Constellation-level autonomous mission planning technology for distributed networking

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ABSTRACT

This paper explores constellation-level autonomous mission planning techniques for distributed network, aiming to address the complexity of mission planning brought about by the increase in the number of remote sensing constellation satellites in the rapidly developing commercial space sector. The article firstly outlines the challenges in constellation mission planning, including the increasing computation requirements, dynamic constellation capacity, the poor adaptability of node destruction, and the difficulty of establishing target selection rules to satisfy the rapid changes of the mission. In this paper, we propose an autonomous mission planning algorithm based on a dual-core processor which includes a mission receiving mechanism, a satellite on-board conflict adjudication based on a point system, a mission management process, a mission conflict processing, and a mission execution and feedback mechanism. The resource consumption and performance indexes of the on-orbit mission planning algorithm are analyzed and the constellations collaborative mission planning algorithm in- orbit validated by using two remote sensing satellites, and the validation results show that that the autonomous mission planning by fast orbital extrapolation is able to execute the imaging tasks precisely.

Keywords: Constellations, autonomous mission planning, distributed

1. INTRODUCTION

With the booming development of commercial space market and technology, and the increasing number of in-orbit remote sensing constellation satellites, more and more imaging missions, such as electric utility inspection, post-disaster assessment, change detection, situational awareness, and other scenarios need to be carried out in cooperation with the constellation-level satellite resources[1], which will make the complexity of the constellation-level mission planning geometrically multiplied[2]. The related technical difficulties are reflected in the following aspects:

1) Constellation task planning computationally demanding counteracts the timeliness of task planning

Assuming that there are M satellites in the current constellation and N areas to be covered by imaging, to fully utilize the satellite resources, it is necessary to evaluate the accessibility of each satellite for each mission, with the total number of calculations and evaluations as $M \times N$ times. As the size of the constellation increases and the number of target areas increases, the amount of computation will increase in a geometric progression. For example, if a constellation of 100 satellites is to photograph 3,000 targets, 300,000 evaluation operations are required. Considering that each operation has predict the orbital and geometric coverage of a single satellite over several days, the time cost of the operations is not practical, which will have a great negative impact on the timeliness of mission planning[3].

2) Traditional constellation mission planning methods are difficult to adapt to capacity expansion and node losses

With the construction of the constellation, the number of satellites in the constellation may be expanded or reduced temporarily due to the expiration of the lifetime. Traditional constellation mission planning generally relies on central node planning and deployment to accomplish the whole constellation mission under the premise of relatively fixed satellite resources, and the applicability of this architecture will be greatly reduced under the elastic networking architecture[3].

3) Priority-based target selection rules are difficult to adapt to the rapid changes in tasks

There are various types and sources of imaging tasks, and in the face of unexpected tasks, how to automatically utilize limited satellite resources to achieve the optimal coverage cost-effectiveness ratio in an unattended situation is a problem

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looking for a quick solution as the traditional priority-based task scheduling rules are difficult to obtain the optimal results in this scenario[4].

2. ON-BOARD AUTONOMOUS MISSION PLANNING

Mission planning is carried out and centrally scheduled by on-board computer satellite management software, which can initiate imaging tasks autonomously based on coordinate information provided by the ground, inter-satellite communication links, or automatically carry out an imaging mission each time the satellite flies over a target based on a library of pre-specified targets[5].

2.1 Segmentation of autonomous task types

According to different imaging target categories, they can be divided into point target missions and area target coverage missions. Point target missions are centered on specific coordinates and supplemented by the length of the mission before and after to achieve a single imaging mission, while area target missions can be regarded as a combination of multiple point target missions to cover a large area[5].

According to the degree of urgency of the mission, it can be divided into emergency and non-emergency missions. Emergency missions require quick planning and execution, and missions with an interval between 5 minutes and 1 second between planning and start of execution [6] (which can be adjusted and defined on-orbit) are categorized as emergency missions, while the rest of the missions are non- emergency missions[7]. According to the source of the task, it can be divided into local target library (anchoring) task and external temporary task, the former target point or area description is stored in satellite fixed memory while the latter comes from inter-satellite or ground satellite communication, both of which can be added, deleted, checked and changed by command.

In addition to the aforementioned target imaging-related tasks, there are also some autonomous tasks that come from satellite subsystem services (e.g., autonomous orbit control, etc.).

