Research on Multi-satellite Observation Multi-region Task Planning based on Genetic Algorithm

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Abstract. Space-based resources play an important role in the observation and handling of emergency events, and are widely used in national economic activities. In recent years, the large increase in the number of orbital spacecraft and the strategic transformation of the aerospace equipment application model have made the practical task planning for multi-type satellites of practical significance. The research and application of space-based regional reconnaissance algorithms are of great significance for improving the comprehensive application efficiency of spacecraft, forming uniform coverage of key areas, and improving the uniformity of satellite resource utilization and situational awareness. Based on the actual background of engineering application, this paper describes the scheduling problem of Earth observation satellites. Under the constraints of satellite resource capability, observable time, conversion time between reconnaissance missions, energy, etc., a multi-satellite multi-target reconnaissance mission is established. Planning model. With the most resource-saving and high situational awareness uniformity as the optimization index, the optimized satellite reconnaissance mission planning scheme is obtained based on genetic algorithm.

1. Introduction

In recent years, the aerospace industry has developed at a high speed, and the types and quantities of orbiting spacecraft have increased dramatically. The spacecraft has a wide coverage area, all weather, all-day time, is not restricted by air borders, and does not involve personnel safety[1]. These observation requests usually have higher timeliness, information acquisition accuracy, and resource usage synergy requirements. They often require multiple types of satellites to cooperate, and diverse spatial tasks urgently need to be played in a unified mission plan[2]. The greatest benefit of spacecraft.

Similar to the French SPOT-5 satellite system[3], the US Landsat-7 satellite system[4], the EO-1 satellite system[5], etc., in the past, China’s satellites were managed separately and independently, according to professional vertical protection, various satellites and their The application system is self-contained, and these departments only perform mission planning for their respective satellites, which is difficult to integrate. There is a difficulty in emergency response, it is unable to efficiently meet the needs of emergency observation, and data from different sources cannot be effectively integrated and mutually verified and guided. After the strategic transformation of the aerospace equipment application model, the front-end proposes satellite observation requirements planning, the back-end satellites' measurement and control, and the unified management of operation and control. The satellite
Joint planning can optimize the integration of resources, realize integrated and multi-method integration of various systems, and improve application efficiency.

The existing satellite mission planning software is for the research of business process processing, model construction and solving algorithms for each series of satellites[6],[7],[8],[9],[10]. The main satellite mission planning models established by scholars at home and abroad include mathematical programming models, constraint satisfaction models and general models. The algorithm for solving the model algorithm is divided into an exact algorithm and an approximation algorithm. The approximation algorithm is further divided into an intelligent search algorithm and a rule-based heuristic algorithm. The satellite mission planning problem has been proved to be an NP-hard problem due to its multi-resource, multi-tasking and multi-time window characteristics. Considering the time and cost problems, most of the approximation algorithms are used to seek the optimal solution of mission planning[11].

From the perspective of engineering application, this paper studies and models multi-star and multi-objective mission planning problems, with the minimum total fuel consumption, average single-point reconnaissance coverage gap, and maximum reconnaissance time. It satisfies the satellite observable time window and task. The satellite attitude adjustment time, the longest continuous working time of the satellite, the satellite energy and other constraints are required, and the genetic algorithm is used to solve the problem.

2. Modeling the Earth Observation Satellite Scheduling Problem

During the on-orbit operation of the Earth observation satellite, the user first requests the product distribution center, and the distribution center converts it into a satellite observation order and submits it to the satellite control center. The control center sends it to the measurement and control center in the form of business data, and takes the form of remote control through the measurement and control station. The satellite is placed on the satellite, and then the satellite starts working. The original data is passed through the telemetry and sent to the user through data processing and product processing[12].

We study the geostationary satellite scheduling problem of point targets, and the regional targets can be converted into point targets. First, unify the point target into a "meta task". And construct the income function to adapt to the differences in income calculation of various targets. Finally, the Earth observation satellite scheduling model is established.

2.1. Atomic Task construction

The work of the Earth observation satellite requires the camera, radar and other payloads to adjust the attitude to the target[13]. In an effective time window, the satellite observes a point target. That is to say, a Atomic Task refers to a time window satellite observing a point target. The subtasks obtained after the point target decomposition are collectively referred to as Atomic Task. \( o_{ijkv} \) indicates that the satellite \( s_j \) decomposes the target task \( l_t \) in the kth time window, and the obtained v subtask, \( o_{ijkv} \) represents an observation activity of the satellite to the mission.

