Multi-level guided collaborative task scheduling algorithm of satellite mission aiming at moving target observation

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ABSTRACT

With the gradual increase in the breadth and depth of remote sensing satellite applications, the continuous observation of targets by multi-satellite coordinated relay has become an important means to improve information assurance capabilities. application. This paper proposes a multi-level guided satellite mission collaborative planning algorithm, and designs a modular process and a final plan verification algorithm for multi-level guidance. At the same time, this paper proposes and standardizes various constraints and inspection procedures in guided planning, and ensures the accuracy and robustness of the planning scheme by introducing effectiveness and delay constraints, uniqueness constraints and energy balance constraints. It can achieve continuous observation of various targets under the premise of meeting the timeliness requirements. The validity and accuracy of the algorithm are verified by the simulation calculation of reconnaissance satellites and point targets, regional targets, and moving targets, and the calculation planning for complex task requirements is realized.

Keywords: Remote sensing satellite, Guided task scheduling, Collaborative algorithm, Constraint test, Moving target observation.

1. INTRODUCTION

In recent years, with the increasing numbers and types of remote sensing satellites, the continuous improvement of functions and uses, its application value and research prospects are also expanding. But at the same time, satellite mission requirements are more stringent, satellite observation targets are more complex, payload imaging requirements are more diverse, and the need for multi-satellite relay observation is increasingly prominent.

Unlike the traditional single-sat mission planning, multi-sat collaborative planning can adapt to the above development needs[1]. Lu et al.[2] proposed a highly mobile satellite mission planning algorithm based on trajectory stitching that reduces energy and time consumption. Li et al.[3] applied PDDL on the modeling planning of inter-satellite transmission tasks with microwave and laser links which effectively solves the problem that is difficult to solve by traditional mathematical model. He et al.[4]proposed a genetic algorithm to encode the target chromosome with real numbers, shortening the chromosome length and improving the efficiency of space exploration multi-sat task planning. Cheng et al.[5] conducted bidding under ECNP based on the fuzzy comprehensive evaluation method of swarm intelligence and multi-attribute decision-making, and designed a multi-sat collaborative planning system MSCPS by using a multi-agent system method.

At present, the research on multi-sat guidance and relay observation is still relatively limited, which makes it difficult to meet the increasingly stringent demand for information assurance. In view of the existing deficiencies in the study of multi-sat collaborative planning, this paper puts forward a multi-level guided satellite task collaborative planning algorithm, designed for the modular process, through multiple constraint test algorithm solves problems such as effectiveness does not meet the user demand, time window conflict, task allocation beyond load, and through the simulation analysis of medium and low orbit satellite observing moving targets verifies the correctness and effectiveness of multilevel guided satellite task collaborative planning algorithm.

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2. DESCRIPTION OF MULTI-LEVEL GUIDED COLLABORATIVE TASK SCHEDULING PROBLEM

2.1. Symbol definition

To facilitate the description, the relevant symbol definition is given in Table 1.

Table 1. Symbol definition

Symbol	Definition
s_i	Time window
$RS = \{RS_1, RS_2, RS_3, RS_4\}$	Satellite resources that meet the corresponding rule sets. In total 4 rule sets
$Y = \{Y_1, Y_2, \cdots, Y_{11}\}$	Set of guidance combinations that passes corresponding constraint test. In total 10 constraint tests
$type(s_i) = \{p_1, p_2, p_3\}$	Satellite type corresponding to the time window s_i. p_1 for microwave satellite, p_2 for optical satellite, p_3 for electric detection satellite
$typeOptical(s_i) = \{q_1, q_2\}$	Optical sensor type corresponding to the time window s_i. q_1 for infrared, q_2 for visible light
ST_{s_i}, ET_{s_i}	Start time and end time of the time window s_i
h_{s_i}, R_{s_i}	Satellite parameters. h_{s_i} is the satellite orbit height corresponding to the time window s_i and R_{s_i} is the sensor resolution corresponding to the time window s_i
$Effectiveness, Delay$	Time effectiveness and delay
$winSen_i$	Set of time windows on the sensor Sen_i
$winS_i$	Set of time windows on the satellite S_i
$\max ProcessNum$	Maximum target processing number of electric detection satellite
$\max mTimes$	Maximum maneuver times per cycle
$\max workingCycles$	Maximum working cycles per day
$\max OperationTime$	Maximum operating time per cycle
$maneuveringSpeed$	Satellite attitude adjustment speed in m/s

2.2 Question description

The problem of multi-level guided collaborative task scheduling can be described as the cooperative observation of a certain target by multiple satellites or sensors under the premise of meeting various satellite constraints. Due to the complex composition of the observation area, diverse imaging types, long mission time or other possible limits, a single satellite cannot complete the task, and multiple types of satellites need to cooperate with each other to observe the target in turn. A schematic representation of the collaborative observations is shown in Figure 1.