2.2 Autonomous task realization process

Autonomous task planning on the satellite is the key to the constellation's "high elasticity and high autonomy", and there are two key points. First is the task receiving mechanism, the constellation center is only responsible for task assignments and task receiving adjudication, which is a mode that does not have high requirements for the "centralized" computational capability, and any satellite under the constellation's autonomous operation mode can serve as a temporary "center" to realize "high elasticity". Second, is a mission planning conflict adjudication system based on point system with-in satellite, through which the fine arrangement of multiple tasks for a satellite under multivariate conditions is realized to maximize the efficiency of the constellation. The on-board satellite autonomous task planning process is as follows:

(1) The satellite adopts dual-core processors, in which the task running on processor 1 is the main task of the satellite, which is used for command & data handling and attitude determination and control tasks, satellite autonomous planning tasks (e.g., orbit control, etc.), as well as the execution of sequences of commands unfolded from each autonomous planning task. Additionally, it can also undertake the planning of external temporary tasks. Processor 2 mainly carries out the planning of regional target planning and the planning of anchored target library tasks. The dual-CPU task allocation is shown in Figure 1.

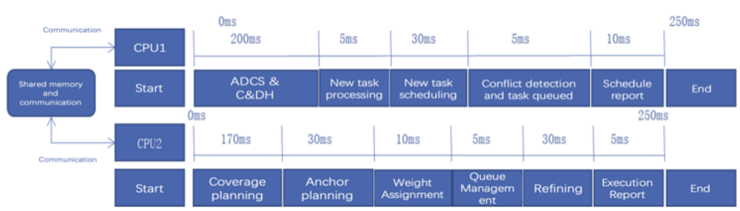

Figure 1. Schematic diagram of dual-CPU task allocation.

(2) The point targets in the locally anchored mission are scanned periodically, and the executable time window and resource dependence are first calculated using the fast planning algorithm, which only considers the simplified circular orbit model of the J2 term ingestion and calculates the possible imaging positions using the spherical geometric relationship, supplemented by the dichotomous method to quickly search for the orbital position of the center of the imaging range of the satellite closest to the target in the center of the imaging range of the laps within the planning timeframe and the

calendrical moments, combined with information such as the view angle range, whether there are imaging conditions can be determined. If such operation can be carried out within 48 hours, it is entered into the queue of point tasks to be planned;

(3) The region planning task in the local target library is planned once per control cycle, and if the planning is not finished in this cycle, the intermediate results are retained to continue planning in the next cycle. During planning, the target region is be divided into grids of specified resolution, and each grid point has a flag to record its current coverage (covered or uncovered); through the simplified orbital model and the vertical projection collision detection algorithm, the satellite quickly search for possible coverage time periods, and then determine the corresponding calendar moments of the start and end of the imaging task with a certain margin. During the same process, the satellite count the new coverage grid points to generate multiple single-point imaging tasks. Finally, single-point tasks that can be executed within 48 hours and contributes the most to the coverage increment are inserted into the queue of the points to be planned and the next planning will be carried out after the execution or abandonment of the task;

(4) When an external temporary task arrives, it is first calibrated and then different planning strategies are adopted according to its degree of urgency: for non-urgent task, the processing is similar to that of the anchoring task, and the fast planning algorithm is used to calculate the preliminary executable time window and resource dependence, if it can be carried out within the specified time (e.g., 48 hours), then it enters into the queue of the points to be planned and the next step is carried out. If it is unable to execute the task, the result is reported through inter-satellite communication and the operation ends. For urgent tasks, the precise orbit forecast model is directly used to predict the orbit with the help of bisection method. Because the time span is very small to guarantee the accuracy and computing time consuming at the same time, if it can be carried out within 48 hours, then it jumps to step 6, on the contrary, through the interstellar feedback the task cannot be carried out and ends the operation;

(5) The task management process quickly searches the queue of points to be planned at regular intervals (once every 250 milliseconds), dynamically adjusts its task score according to different target types and waiting times, and calculates the resource dependencies required to execute the task;

(6) The process iterates through the queue of planned tasks and check whether the current pending point task overlaps with the planned task in terms of time window and dependent resources (task conflict);

(7) If there is no task conflict, then the current point task to be planned is directly inserted into the queue of planned tasks, and if the task is an external temporary task, it is also be confirmed and fed back through interstellar communication (task planning report), and vice versa, the next step is be executed;

(8) If a task conflict is detected, try to see if the task can be merged; if the task can be merged, merge the two conflicting tasks and insert the merged task into the queue of planned tasks; if the task is an external temporary task there is also confirmation feedback through interplanetary communication (task planning report), otherwise perform the next step;