The Atomic Task is represented by a six-element array: \( o_{ijkv} = \{ \text{AtomicID}, \text{TaskID}, \text{SatID}, \text{Win}, \text{Angle}, \text{Coordinate} \} \). Among them, AtomicID is the Atomic Task identifier; TaskID is the target observation task identifier; SatID is the satellite resource identifier used by the observation activity; Win indicates the start and end time of the observation activity; Angle is the side view angle adopted by the satellite in the observation activity, that is, imaging Attitude; Coordinate identifies the coordinate information of the observation activity to the ground coverage area. The Atomic Task coordinate information of the point target decomposition is the latitude and longitude coordinates of the point target.

After the point target is decomposed, information about the observed resources, time and angle is determined in each Atomic Task. These Atomic Tasks are irreducible, and can be completed by a...
single satellite. Therefore, this paper uses each Atomic Task as the basic element of scheduling, which facilitates the unified scheduling of point targets.

Set in the scheduling period, the number of available time windows for the satellite $s_j$ to the task $t_i$ is $N_{ij}$, and $o_{jkv}$ indicates that the satellite $s_j$ performs a reconnaissance task on the task $t_i$ in the $k$th time window, which is the $v$th subtask of the task $t_i$. Therefore, there are: task $t_i$ based on the satellite $s_j$ decomposition of the Atomic Task set $O_{ij} = \{O_{i1}, O_{i2}, \ldots, O_{iN_{ij}}\}$. The Atomic Task set of task $t_i$ decomposition is $O_i = \{O_{i1}, O_{i2}, \ldots, O_{iN_i}\}$.

The Atomic Task set obtained after each task is decomposed is called the Atomic Task Group of the task.

$$O_i = \bigcup_{j=1}^{N_i} \bigcup_{k=1}^{N_{ij}} o_{jkv}, \quad i \in [1, \ldots, N_T]$$

(1)

Where $N_{ij}$ is the number of time windows of the satellite $s_j$ to the task $t_i$; $N_{jk}$ is the number of atomic task constructed within the $k$-th time window of the satellite $s_j$ and the task $t_i$. $v$ indicates that the atomic task is the $v$th subtask of the atomic task group. The time window of the atomic task $o_{jkv}$ is $[w_{j1}, w_{jk}]$ and the observation angle of $s_j$ to $t_i$ in this time window is $g_{jikv}$.

In summary, the atomic task concept can completely describe the observation tasks of satellite-to-point targets. One observation task can contain multiple atomic tasks, and they are a one-to-many logical relationship. Therefore, the process of satellite resource scheduling is essentially the process of selecting atomic tasks.

### 2.2. Revenue function construction

#### 2.2.1. Multi-objective evaluation system

The earth observation satellite resource scheduling is to obtain the maximum comprehensive benefit under the condition of satisfying various constraints within a certain period of time, with the least resource consumption and the best imaging effect[14]. In summary, the main optimization indicators considered in this paper are:

1) Under the conditions of meeting various resource constraints, arrange as many observation tasks as possible, and prioritize tasks with high importance levels;

2) The satellite resources consumed for completing all observing tasks are the least. The resource consumption of this paper considers the number of satellites used and the number of observation windows, and is only used as a constraint for satellite energy consumption.

3) The observation coverage gap is average and the observable time is the largest.

Next, the corresponding income function is constructed separately for the above optimization indicators.

#### 2.2.2. Income function

1) The number of observation tasks completed the most

A point target can be considered as a completed task by arranging only one atomic task. There are only two states, scheduled and unscheduled. Therefore, the revenue of the task can be calculated based on the completion status of its atomic task. When the task is completed, the revenue of the task is $\text{cost}$, and the completion status of its atomic task is defined as:

$$x_{jikv} = \begin{cases} 1, & \text{If the atomic task } o_{jkv} \text{ is executed} \\ 0, & \text{otherwise} \end{cases}$$

(2)

According to the arrangement state of the atomic task of task $t_i$, the gain of the satellite observation task $t_i$ can be obtained, and the income function of the point target is:
The point target has a unique constraint that only one imaging can be scheduled. During the scheduling process, only one meta-task that arranges the point target is selected, so the revenue of the point target is not repeated here.

