variables, respectively a_j, i_j, Ω_j, u_j $(1 \le j \le n$, n is the number of satellites) said. Since the system cost determines the number of satellites in the constellation, the satellite number n is not used as an optimization variable.

3.2 Regional Coverage Network Optimization Mathematical Model

The regional coverage network optimization problem in this paper refers to the reasonable selection of the orbit parameters and networking parameters of the networked satellites in the case of the number of satellites required for a given network, the orbital type of the satellite, and the geographic location of the network coverage target, to achieve the best possible coverage performance of the constellation formed by the networking.

3.2.1 Constraints

The following constraints must be met during the satellite network coverage optimization process:

(1) In order for the satellite to achieve continuous coverage of the target, the satellite orbital inclination i is constrained by the target latitude φ:

$$\varphi \leq i \leq \varphi + 5^\circ$$

(2) The orbital planes in the constellation are arranged in order:

$$0^\circ \leq \Omega_1 < \Omega_2 < \cdots < \Omega_n < 360^\circ$$

(3) Need to meet the lighting conditions, the sun's elevation angle meets the constraints:

$$\delta \geq 5^\circ$$

3.2.2 Optimization Objectives

Considering that the average revisiting time can affect the satellite's ability to quickly revisit the target to a certain extent, generally, the shorter the average revisiting time, the stronger the satellite's ability to quickly revisit the target, so the average revisiting time is minimized to optimize. The target, its mathematical expression is as follows (2–5).

$$Q_2 = \min\left(\frac{\sum_{i=1}^{n} InT_i}{n}\right)$$

Where InT_i is the interval between two observations of the satellite adjacent to the target area.

3.3 Genetic Algorithm Based on Continuous Optimization Variables

Genetic algorithms (GA) are a kind of random search algorithm based on biological evolution mechanism. The main steps are as follows:

(1) Encoding method. The orbital parameters of each satellite in the network system, namely the orbital height, the orbital inclination, the ascending node and the initial

latitude, are expressed as a_k, i_k, Ω_k, u_k ($1 \leq k \leq n$, n is the number of satellites). A pool of population genes with a population of m can be expressed as:

$$\left.\begin{array}{c} a_{11}, i_{11}, \Omega_{11}, u_{11}, a_{12}, i_{12}, \Omega_{12}, u_{12}, \cdots a_{1n}, i_{1n}, \Omega_{1n}, u_{1n} \\ a_{21}, i_{21}, \Omega_{21}, u_{21}, a_{22}, i_{22}, \Omega_{22}, u_{22}, \cdots a_{2n}, i_{2n}, \Omega_{2n}, u_{2n} \\ \vdots \\ a_{m1}, i_{m1}, \Omega_{m1}, u_{m1}, a_{m2}, i_{m2}, \Omega_{m2}, u_{m2}, \cdots a_{mn}, i_{mn}, \Omega_{mn}, u_{mn} \end{array}\right\} m$$

(2) The initial population is randomly generated. This paper uses a random method to generate chromosome strings from the initial population.

(3) Evaluation of fitness value. This paper directly uses the objective function in Sect. 2.2.2 as the fitness function.

(4) Genetic operators, including selection operators, crossover operators, and mutation operators. For the selection operator, the higher the fitness function value, the higher the probability of being selected to pass to the next generation; using the single-point crossover operator, that is, arbitrarily selecting two individuals after the selection operator operation, randomly generating a cross Point position, the two-part gene code with the intersection point as the boundary is exchanged to form two new sub-individual replacement individuals; the basic bit mutation operator is used to realize the probability replacement of the gene code, and provide opportunities for the generation of new individuals to maintain the diversity of the population.

(5) Termination conditions. The search is terminated when the genetic algebra is greater than a certain set algebra or the fitness value of the current population is less than the fitness limit. The chromosome with the greatest fitness after termination of the search is an approximate optimal solution, and the networking parameters are obtained by decoding the chromosome to determine the optimal networking scheme.

4 Simulation Examples and Analysis

4.1 Simulation Environment and Conditions

In the test simulation, all algorithms and programs are implemented with MATLABR2012a programming software. The target and satellite model establishment and time window calculation are all implemented by STK9.2 simulation software (Fig. 3).