(9) If the tasks are in conflict and cannot be merged, the higher- value tasks are inserted into the queue of planned tasks according to their scores, and the lower-value tasks are replaced; the first-come, first-served principle is adopted for tasks with the same scores; and the replaced task is an external temporary task, which is given up through interstellar feedback in order to be re-assigned by the constellation;

(10) In order to avoid imaging or off-target imaging caused by excessive orbit extrapolation errors caused by planning too far in advance, a forecast (precision forecast) is re-run 5 minutes (adjustable) before the execution of the planned mission to minimize the orbit extrapolation errors and to re-generate key execution parameters such as the moment of the center of the image calculation based on the results of the precision forecast (this step is not required for the urgent mission in step 4);

(11) Upon reaching the task execution window, a sequence of commands is automatically generated based on the task execution parameters, and satellite completes all the operations required for the task;

(12) Feedback on the status of task execution via interstellar after task execution (Task Execution Report);

(13) After the imaging task is completed, a command is automatically generated to create a target recognition or data transfer task to complete the subsequent work based on the task information.

For the target identification and data transmission tasks are similar to the previous planning process, except that forecast planning actions such as orbit extrapolation and geometric operations are not required, and task management mechanisms such as conflict detection are identical.

The specific process is shown in Figure 2. Tasks in both the queue of tasks to be planned and the queue of planned tasks can be deleted or aborted by commands, and the flexible insertion, replacement, deletion and termination of tasks can be realized by combining with the previous management mechanism. In addition, the execution process of each task is recorded in the full-flow task log, the current status of the task can be switched to display the specified telemetry packages, and the automatically generated command sequences can be automatically generated into a binary file or text file for downloading and checking, which can provide a hand for the tracking and management of the task and even for the ground debugging.

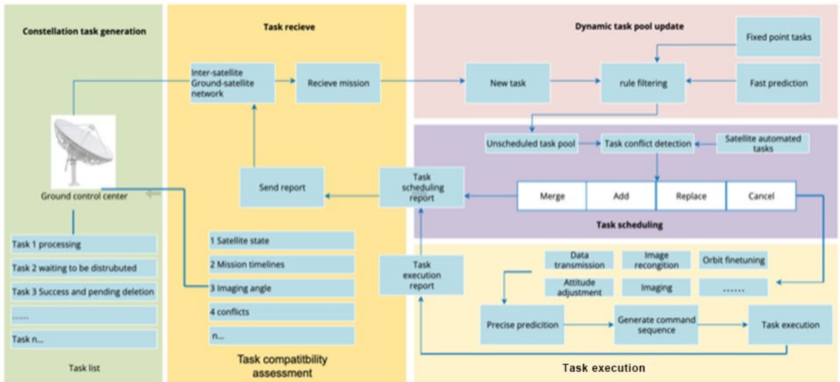

Figure 2. Autonomous task planning execution process.

3. PERFORMANCE ANALYSIS OF ON-ORBIT MISSION PLANNING ALGORITHMS

The attributes and parameters of autonomous missions take up the memory storage resources of on-board computers, and the forecast planning of autonomous missions involves complex operations such as orbital extrapolation and geometric and logical operations, which take up the computing time of on-board computers. The resource consumption of the point-target task and the regional target coverage task are quite different and it is analyzed separately.

3.1 Analysis of resource consumption for point target missions

According to the experience of on-orbit operation, the mission description information and parameters (such as imaging coordinates, imaging modes, etc.) occupy about 200 bytes, the parameter configuration information generated for the mission-related load is about 100 bytes, and the programmed instruction sequences generated in the final execution are about 1k bytes, therefore, the memory resources occupied by supporting 100 autonomous missions is about 130k bytes, which is far satisfied by the memory of the computer.

