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Research Progress on Requirements Integrated Preprocessing and Mission Planning for Earth Observation Satellites

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Abstract. The scale of Earth observation satellite system continues to expand and its application is becoming more and more extensive, which puts forward higher requirements for satellite mission planning system. This paper summarizes and analyzes some key issues in the mission planning of earth observation satellites. Firstly, the development status and the trend of earth observation satellites are introduced. Secondly, we summarize and analyze complex requirements of observation decomposition method, the priority of requirements determination method, the model construction and solving methods of single-satellite scheduling, multi-satellite integrated scheduling and multi-satellite dynamic scheduling in the process of requirements Integrated Preprocessing and mission planning. Finally, we discuss the problems that still need to be solved and the direction of research.

1. Introduction

Earth observation satellites include optical imaging satellites, SAR (Synthetic Aperture Radar) imaging satellites, missile early warning satellites, electronic reconnaissance satellites, ocean surveillance satellites, meteorological satellites and other types [1]. Earth observation satellites use the sensors they carried to obtain images and signals of specific areas according to the user requirements, and send the information back to the ground for analysis and judgment [2]. Earth observation satellite is currently the satellite with the largest number of launches and the widest application range in the world. Its unique space location advantage plays an important role in national defense construction and social development.

In recent years, the boom in the development of civil and commercial earth observation satellites has led to the continuous expansion of the scale of space earth observation systems and their wider application. It has also given rise to many problems such as complicated and diverse user requirements and difficulties in the unified scheduling of satellite. How to use operational research knowledge and computer technology to coordinate and dispatch satellite and ground station resources has become an urgent problem in space engineering. Therefore, relevant researchers in various countries have been committed to this aspect of research.

2. Development status of earth observation satellites

Since the United States successfully launched the world's first earth observation satellite Discovery 1 on February 28, 1959, the earth observation satellite has undergone nearly 60 years of development. The capability of space earth observation system has been steadily improved, its scale has been continuously expanded, and its application has become more and more extensive. As of September 31, 2018, the world has successfully launched 8,126 spacecraft, of which Earth observation satellites are



the most numerous satellites, with 2,865, accounting for more than 35%. In terms of imaging type, the number of optical imaging satellites is the largest, accounting for more than 60% [3-6]. In addition, there are satellites carrying infrared, ultraviolet, microwave and other sensors, which can integrate the acquired information. These satellites carrying one or more sensors tend to form constellations for observation more and more, so as to enhance the capability of quick revisit, such as Flock constellation, Lemur constellation and SkySat constellation. The development of global civil space has accelerated this trend. Satellites with different sensors, different orbits and different administrative departments have entered space in large quantities, which has brought great challenges to the management of satellite resources and to meet the requirements of users. This paper is based on this background to introduce the research status of earth observation satellite requirements integrated preprocessing planning and mission planning.

3. Research on requirements integrated preprocessing

The tasks of satellite observation can be classified from different perspectives. How to accurately understand the user requirements and make a priority ranking is a key step before the mission planning. This chapter will focus on summarizing and analysing the integrated preprocessing of the user observation requirements.

3.1. Complex requirements decomposition

The requirement that satellites cannot complete at a time is called the complex requirement. The complex observation requirement mainly includes: regional target observation, periodic observation, multi-sensor cooperative observation, multi-satellite cooperative observation, moving target searching and tracking, etc. This paper analyses the following three complex observation modes and introduces the research progress on them.

3.1.1. Regional target observation. Regional target refers to the target that satellites cannot completely cover by one-off observation due to the limitation of remote sensing width. Now, there are mainly two methods to decompose regional targets: one is Rivett C's proposal to decompose regional targets into multiple point targets for independent observation [7], but this method may lead to more overlap of observation bands, thus reducing observation efficiency. The other is to realize the decomposition of regional targets by splicing observation strips [8]. This method is also divided into static decomposition method and dynamic decomposition method. Static decomposition refers to decomposing regional targets into parallel strips according to a fixed strip width in advance, while dynamic decomposition method selects the width and direction of strips according to the satellites that transit through the targets. Static decomposition method is suitable for single-satellite observation, while dynamic decomposition method is suitable for multi-satellite joint observation [9-10].