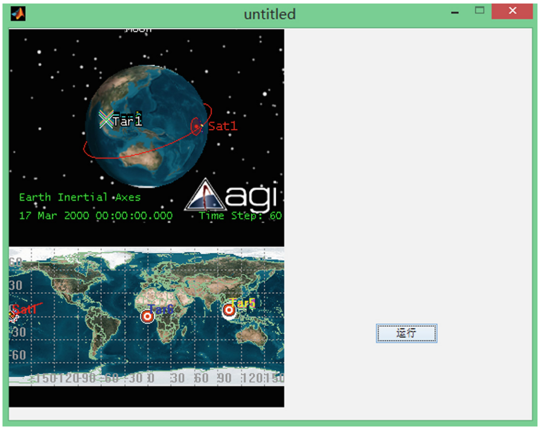

Fig. 3. GUI operation diagram

4.2 Analysis of Simulation Results

The number of satellites is set to one to four, the orbital inclination angle range is (20°, 30°), and the orbital height range is (500 km, 1000 km). The range of the ascending node and the initial latitude of the satellite in the constellation are both varied in (1°, 360°). The optimized orbital parameter values are shown in Table 1. The relationship between the average revisit time optimization result and the number of satellites is shown in Fig. 4.

Table 1. Optimize the orbit parameters and optimization results.

Number of satellites	Orbital height/km	Orbital inclination/deg	Ascending node right ascension/deg	Initial latitude angle/deg	Average revisit time/s
1	6960.24384	23.8432884	332.6851722	101.0735087	9782.17271
2	6918.79902	20.4639945	339.5476814	94.78888381	6448.15512
	6909.52367	20.1011046	291.7468287	71.36647551	
3	6960.56384	23.8413242	332.6553142	102.0735087	4252.26223
	6938.05164	21.1285090	184.3200334	37.31650155	
	6950.81939	23.6590556	332.6875425	316.0013522	
4	6960.24272	23.8767674	333.7576766	101.8524243	3025.15413
	6909.52243	20.1243893	291.7689667	71.27389724	
	6938.05776	21.7676676	184.3376764	37.85675242	
	6950.82339	23.6572722	332.6727865	316.0212352	

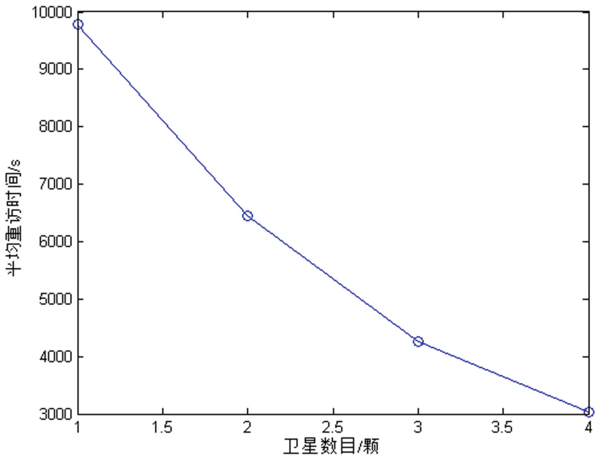

Fig. 4. Relationship between the average revisit time and the number of satellites

As can be seen from the above figure, the number of satellites has increased from 1 to 3, and the rate of decline is relatively fast, 3 to 4, and the average revisiting time has slowed down significantly. Since then, increasing the number of satellites will lead to an increase in system cost line type. However, coverage performance optimization benefits are reduced, so consider using four satellites to form a networking solution.

On the other hand, from the coverage of the target area, the optimization results obtained under the respective satellite numbers are brought into the STK for simulation verification, and the regional coverage results are shown in Table 2.

Table 2. Relationship between coverage of target area and number of satellites.

Number of satellites	Target area coverage
1	64.43%
2	100%
3	100%
4	100%

It can be seen from the above table that by increasing the number of satellites, the average revisit time of the satellite to the target area is shortened, and the coverage of the target area can be improved. When the number of satellites reaches two, full coverage of the target area can be achieved within the simulation period, and the number of satellites continues to increase, and only the average revisit time is shortened.

5 Conclusion

In this paper, based on the design and optimization of small satellite network for hotspot target, a genetic algorithm based design and optimization method for regional coverage satellite network orbit is proposed: (1) Based on the analysis of satellite coverage characteristics, a satellite coverage model is established. This model gives the satellite coverage performance index including time characteristics and spatial characteristics, and discusses coverage calculation and coverage judgment conditions. (2) Research on satellite orbit design and optimization for area coverage is launched, and this paper proposes a genetic algorithm which covers the satellite network design and optimization algorithm. Also the algorithm flow and corresponding constraint checking rules are designed in detail. (3) The rationality, feasibility and effectiveness of the algorithm are verified by simulation examples, which provides a useful solution reference and technical ideas for regional space mission.

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