2) Minimal resource consumption

Suppose the satellite's resource set is \( S = \{s_1, s_2, \cdots, s_{N_s}\} \), and whether the satellite \( s_j \) participates in the observation task is defined as:

\[
y_j = \begin{cases} 
1, & \text{if the satellite } s_j \text{ is involved in the observing mission} \\
0, & \text{otherwise}
\end{cases}
\]  

According to the state of arrangement of all observation tasks, the satellite resource use income function of participating in the observation task can be obtained as follows:

\[
CSat(s_j) = \sum_{j=1}^{N_s} y_j
\]  

Assuming that the window resource set of task \( t_i \) is \( \text{Windows}_i = \{v_{i1}, v_{i2}, \cdots, v_{iN_{\text{windows}_i}}\} \), according to the arrangement state of all observation tasks, the satellite window resource usage benefit function of the participating observation tasks can be obtained as follows:

\[
C\text{Windows}(i) = \sum_{i=1}^{N_{\text{windows}_i}} N_{\text{windows}_i}
\]  

3) Optimal observation time

When some specific targets are being reconnaissance, the user has corresponding requirements for time. For example, the length of each observation is not less than \( \text{Time}_{\text{sec}} \); the maximum invisible duration cannot exceed \( \text{Time}_{\text{blind}} \); the average coverage gap is observed. Among them, the maximum invisible duration can be regarded as the constraint constraint of the observation coverage gap evaluation, so it can be represented by a gain function. Considering the observation task time optimization index contains multiple aspects, which can be established separately when constructing the time benefit function, as follows:

(a) The longest total observation time

Under the various constraints, the total observation time of the atomic task set \( O_i \) is as follows:

\[
C\text{Time}_{\text{sec}}(t_i) = \sum_{j=1}^{N_s} \sum_{k=1}^{N} (w_{ek} - w_{sjk})
\]  

(b) Observation coverage gap average

Assume that the starting time of the total observation mission planning is \( \text{Time}_{\text{start}} \) and the ending point is \( \text{Time}_{\text{end}} \). In order to meet the maximum invisible duration requirement, at least \( N_{\text{all}_i} \) atomic tasks are required to complete the task \( O_i \), namely:

\[
N_{\text{all}_i} = \text{floor}\left(\frac{\text{Time}_{\text{end}} - \text{Time}_{\text{start}}}{\text{Time}_{\text{blind}}}\right)
\]  

Assuming that the task \( O_i \) that satisfies the constraint actually has \( N_{\text{actual}_i} \), the average coverage of the observation gap is expressed by the standard deviation of the time interval between the atomic tasks \( o_{ijkv} \), namely:
In summary, under the conditions of the observing task, the income function of the coverage average of the reaction observations is as follows:

$$\sigma_i = \sqrt{\sum_{l=1}^{N_{\text{actual}}-1} \left( (ws_{i(l+1)} - we_{il}) - \mu_i \right)^2 + \left( Time_{\text{blind}} - \mu_i \right)^2}$$

(9)

$$\mu_i = \frac{\sum_{l=1}^{N_{\text{actual}}-1} (ws_{i(l+1)} - we_{il}) + Time_{\text{blind}}}{N_{\text{actual}}-1}$$

(10)

2.2.3. Satellite scheduling model. After the point target is uniformly represented as a atomic task, the earth observation satellite scheduling model can be established based on the actual problem constraints[15]. Considering the constraints in the earth observation satellite scheduling problem, if the model is modeled by using the planning model, the knapsack problem model and the graph theory, it is difficult to express and deal with various complex constraints. The Constraint Satisfaction Problem (CSP) can describe various variables and constraints in a problem with a more natural language with certain semantics[16]. The modeling process is relatively straightforward and simple. Therefore, this paper uses the constraint satisfaction problem to establish a geostationary satellite scheduling model.

