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Research on the Configuration Design Method of Heterogeneous Constellation Reconstruction under the Multiple Objective and Multiple Constraint

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Abstract. Aiming at the problem of configuration design of heterogeneous constellation reconstruction, a design method of heterogeneous constellation reconstruction based on multi objective and multi constraints is proposed. At first, the concept of heterogeneous constellation is defined. Secondly, the heterogeneous constellation reconstruction methods were analyzed, and then the two typical existing design methods of reconstruction, phase position uniformity method and reconstruction configuration design method based on optimization algorithm are summarized. The advantages and shortcomings of different reconstruction configuration design methods are compared, finally the heterogeneous constellation reconstruction configuration design is currently facing problems are analyzed and put forward the thinking about the reconstruction index system of heterogeneous constellation and the selection of optimal variables and the establishment of constraints in the optimization design of the configuration.

INTRODUCTION

In 2016, China launched 3 Beidou satellites, the number of orbiting satellites of Beidou satellite navigation system currently has reached 22. Is expected in 2020, to build a global satellite navigation system, which will be another global satellite navigation system after the GPS (Global Position System) of America, the GLONASS of Russia and the GALILEO of EU. Different from GPS and GLONASS satellite navigation system, Beidou satellite navigation system uses a heterogeneous constellation configuration, the type of track included GEO, IGSO and MEO, which makes the Beidou satellite navigation system has stronger regional coverage and greater stability.

Whether the Beidou satellite navigation system or other satellite systems, after the completion of space deployment of constellation, the constellation space configuration is not set in stone[1]. when one or more satellite constellation failure or ground mission requirements changes, by calling the backup satellite or maneuvering other orbiting satellites to maximize the performance of damaged constellation, or to build a different constellation configuration which can better meet the demands of a new task, to improve the stability, reliability and flexibility of the space system will be particularly important.

THE CONCEPT OF HETEROGENEOUS CONSTELLATION RECONFIGURATION

Heterogeneous Constellation

In the early days of the constellation, most constellations are homogeneous constellation. But with the diversification and complexity of space missions, our focus gradually shifted from the global to regional, the distribution mode of the satellites in the constellation also gradually from uniform to personalization, the configuration

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of constellation system is also more and more complex, resulting in a lot of different heterogeneous constellations. But at present, there is no clear definition for the heterogeneous constellation, the typical definitions are:

1. Constellation called heterogeneous constellation composed of a variety of orbits.
2. The constellation different from Walker are collectively referred to as the heterogeneous constellation[2].

To better reflect the characteristics of heterogeneous constellation, easy to carry out research, in this paper, the concept of heterogeneous constellation was further clarified, on the basis of the predecessors. The heterogeneous constellation that conforms to the following conditions:

1. The constellation has obvious mission requirements, namely all satellite revolves around the same specific tasks.
2. The constellation has a relatively fixed space geometric configurations.
3. The space structure of constellation does not have the same uniformity and symmetry as Walker.

According to the division of the coverage area, the heterogeneous constellation can be divided into the global heterogeneous constellation and the regional heterogeneous constellation, as shown in table 1.

TABLE 1. Global heterogeneous constellation and regional heterogeneous constellation

Classification of Heterogeneous Constellations	Definition
Global Heterogeneous Constellation	The coverage area of the constellation is longitude -180 degrees to 180 degrees, latitude -90 degrees to 90 degrees, the constellation contains different types of orbits, the number of satellite on different orbits are not the same. For example, the elliptical orbit and the equatorial orbit are used in the communication constellation and the early warning constellation; the IGSO orbit, the GEO orbit and the MEO orbit are used in navigation constellations. The typical representatives are the Ellipso satellite communications system and the Beidou satellite navigation system.
Regional Heterogeneous Constellation	Regional heterogeneous constellation is designed to coverage a specific area of the earth's surface, the relative distance between different satellites is close, each satellite work together, in the constellation. The typical representative is the Russian Molniya satellite communications system.

Constellation Reconstruction

Constellation reconstruction is a kind of way to improve the performance of constellation or meet the requirements of the new task by adjusting the existing configuration in the face of system failure, environmental challenge and task change. According to the different application scenarios of constellation reconstruction, the constellation reconfiguration can be divided into the satellite failure reconstruction and the ground mission change reconstruction[3,4]. According to the different stages of the reconstruction process, constellation reconstruction can be divided into two aspects: reconstruction configuration design and reconstruction process control.

Reconstruction configuration design is the foundation and key of the whole constellation reconstruction task, which is the precondition of the constellation performance, this paper mainly studied on this issue.