3.1.2. Multi - satellite cooperative observation. The efficiency of satellites cooperative observation with different sensors is higher than that of large and complex single satellite observation, and the robustness of multiple satellites is stronger, but the integrated mission planning of multiple satellites is far more complex than that of single satellite. Different researchers design different rules and algorithms for different emphases to solve the problem of multi-satellite integrated mission planning. Literature [11] proposed a multi-satellite cooperative observation strategy based on target priority ranking and space-time constraints for satellite observation in natural disaster areas. Literature [12] established a constraint satisfaction model for mission planning of cooperative observation of high and low orbit satellites. Literature [13] greatly improved the recognition capability and positional accuracy of multi-satellite cooperative observation.

3.1.3. Moving target searching and tracking. The searching and tracking of moving targets generally need some prior information. If the region of the moving target is known, the LEO imaging satellite constellation can be used to search for the specified region, and a motion prediction model of the

target needs to be established. Berry P E [14-15] established a target motion prediction model based on Gaussian distribution using Bayesian estimation technology. If the target has electromagnetic signals, it is more reliable to use electronic reconnaissance satellites and optical imaging satellites to search for moving targets in cooperation [16]. At present, there is still no general and effective method for searching and tracking moving targets with camouflage, no electromagnetic signals and agile movement, which is a research focus in the field of military reconnaissance satellites.

3.2. Prioritization of Requirements

At present, determining priority of user requirements is still mainly through relevant experts or commanders. However, with the increasing number of requirements, the efficiency of relying on people to determine the priority of these needs is becoming lower. How to use computers to automatically determine an appropriate observation priority according to certain rules is of great importance to subsequent mission planning. On the basis of analysing the engineering requirements of TT&C resources, literature [17] studied nine basic principles of resource priority and proposed a method to solve the problem of priority based on improved TOPSIS method (Technique for Order Preference by Similarity to an Ideal Solution). Literature [18] used the same method to analyse the priority of earth observation satellite resources. In the research on the quantification of requirements value, literature [19] analysed the STT (Strategy To Task) framework of RAND Company and the application of STT in ISR(Intelligence, Surveillance and Reconnaissance), and made some improvement on STT framework in the calculation of requirements value. Literature [20] proposed a concept of time margin to reflect the degree of satisfaction of meeting tasks' urgency, and established a mission planning model based on priority and time margin. We concluded that there are many researches on priority evaluation of requirements or tasks, but it is mainly similar to expert systems that establish certain rules to actively assign parameter values to some influencing factors, with lacking evaluation of results.

4. Research on Mission Planning Model

Mission planning of Earth observation satellites is a complex combinatorial optimization problem including multi-task and multi-constraint. Different mission planning models and corresponding solving methods need to be established according to different types of earth observation satellites and tasks including conventional and emergency tasks or static and dynamic task. From the current research situation, satellite mission planning modeling can be divided into single-satellite mission planning and multi-satellite mission planning modeling. The established models are shown in Figure 1.

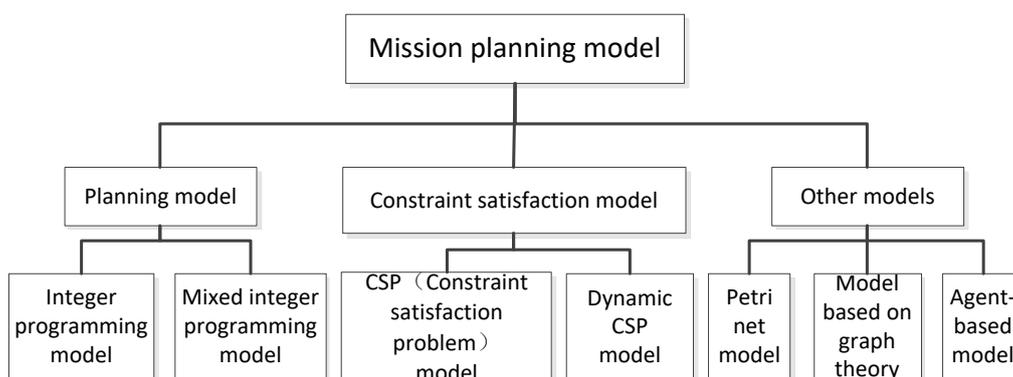


Figure 1. Mission planning model.