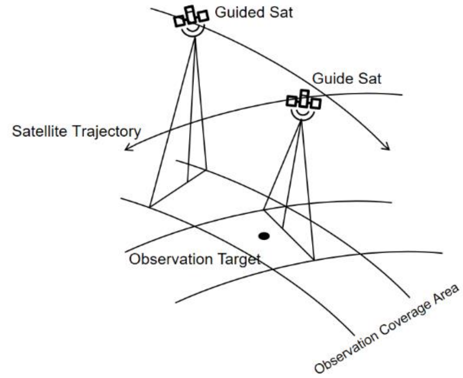


Figure 1. Collaborative observation.

The guide satellite first observes the target, obtains the target information and gives the real-time position of the target, and then guides the guided satellite to continue the observation according to the information given by the guide satellite. After the observation of the guided satellite, the next satellite can be guided to complete the multi-level collaborative observation, and finally achieve the full coverage of the regional observation or the reconnaissance and collection of different types of information parameters of the observation target.

3. ALGORITHM DESIGN OF MULTI-LEVEL GUIDED COLLABORATIVE TASK SCHEDULING

3.1 Process design

The process of multi-level guided collaborative task scheduling algorithm includes three parts: parameter setting, planning calculation and result processing.

3.1.1. Parameter settings.To conduct guided collaborative task scheduling, the necessary planning parameters must be input and set first. The required parameters can be divided into four parts: collaborative layers, effectiveness and delay, guide rules, and target selection. The collaborative layers represents the actual number of guiding layers; Effectiveness refers to the maximum interval between the time window between the guided satellite and the guided satellite, delay refers to the minimum value of the interval; Guide rule refers to the restriction of the guided or guided resource, including high orbit (> 20000km), middle orbit (2000km-20000km), low orbit (<2000km), low resolution, high resolution, electric detection, optical, microwave, infrared, visible light, etc.; Target selection is the selection of a target object that needs to perform a guided collaborative observation task, including point target, regional target, moving target, etc.

3.1.2. Planning calculation. In the planning calculation part, the generation and screening of all feasible collaborative scheduling schemes are completed, and the optimal planning results are finally obtained. The basic process is as follows: according to the selected guide rules, the available satellite resources that meet the constraints of the rules are selected at each level, and then pass the constraints test, exclude the guidance combination that does not meet the requirements, and finally get an effective guided satellite mission collaborative scheduling scheme.

After importing the selected rules, the method of " first union and then intersection" may be adopted. Divide the rules into 4 rule sets: RS_1, RS_2, RS_3, RS_4

The first union (orbit constraint): high orbit, medium orbit, low orbit

The second union (resolution constraint): low resolution, high resolution

The third union (sensor type constraint): electric detection, optics, microwave

The fourth union (optical constraint): infrared, visible light

Let $C_i(i=1,2,3,4)$ be the conflict set with $C_i=\{s_j \mid s_j \in [RS_i]\}$, where $[RS_i]$ are all the time windows that satisfy the rule set. Ultimately, the set of available satellite resources meeting all rule constraints is $T=C_1 \cap C_2 \cap C_3 \cap C_4$.

In the constraint test, the guidance combinations that did not pass the test will be deleted after each test to get the set of guidance combinations $Y_i(i \in [1,10])$ that passed the constraint test respectively. Until all the constraint tests are completed, the resulting guidance combination set Y_{10} will be presented as an effective set of guided collaborative task scheduling schemes.

3.1.3 Results processing. After completing the process of the constraint test, all the guidance combination schemes that pass the test will be saved as a task chain. After visualizing all available task chains in a Gantt diagram, the user can view the planning results and make manual selection.

3.3. Constraint test design in the collaborative task scheduling algorithm

3.3.1. Effectiveness and delay constraint test. Effectiveness refers to the maximum time of the interval between the guide and guided time window and delay refers to the minimum time of the interval. The guidance combination set without overlapping time windows is given by $Y_{1a}=\{(s_j,s_k) \mid s_j \in Z_1, s_k \in Z_2, ST_{s_k}-ET_{s_j} \ge 0\}$, the guidance combination set satisfies effectiveness constraint is given by $Y_{1b}=\{(s_j,s_k) \mid s_j \in Z_1, s_k \in Z_2, ST_{s_k}-ET_{s_j} \le Effectiveness\}$ and the guidance combination set satisfies delay constraint is given by $Y_{1c}=\{(s_j,s_k) \mid s_j \in Z_1, s_k \in Z_2, ST_{s_k}-ET_{s_j} \ge Delay\}$. It can be deduced that the guidance combination set that passes the effectiveness and delay constraint test is $Y_1=Y_{1a} \cap Y_{1b} \cap Y_{1c}$.