In terms of machine time occupation, the satellite first reduces the orbit traversal search range by simplifying the orbit model, spherical geometry and collision detection algorithms for fast planning; then it adopts the analytical method for orbit extrapolation, the G84 standard ellipsoid in combination with the nominal orbital position, the satellite attitude and the imaging viewpoint to compute the ground imaging and the imaging range, and utilizes the dichotomous method to reduce the search time for the optimal imaging moment. The on-orbit test results show that the single-point forecasting operation (calculating the orbital position and imaging for a given calendar element moment) takes about 150 microseconds. For the coarse prediction, the three-dimensional geometric equations are solved to calculate the possible imaging time zones, and then the imaging window is determined by traversing the orbital positions within the zones by the bisection method. The equations take less than 100 microseconds to solve, and the dichotomous traversal takes 2.7 milliseconds even though the number of optimization worst- case operations is 18 for a 48-hour (1-second interval) time interval, which takes 0.27 seconds to plan for 100 missions. Before task execution and then centered on the coarse forecast moment before and after the 1-minute time period using bisection method for fine forecast (time interval of 1 ms), a total of up to 17 times the number of operations, the total time consumed 2.55 milliseconds, after the conflict detection of the task of the fine forecast will not be carried out at the same time, the time consumed does not need to be multiplied by the number of the total number of tasks.

3.2 Analysis of resource consumption for regional coverage planning task

For a 1-degree x 1-degree rectangular area (about 12,000 square kilometers), the memory footprint of the grid points is shown in Table 1 (a single grid point contains 8 bytes of latitude and longitude with 4 bytes of state information):

Table 1. Memory usage statistics for 1 degree × 1 degree rectangular area grid points.

Granularity	Resolution	Grid amount	Grid point memory usage (bytes)
4′	8 km	256	3072
2′	4 km	961	11532
1′	2 km	3721	44652
30″	1 km	14641	175692
15″	0.5 km	58081	696972

For a granularity of 1′, a single task takes up about 140kB of memory, and even if it is accurate to 15″, a single task takes up about 700kB of memory. storing 100 tasks at the same time takes up a total of no more than 70MB of memory, and there is still a plenty of memory available remaining in the on-board computer.

Algorithmically, the vertical projection detection method in the collision detection algorithm is used in conjunction with the range of imaging strips to calculate the possible imaging time zones, and future orbit path within that time zone is searched for the one coverage mission that contributes the most to the total coverage. For an area of about 12,000 square kilometers, which is 1 degree x 1 degree, the time cost of the vertical projection collision detection evaluation calculation is about 3-5 milliseconds, and the satellite orbital plane sweeps over the given area for about 960 seconds in 48 hours (taking into account a total of 4 orbit adjustments), and makes nearly 3,000 single-point prediction operations at 1/3 of a second intervals are required to perform a point-by-point prediction of the orbits within the time frame, with each single-point forecast consuming about 150 microseconds, thus calculating the maximum contribution to the coverage rate. The calculation that searches the largest contribution to coverage was thus calculated to take no more than 500 milliseconds in total.

3.3 Analysis of performance indicators

The satellite management software uses a 250 ms control cycle, two processor cores can process different tasks in parallel, according to the task planning machine time allocation, CPU1 and CPU2 generate the task planning report and the task execution report in each control cycle (250 ms), the report is transmitted through the CAN bus, the CAN bus communication cycle 1 second.

The performance metrics of autonomous task planning can be obtained based on the aforementioned memory footprint, total machine time allocated for each task planning process during the control cycle, and individual task planning elapsed time as shown in Table 2:

Table 2. Performance metrics statistics for autonomous task planning.

Serial number	Indicator name	Indicator values
1	Total number of targeted tasks for support points	5000
2	Supports 1-second rapid response target imaging missions	25
3	Supporting large area target coverage missions	100
4	Point target task planning time	≤5 ms
5	Regional targets cover mission planning time	≤500 ms
6	Minimum time interval for mission-centered moment planning	≤ 1 ms
7	Imaging center deviation due to task planning	≤ 50 m
8	Mission planning log report generation time	1s
9	On-orbit mission planning time	0.27s/100 targets

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3.4 In-orbit validation

In-orbit validation of the constellation cooperative mission planning algorithm was carried out using two remote sensing satellites. Autonomous imaging missions of the point target are uplinked to the two satellites through ground stations, and the two satellites carried out the autonomous mission planning by fast orbit extrapolation. The final imaging area, as shown in Figure 3, can completely cover the planning area, which verifies the correctness of the algorithm.

Figure 3. Autonomous task planning point target task execution results.

4. CONCLUSION

Starting from the difficulties faced by autonomous mission planning in distributed networking constellations, this paper proposes a program of autonomous negotiation and conflict resolution for constellation-level mission planning. The autonomous mission planning technology proposed in this paper can effectively cope with the challenges of gradual expansion of the constellation scale, improve the efficiency and accuracy of mission planning, and can be widely applied to networking remote sensing constellations, which is of reference significance for promoting the development of space technology.

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