4.1. Modeling of Single Satellite Mission Planning

Different earth observation satellites have different characteristics in their mission planning. When SAR satellites perform imaging missions to the earth, they are not affected by meteorological factors such as cloudiness and illumination, can switch working wave positions for observation, and the power consumption of equipment in standby state is very small, which is quite different from visible satellites in terms of working mode and sensor constraints. Therefore, there are differences in the mission planning models and algorithms between visible light satellites and SAR satellites.

For SAR imaging satellites, De Florio S [21] proposed two mission planning methods, sequential insertion method and intermediate insertion method. Bianchessi N and Righini G [22] have studied the mission planning of COSMO-SkyMed SAR satellite, developed a construction algorithm with foresight and retrospective ability, and achieved the goal of shooting and transmitting 1800 images every day. For optical imaging satellites: Bensana E [23], Vasquez M [24], and Gabrel V [25] have all studied mission planning of French SPOT5 satellite. [25] established an integer programming model, but did not consider the constraints of data transmission. [26] established a constraint satisfaction model similar to the 0-1 knapsack problem, which takes into account the constraints stored on the satellite but also does not consider the data transmission constraints. [27] established an integer programming model based on graph theory and mathematical programming knowledge, but neither on-board storage constraints nor data transmission constraints were considered.

4.2. Modeling of Multi - Satellite Integrated Mission Planning

The planning of multi-satellite joint observation mission is very complicated. One of the most important factors is that it contains many constraints, and the actual constraints for specific problems are not the same. This paper summarizes the main constraints of mission planning for earth observation satellites, as shown in Figure 2.

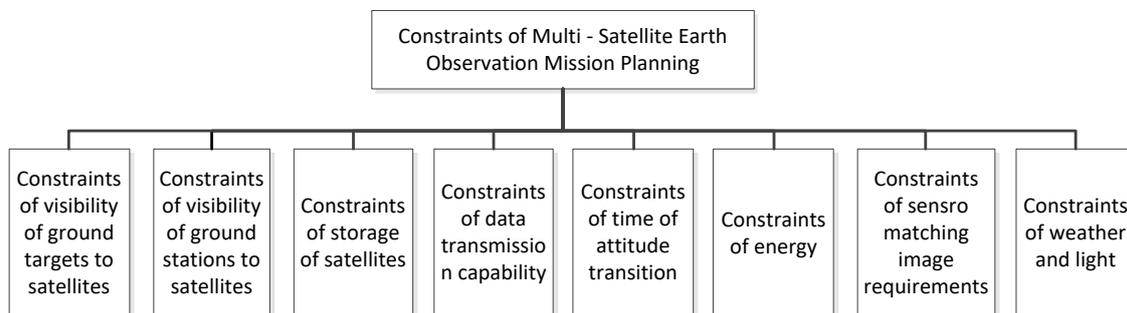


Figure 2. Constraints of Multi - Satellite Earth Observation Mission Planning.

For the complex constraints, the researchers have made targeted studies respectively. Literature [26] considered various data compression ratios of data storage, and on this basis establishes a time-ordered acyclic directed constraint model. Literature [27] divided the multi-satellite mission planning into two phases: imaging to the ground and data return, and establishes a model based on phase optimization. Literature [28] proposed a closed-loop control model for satellite imaging, which takes into account uncertainties such as targets, imaging sensors and environment. Frank J [29] considered the constraints of storage capacity, data download speed and task priority in his model, but the disadvantage is that the required resources need to be declared before planning.