3.3.2. The uniqueness constraint test. The unique constraints include optical satellite, microwave satellite, and electric detection satellite unique constraints. Assume that an optical sensor of an optical satellite can observe only at one target at the same time; only one microwave sensor can work at the same time; the electric detection satellite must process targets less than the maximum processing number; the sensor is always on in the observation time window.

Take optical satellites as an example, the guidance combination set that passes the uniqueness constraint test is given by:

$$Y_{2j}=\{(s_j,s_k) \mid (s_j,s_k) \in Y_1, type(s_j)=p_2, \exists winSen_i, s_j \in winSen_i \\ and \forall s_n \in winSen_i, (ST_{s_n}-ET_{s_j}) \times (ST_{s_j}-ET_{s_n}) \le 0\} \quad (1)$$

$$Y_{2k}=\{(s_j,s_k) \mid (s_j,s_k) \in Y_1, type(s_k)=p_2, \exists winSen_i, s_k \in winSen_i \\ and \forall s_n \in winSen_i, (ST_{s_k}-ET_{s_n}) \times (ST_{s_n}-ET_{s_k}) \le 0\} \quad (2)$$

$$Y_2=Y_{2j} \cap Y_{2k} \quad (3)$$

Therefore, the final guidance combination set that satisfies the uniqueness constraint is Y_A with $Y_A=Y_2 \cap Y_3 \cap Y_4$.

3.3.3. Energy balance constraint test. The energy balance constraints include the maximum maneuver times per cycle, the working cycles per day, the maximum operating time per cycle, the maximum operating time in n-cycles, and the maximum operating time per day.

The guidance combination set that passes the maximum maneuver times per cycle constraint test is given by:

$$Y_{5j} = \{(s_j, s_k) \mid (s_j, s_k) \in Y_A, \exists winS_i, s_j \in winS_i$$
$$and \forall s_q \in winS_i, mTimes_{s_q} \leq \max mTimes\} \quad (4)$$
$$Y_{5k} = \{(s_j, s_k) \mid (s_j, s_k) \in Y_A, \exists winS_i, s_k \in winS_i$$
$$and \forall s_q \in winS_i, mTimes_{s_q} \leq \max mTimes\} \quad (5)$$
$$Y_5 = Y_{5j} \cap Y_{5k} \quad (6)$$

where $mTimes_{s_j}$ is the times of maneuvers in one single cycle.

The guidance combination set that passes the working circles per day constraint test is given by:

$$Y_{6j} = \{(s_j, s_k) \mid (s_j, s_k) \in Y_A, \exists winS_i, s_j \in winS_i and \left|Cycles_i\right| \leq \max workingCycles\}$$
$$Y_{6k} = \{(s_j, s_k) \mid (s_j, s_k) \in Y_A, \exists winS_i, s_k \in winS_i and \left|Cycles_i\right| \leq \max workingCycles\} \quad (7)$$
$$Y_6 = Y_{6j} \cap Y_{6k} \quad (8)$$

where $|Cycles_i|$ is the number of cycles that the satellite works in one day.

The guidance combination set that passes the maximum operating time per cycle constraint test is given by:

$$Y_{7j} = \{(s_j, s_k) \mid (s_j, s_k) \in Y_A, \exists winS_i, s_j \in winS_i ando T_{s_j} \leq \max OperationTime\} \quad (9)$$
$$Y_{7k} = \{(s_j, s_k) \mid (s_j, s_k) \in Y_A, \exists winS_i, s_k \in winS_i ando T_{s_k} \leq \max OperationTime\}$$
$$Y_7 = Y_{7j} \cap Y_{7k} \quad (10)$$

where oT_{s_j} is the operating time of the satellite in one single cycle.

Similarly, guidance combination sets that respectively pass the maximum operating time in n-cycles and the maximum operating time per day are Y_8 and Y_9. The guidance combination sets that meet the energy balance constraints are $Y_B = Y_5 \cap Y_6 \cap Y_7 \cap Y_8 \cap Y_9$.