ANALYSIS AND COMPARISON OF EXISTING METHODS

Configuration design of constellation is the process of establishing the mathematical model of the reconstruction and obtaining the final configuration according to the different reconstruction scenarios and use existing indicators and methods. The existing methods of reconfiguration design mainly include phase uniformity method and reconstruction configuration design method based on optimization algorithm.

The Phase Uniformity Method

The phase uniformity method is a kind of reconstruction strategy aiming at satellite failure in constellation to improve the performance of constellation by adjusting the phase angle of the satellite in the constellation[5]. First, according to the number of failed satellites in the constellation and the orbit of the failed satellite, the failure can be divided into three types: single satellite failure, multi coplanar satellite failure and multi non-coplanar satellite failure. For single satellite failure, through adjust the phase angle of one or two adjacent satellites, the position vacancy caused

by the failure of satellite can be filled by multi adjacent satellite; For multi coplanar satellite failure, by adjusting the phase angle of all the satellites in this plane, make the satellite in the orbit plane distributing evenly; For multi non-coplanar satellite failure, by adjusting the phase angle of all the satellites in the constellation, make the satellite of the whole constellation distributing evenly, and the whole process of the method is shown in Fig.1.

Due to the only existence of coplanar orbital maneuver, the method has many advantages, including energy saving, implementation simplicity, simple process, little damage to the original configuration and strong ability of recovery. However, this method can only be applied to the reconstruction of satellite failure, and the object of the reconstruction must be coplanar, multi-satellite and multi-track, the method is not suitable for other configurations.

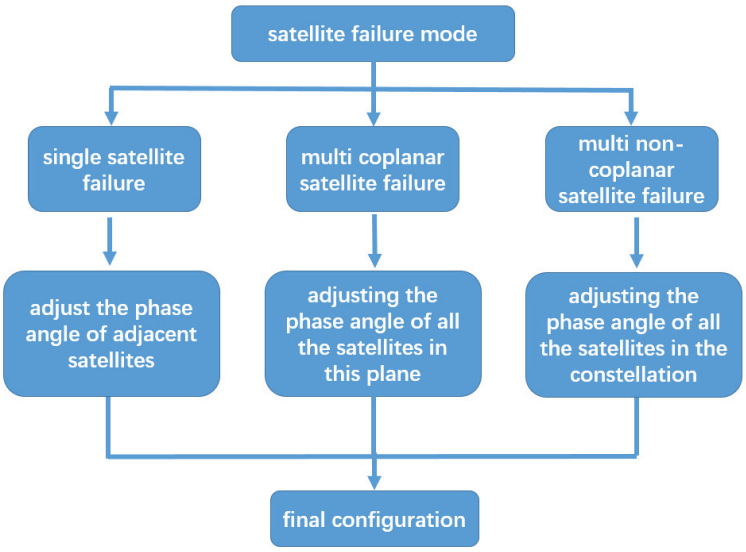

FIGURE 1. The diagram of the phase uniformity method

The Design Method of Reconstruction Configuration Based on Optimization Algorithm

The design method of reconfigurable configuration based on optimization algorithm[6,7], firstly, according to different scenarios and requirements, an effective reconstruction strategy is determined. The reconstruction strategy generally includes the purpose of reconstruction, the method of reconstruction and the constraint of reconstruction.

The purpose of reconstruction is the expected result achieved by reconstruction. From the existing literature, the one or several coverage performance index or new task requirements are used as the purpose of reconstruction.

The method of reconstruction is the method and means of configuration adjustment, such as, whether or not to supplement new satellites in the process of reconstruction, how to maneuver the on-orbit satellites, which satellites in the constellation should be adjusted, and which parameters of the satellite should be changed.

The constraint of reconstruction is some constraints and restrictions of the reconstruction process, such as the time of reconstruction and the energy of reconstruction.

Then, the mathematical model of reconstruction configuration design is established, using the existing optimization algorithms such as genetic algorithm, auction algorithm and particle swarm optimization algorithm, the optimal solution of the model is obtained. This method can not only solve the satellite failure reconstruction but also the ground mission change reconstruction, and the whole process of the method is shown in Fig.2.

Analysis and Comparison

The above two methods are compared and analyzed, as shown in Table 2.

Through the study of the above two kinds of methods, it can be found that the existing methods mainly evaluate the reconstruction process from two aspects: the performance of the reconstructed constellation and the cost of the reconstruction, or as a goal to design the reconstruction configuration and reconstruction process. It is feasible when the constellation configuration is not complex, and the mission is not sensitive to the timeliness. However, with the

complexity of constellation, the depth of the application of military and civilian fields is increasing, and the current method has obvious shortcomings.