In multi-satellite mission planning, mission composition is a key link, which is an important strategy to reduce mission conflicts and improve the efficiency of satellite observation. The composition of multiple atomic task must meet certain conditions. If we assuming the composite task COM_{ij} includes atomic-task set as SO_{ij} , Start-time set of SO_{ij} as SWS_{ij} , end-time set of SO_{ij} as SWE_{ij} , and observation angle set as SA_{ij} . The time window of atomic-task is $[we_{ijkv}, ws_{ijkv}]$ and the angle of it is a_{ijkv} . $Span_i$ and Δa_i represent the maximum single boot time and viewing angle of satellite S_i . Then the conditions that the atomic task in SO_{ij} can be composed are:

$$\max_{w_{e_{ijkv}} \in SWE_{il}} w_{e_{ijkv}} - \min_{w_{s_{ijkv}} \in SWS_{il}} w_{s_{ijkv}} \leq Span_i \tag{1}$$

$$\max_{a_{ijkv} \in SA_{il}} a_{ijkv} - \min_{a_{ijkv} \in SA_{il}} a_{ijkv} \leq \Delta a_i \tag{2}$$

Many researchers have studied the methods of satellite observation missions composition. Liu X L [30] developed a dynamic planning algorithm to find the best task composition plan for each satellite. Literature [31] proposed a dynamic merging (DM) strategy and designs a candidate merging task set establishment (CMTSE) algorithm. Literature [32] proposed a repair technology to overcome the problem of reduction of task imaging opportunity caused by composite.

In addition to task composition, revenue calculation of multi-satellite task planning is also one of the keys. At present, the research on revenue function of task planning model is still mainly focused on task completion based on the sum of task priorities P_j , as shown in Equation (3).

$$C = \sum_{j=1}^{N_j} x_j \times P_j, \quad x_j = \begin{cases} 1, T_j \text{ is arranged to observe} \\ 0, T_j \text{ is not arranged to observe} \end{cases} \tag{3}$$

However, as the satellite mission planning model becomes more and more complex, it is not comprehensive to only consider the completion of the mission, and some other optimization criteria are also proposed in some literatures. Literature [33] put forward the optimization objectives of maximizing the observation benefit, minimizing the number of sidesteps and minimizing the total sidesteps angle. Literature [34] put forward a comprehensive evaluation model considering the conflict of ground receiving resources.

4.3. Modeling of Satellite Dynamic Mission Planning

In 2002, Pemberton of Veridian Company of France conducted the first research on satellite dynamic mission planning and discussed the general characteristics of this problem. Literature [36] summarizes five characteristics of dynamic scheduling of earth observation satellite missions on the basis of it, as shown in Table 1.

Table 1. Dynamic scheduling characteristics of earth observation satellites.

Insertion of new tasks	Users urgently need to observe some targets and request temporary insertion of some tasks.
Cancellation of scheduled tasks	Some changes in user's requirements result in cancellation of corresponding tasks.
Changes in tasks attributes	It mainly refers to the change of priority of certain tasks.
Changes in external environment	The sudden change of weather causes the task to be unable to be completed or delayed.
Changes in satellites state	The satellite encounters a failure during its operation, which prevents it from completing its observation tasks on time.

When disturbances occur, the imaging mission may undergo the following changes:

- The mission is completed as required, but the satellite resources for completing the mission change.
- The completion time of the mission changes and the satellite resources for completing the mission remain unchanged.
- The time for completion of the mission changes, and the satellite resources for completing the mission change.
- The task is deleted.

Although there are various disturbance factors in the implementation of imaging satellite scheduling schemes, they can be essentially attributed to a kind of dynamic scheduling problem

oriented to newly inserted tasks. Compared with conventional scheduling, dynamic scheduling has higher requirements, mainly reflected in the following three aspects:

- The robustness of the scheduling scheme is as strong as possible.
- The difference between the new plan and the original plan is as small as possible.
- The new scheme is generated as fast as possible.

Robustness and profitability of dynamic scheduling are often in conflict. Schemes with good profitability may have poor robustness, resulting in difficulties in adjusting in interference. Schemes with good robustness may have poor profitability, resulting in waste of satellite resources.