3.3.4. Satellite attitude adjustment time constraint test. The guidance combination set that passes the Satellite attitude adjustment time constraint test is given by:

$$Y_{10j} = \{(s_j, s_k) \mid (s_j, s_k) \in Y_B, \exists winS_i, s_j \in winS_i and mT_{s_j} \leq \Delta T_{s_j}\} \quad (11)$$
$$Y_{10k} = \{(s_j, s_k) \mid (s_j, s_k) \in Y_B, \exists winS_i, s_k \in winS_i and mT_{s_k} \leq \Delta T_{s_k}\} \quad (12)$$
$$Y_{10} = Y_{10j} \cap Y_{10k} \quad (13)$$

where mT_{s_j} is the time of attitude adjustment.

Combining all 10 constraint tests, the set that satisfies all constraints is Y with $Y = Y_A \cap Y_B \cap Y_{10}$.

4. SIMULATION EXPERIMENTS AND ANALYSIS

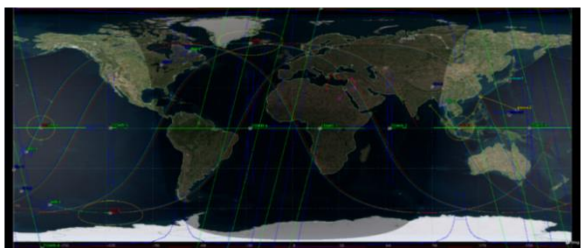
4.1 Simulation environment

In the simulation experiments, all algorithms and programs are implemented using the C# language and the Visual Studio software. The simulation computer environment is Intel Core i5-1240P @ 1.70GHz, 16GB RAM.

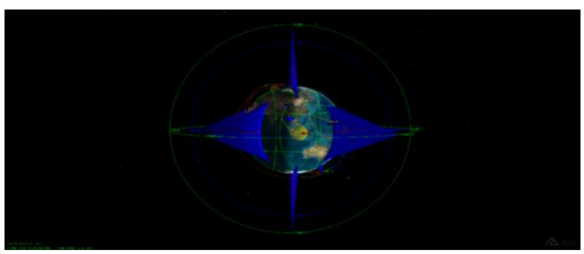
4.2 Simulation scenario description

This paper takes the collaborative observation task of medium and low orbit satellites observing multiple moving targets as the basic scenario, conducting the collaborative observation of moving targets such as ships and aircraft through a satellite network composed of multiple optical, microwave and electric detection satellites. Use Visual Studio to establish the scenario of the simulation, and discuss and analyze the results.

In this paper, 28 remote sensing satellites are set up to carry single or multiple payloads. 6 different moving targets are created on the earth's surface, each with a different trajectory, velocity and observation benefits. The scheduling period is set for one day (24h), and the rule of collaborative scheduling is a 2-level planning of medium orbit-low orbit-optical satellite, which simulates the scenario of first fuzzy search by the medium orbit satellite, then close range reconnaissance by the low orbit satellite, and finally detailed observation by the optical satellite. The 2D and 3D schematic of the simulation scenario are shown in Figure 2.



(a) 2D schematic of scenario



(b) 3D schematic of scenario

Figure 2. Schematic diagram of the simulation scenario

This experiment is simulated and analyzed based on the above scenario.

4.3 Simulation results and analysis

Aiming at 6 moving targets, a total of 1273 time windows in the task time are first calculated. The distribution of time windows before planning is shown in Figure 3.

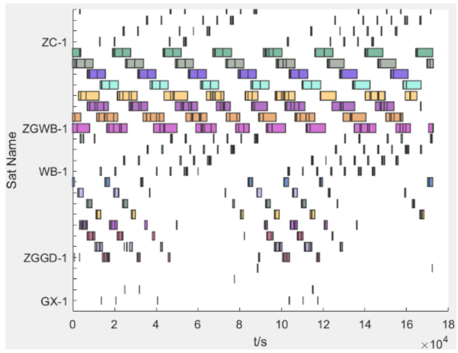
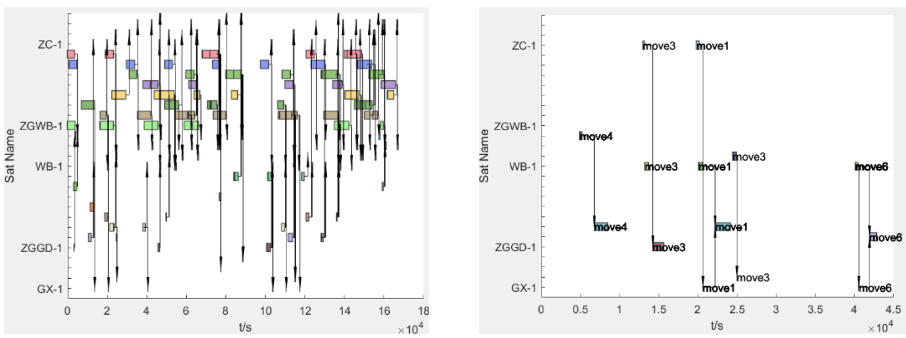


Figure 3. Gantt chart of time window distribution before planning

After selecting the rules and starting the collaborative scheduling, the effectiveness and delay constraint test is conducted first. The distribution of the time windows that pass this constraint test is shown in Figure 4.