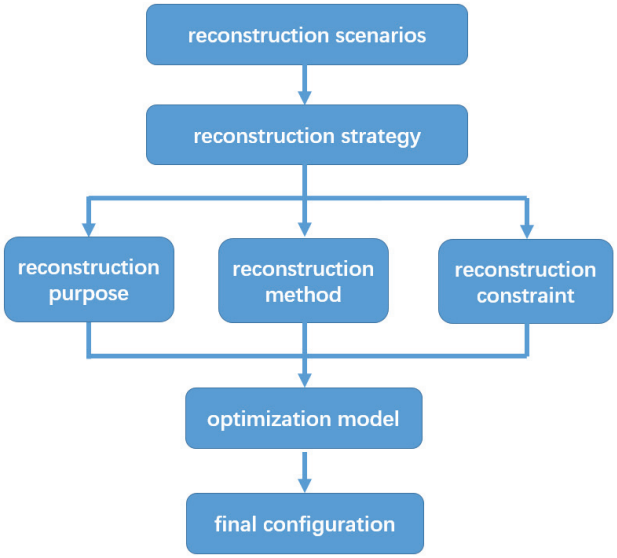

FIGURE 2. The diagram of the design method of reconfigurable configuration based on optimization algorithm

TABLE 2. Comparative analysis of different methods.

Method	Advantages	Disadvantages
The Phase Uniformity Method	Energy saving, implementation simplicity, simple process, little damage to the original configuration and strong ability of recovery.	Only apply to satellite failure reconstruction. The object of the reconstruction must be coplanar, multi-satellite and multi-track. Cannot guarantee the optimality of the final configuration.
The Design Method of Reconstruction Configuration Based on Optimization Algorithm	Wide range of applications. No special requirements for the reconstruction object. Can guarantee the optimality of the final configuration.	Lack of mature mathematical models and specific reconstruction indexes. The process is complex and difficult to realize.

First of all, the existing methods usually only consider the performance of coverage when evaluate the constellation[8]. But for a satellite system with complex features, we should also consider the fault tolerance, stability, scalability, information transmission, etc. In the same time, the time and energy of reconstruction is the most important consideration in the assessment of the reconstruction process. These two indexes are very important in the constellation reconstruction, but they cannot fully evaluate the pros and cons of the whole reconstruction process, we should also consider the number of adjusted satellites, the distribution of reconstruction energy, the compromise of reconstruction cost, and so on.

Then, no matter the phase uniformity method or the design method of reconfigurable configuration based on optimization algorithm, there is a lack of mature mathematical model, efficient optimization method and systematic design scheme at present. Especially in the process of optimization of reconstruction configuration, the selection of the optimization variables and the establishment of the constraints, are lack of effective methods and unified models.

THE CONFIGURATION DESIGN METHOD OF HETEROGENEOUS CONSTELLATION RECONSTRUCTION UNDER THE MULTIPLE TARGET AND MULTIPLE CONSTRAINT

The Establishment of the Index System of Reconstruction

According to the characteristics of the heterogeneous constellation reconstruction, this article from the effects on the constellation performance in the process of reconstruction, the number of adjusted satellites, the recovery ability of reconstruction configuration, the distribution of reconstruction energy, the compromise of reconstruction cost these five aspects.

The reconstruction index of the heterogeneous constellation is presented, as shown in Table 3. In addition, the above mentioned constellation performance index and reconstruction cost (reconstruction energy, reconstruction time) also belongs to the category of heterogeneous constellation reconstruction index. For different types and tasks of the satellite system, the indexes need to be concerned about are not the same, the priority of different indexes are also different.

TABLE 3. Global heterogeneous constellation and regional heterogeneous constellation

Reconstruction Index	Index Definition
The Decline of Constellation Performance in the Process of Reconstruction	The reconfiguration control will lead to the suspension of the satellite service, which leads to the further decline of constellation performance. Therefore, the impact of constellation reconfiguration on performance is an important factor to be considered. Constellation reconstruction should try to avoid the impact on the coverage performance of the key areas, and try to complete the reconstruction without affecting the overall performance of the constellation.
The Number of Adjusted Satellites	The number of adjusted satellites will have a direct impact on fuel consumption, reconstruction time and the constellation performance, therefore always hope that by adjusting the limited number of satellites to maximize the constellation performance or meet the mission requirements, and does not need to adjust all the satellite, we need to choose the appropriate strategy to determine which satellite should be adjusted.
The Recovery Ability of Reconstruction Configuration	Reconstruction is just a short-term consideration to repair and improve the constellation performance, When the replacement satellite is deployed or the ground mission is cancelled, the constellation should be able to recover to the basic configuration through reconstruction, therefore, the capacity and cost of the constellation to recover to the basic configuration should be reflected in the constellation reconstruction configuration design.
The Distribution of Reconstruction Energy	The on-orbit working time of different satellites is not the same, leading to the different propellant carried by each satellite before the reconstruction. If we only consider the total energy needed to complete the reconstruction without considering the distribution of the reconstructed energy, it will lead to the service time of constellation uncertain after reconstructing. So it is necessary to consider the distribution of reconstruction energy.
The Compromise of Reconstruction Cost	Constellation reconfiguration is actually a process mutual of compromising and balancing between different constraints, such as the pursuit of reconstruction in the shortest time, the consumption of energy will be a lot; complete the reconstruction with the least energy, the reconstruction of the time will be very long. Therefore, the compromise and balance of various constraints in the reconstruction process are also the factors to be considered.