Aiming to the dynamic scheduling problem of agile imaging satellites, literature [35] summarized three kinds of uncertain factors and proposed a proactive scheduling strategy. Literature [36] proposed a rolling dynamic task planning strategy, which aims to decompose the complex dynamic planning problem into a plurality of simple static planning subproblems. Literature [37] established a dynamic constraint satisfaction model with two-level optimization objectives, in which the first-level index is still the sum of maximizing the task priority and the second-level index is the minimum disturbance.

5. Research on Mission Planning Algorithm

The algorithms for solving imaging satellite mission planning problems are mainly divided into two categories: deterministic algorithms and uncertain algorithms. Deterministic algorithm is also called exact algorithm, which searches the solution space completely. Uncertainty algorithm includes intelligent optimization algorithm and heuristic algorithm, as shown in Figure 3. The classical intelligent optimization algorithms include genetic algorithm, tabu search algorithm, simulated annealing algorithm and the improvement methods of these methods. Heuristic algorithm is an algorithm based on intuitive or empirical construction.

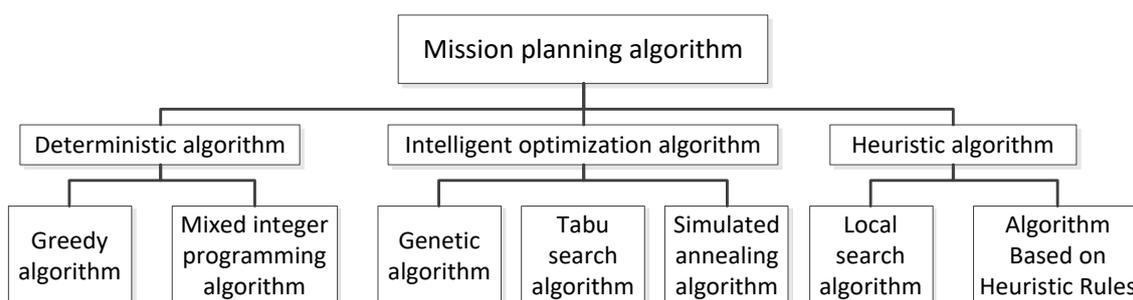


Figure 3. Mission planning algorithm.

Lemaitre M [38] studied and compared greedy algorithm, constrained programming algorithm, dynamic programming algorithm and local search algorithm for the mission planning system of Pleiades (Agile Satellite). Bensana E [39-40] studied and compared the computational performance of different algorithms under different scale problems. Li H J [41] designed a heuristic search algorithm of the graph. A large number of studies show that the deterministic algorithm can obtain the optimal solution for small-scale problems and the algorithm is stable. However, for large-scale combinatorial optimization problems such as multi-satellite task planning, deterministic algorithms are prone to fall into local optimal solutions and take too long to solve. Therefore, most of the current research focuses on uncertain algorithms. At the same time, some researchers proposed hyper-heuristic algorithms [18] For the multi-satellite cooperative observation problem.

6. Conclusions

In the research of requirements integrated preprocessing, the input of existing requirements is mostly accurate input, which requires users have relevant space knowledge. However, if the mission planning system has the ability to deal with natural language knowledge, it will greatly improve the intelligence level of the system, which is conducive to the promotion of military operations and commercial

operations. In the research of mission planning, the current research is still mostly focused on batch planning tasks. In the future, user requirements are likely to be proposed at any time, which requires high timeliness of observation information so offline scheduling can no longer meet user requirements. Therefore, the on-line scheduling of satellites is the trend of development, which requires researchers to make breakthroughs in the field of satellite autonomous mission planning.

Moreover, the integration of mission planning and multi-source observation data is also an important trend. Using the fusion of multi-source data to realize automatic target recognition, automatic labelling and selecting imaging mode, and the most effective information for users is directly provided to reduce the time for users to process and analyze by themselves. Nowadays, the human society is changing from the information era to the intelligent era, and the overall planning of earth observation satellites will inevitably develop towards intelligence and refinement.

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