(a) First-level test results (b) Second-level test results

Figure 4. Gantt chart of the distribution of effectiveness and delay constraint test results

Then, the uniqueness constraint test, energy balance constraint test and satellite attitude adjustment time constraint test are carried out. The distribution of the time windows that pass all constraint tests is shown in Figure 5. This chart is also the final result distribution chart of multi-level collaborative scheduling.

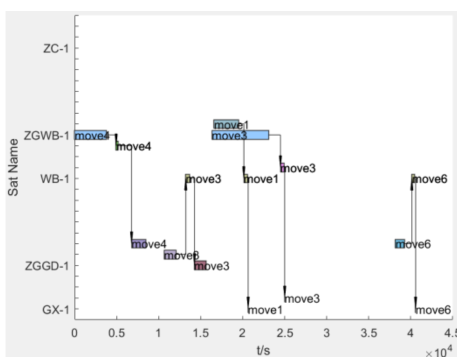


Figure 5. Gantt chart of the result distribution of multi-level collaborative scheduling

From above results, we can derive that in the effectiveness and delay constraint test, the original discrete time windows are arranged and combined, and graded paired into the form of guidance combinations according to the selected collaborative rules. For the 6 moving targets, there are 777 guidance combinations in the first level (i.e., medium-orbit satellites guide low-orbit satellites) and 85 guidance combinations in the second level (i.e., low-orbit satellites guide optical satellites). However, after the uniqueness constraint test, energy balance constraint test and satellite attitude adjustment time constraint test, it can be seen from the figure that all the guidance combinations that do not meet the constraint requirements are deleted, and the remaining 5 guidance chains are the effective collaborative scheduling schemes that meet all the constraints. This shows that the multi-level guided collaborative task scheduling algorithm can cover the whole process of collaborative planning, and the designed constraint tests can screen out the reasonable and effective scheduling schemes, and accomplish accurately and stably the computational planning of complex task requirements.

5. CONCLUSION

This algorithm mainly studies the problem of guided collaborative task scheduling, and proposes a multi-level guided collaborative task scheduling algorithm with full consideration of effectiveness and delay constraints, uniqueness constraints, energy balance constraints and attitude adjustment time constraints. The collaborative scheduling process is designed, and the standard process is divided into three main parts: parameter setting, planning calculation and result processing. The constraint satisfaction model of guided collaborative task scheduling is established, including effectiveness and delay constraint tests, uniqueness constraint tests, energy balance constraint tests and attitude adjustment time constraint test, and the mathematical expression of main constraint test processes are given in detail. Finally, taking the collaborative observation task of medium and low orbit satellites on multiple moving targets as a scenario, it verifies the validity and accuracy of the algorithm, which provides a useful idea and method for solving the collaborative scheduling problem of multi-level guided satellite missions.

REFERENCES

[1] Xiang, S., Chen,Y, G,, Li, G, L. and Xing, L, N., "Review on Satellite Autonomous and Collaborative Task Scheduling Planning," Zidonghua Xuebao/Acta Automatica Sinica, 45(2), 252-64 (2019).

[2] Lu, M., Fan, D., Yu, L. and Li, M., "A Task Planning Algorithm for High-Mobility Satellites Based on Trajectory Splicing," Proceedings of the 2022 2nd International Conference on Mechatronics Technology and Aerospace Engineering, Institute of Physics. 2457(1), 1-1 0(2023).

[3] Li, X., Li, C, G., Guo, X, Y. and Qu, Z., "A Modeling Method for Inter-Satellite Transmission Tasks Planning in Collaborative Network based on PDDL," Proceedings of the 14th IEEE International Conference on Electronic Measurement and Instruments, Institute of Electrical and Electronics Engineers Inc, 1460-1467 (2019).

[4] He, D, L., Feng, X, E. and Lei, M, J., "Real genetic coding multi-star task planning algorithm for deep space exploration mission," Kongzhi Lilun Yu Yingyong/Control Theory and Applications, 36(12), 2055-64 (2019).

[5] Cheng, S, W., Chen, J., Shen, L, C. and Tao, Y., "ECNP-based method of distributed dynamic task allocation for multiple observation satellite planning," Proceedings of the Proceedings - 2nd IEEE International Conference on Advanced Computer Control, IEEE Computer Society, 325-328 (2010).