The Establishment of Objective Function and Constraint

Usually, the objective function is made up of one or more performance indexes of constellation, such as the revisit time, covering multiplicity, response time, percentage of coverage, fault tolerance of constellation, extensibility of

constellation etc. There is no fixed pattern or dominant analysis formula of the objective function. For different types of constellation, the focus of the performance index is not the same, the importance of the selected performance index is also different.

At the same time according to the mission requirements, many performance indicators have different requirements in different regions, different configurations of constellation have different coverage performance on the different regions, so the key to establishment of objective function is how to select and distribute the performance index.

The constraint is the restriction on the reconstruction configuration design of heterogeneous constellation. In addition to the reconstruction time and reconstruction energy, the effects on the constellation performance in the process of reconstruction, the number of adjusted satellites, the recovery ability of reconstruction configuration, the distribution of reconstruction energy and the compromise of reconstruction cost, are all belong to the constraint.

The constraint in the constellation reconfiguration design is not only complex, but also multi-class and multi-level. The constraints not only exist the differences in the amount of computation, but also often fuse with each other. Therefore, the organization and processing of constraint are the key points and difficulties in the optimal design of reconstruction configuration.

Method flow

The general flow chart of the configuration design method for the reconstruction of the heterogeneous constellation under the multiple targets and multiple constraints is shown in Fig.3

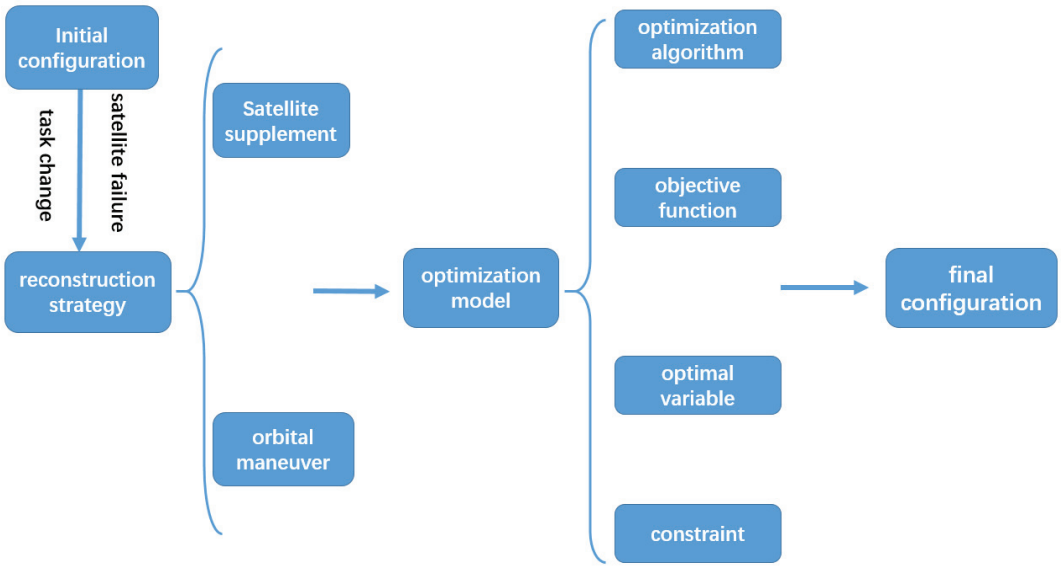

FIGURE 3. The diagram of the configuration design method for the reconstruction of the heterogeneous constellation under the multiple targets and multiple constraints.

CONCLUSION

The research on the reconstruction configuration design of heterogeneous constellation is of great strategic significance and application value to enhance the ability to deal with complex and changeable ground mission and improve the stability, reliability and flexibility of our existing space system. Heterogeneous constellation will be a trend of the future development of the constellation, but at home and abroad, the research of constellation reconstruction starts late, and most of them remain in the homogeneous constellation. Moreover, there is no mature model and index for the design of reconstruction configuration of heterogeneous constellation, which is what the author needs to study and solve.

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The author's main research direction is the analysis and design of space mission, constellation configuration design. Studying for a master's degree at Equipment Academy of PLA. This paper puts forward the problem and thought, which is what the author needs to solve and research in the next study.

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