The decision variables for the Earth observation scheduling problem are expressed as:

$$X = \{ x_{ijk} | i = 1, \cdots, N_T; j = 1, \cdots, N_s; k = 1, \cdots, N_g; v = 1, \cdots, N_v \}$$

$$Y = \{ y_j | j = 1, \cdots, N_s \}$$

among them

$$x_{ijk} = \begin{cases} 1, & \text{If the atomic task } a_{ik}, \text{ is executed} \\ 0, & \text{otherwise} \end{cases}$$

(12)

$$y_j = \begin{cases} 1, & \text{If the satellite } s_j \text{ is involved in the observing mission} \\ 0, & \text{otherwise} \end{cases}$$

(13)

Since the earth observation task corresponds to the observation activity of the satellite and is the main inspection object when dealing with various constraints, first, the start time set \(SWS_j\), the end time set \(SWE_j\), and the observation angle set \(SG_j\) corresponding to the task set of the decision variable are derived:

$$SWS_j = \{ ws_{ijk} | x_{ijk} = 1, i \in [1, N_T] \}$$

$$SWE_j = \{ we_{ijk} | x_{ijk} = 1, i \in [1, N_T] \}$$

(14)

$$SG_j = \{ g_{ijk} | x_{ijk} = 1, i \in [1, N_T] \}$$

The following is an optimization model for the geostationary satellite scheduling problem. According to formula (3-19), the total return of the satellite observation point target can be obtained as follows:
According to formula (3-21), the total revenue of satellite resources can be obtained as follows:

$$C_{resource} = C_{Sat}(s_j) + C_{Windows}(i) = \sum_{j=1}^{N_s} y_j + \sum_{i=1}^{N_r} N_{windows,i}$$  \hspace{1cm} (16)

According to formulas (3-22) and (3-24), the total return of observation time can be obtained as follows:

$$C_{Time} = \sum_{i=1}^{N_r} \left[ \sum_{j=1}^{N_s} \left( C_{Time_{see}}(t_i) + C_{Gap}(\sigma_i) \right) \right]$$

$$= \sum_{i=1}^{N_r} \sum_{j=1}^{N_s} \sum_{k=1}^{N_f} \left( w_{ijk} - w_{ijk} \right) + C_{Gap}(\sigma_i)$$  \hspace{1cm} (17)

Among them, the expression of $\sigma_i$, $C_{Gap}(\sigma_i)$ are (9), (11).

In summary, the optimization goal of this paper scheduling problem is:

$$\max J = p_{\text{Spot}} \cdot C_{\text{Spot}} + p_{\text{Resource}} \cdot C_{\text{Resource}} + p_{\text{Time}} \cdot C_{\text{Time}}$$  \hspace{1cm} (18)

Among them, $p_{\text{Spot}}$, $p_{\text{Resource}}$, $p_{\text{Time}}$ are the penalty factors for each sub-indicator.

The following constraints must be met for the geostationary satellite scheduling problem:

1) The uniqueness constraint of the point target, that is, each point target can only be observed once:

$$\forall i = 1, \ldots, N_r : \sum_{j=1}^{N_s} \sum_{k=1}^{N_f} x_{ijk} \leq 1$$  \hspace{1cm} (19)

2) Satellite storage constraints:

$$\forall j = 1, \ldots, N_s : \sum_{m=1}^{N_m} (w_{jmin} - w_{jmax}) m_j \leq M_j$$  \hspace{1cm} (20)

Which, $N_m$ is the number of tasks performed by the satellite $s_j$.

3) Satellite energy constraints:

$$\forall j = 1, \ldots, N_s : \sum_{m=1}^{N_m} (w_{jmin} - w_{jmax}) p_j + \sum_{l=1}^{N_{gul}} \left| g_{j|l+1} - g_{j|l} \right| \rho_j \leq P_j$$  \hspace{1cm} (21)

The satellite consumes a certain amount of electrical energy for imaging and side-swinging activities. Therefore, the satellite's energy consumption is expressed as a function of the satellite's observation time and the side view angle of the remote sensor. The energy consumed by the satellite cannot exceed its maximum energy limit.

3. Solving scheduling problem based on genetic algorithm

The genetic algorithm is a global optimization algorithm, which has the advantages of fast global optimization and is suitable for real-time engineering applications[17]. Since the satellite's observation activities have a strict timing relationship, it is necessary to extrapolate the existing satellite resources according to the user's scheduling requirements before scheduling. Next, based on the orbital extrapolation results and the target point information, information such as the satellite resources and the observation time window that can perform the reconnaissance task are counted. The pre-processed information storage format is as follows:
\[
\text{Data}_{in,nx6} = \begin{bmatrix}
Sat_1 & Target_1 & WS_1 & WE_1 & \text{Continue}_1 \\
Sat_2 & Target_2 & WS_2 & WE_2 & \text{Continue}_2 \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
Sat_n & Target_n & WS_n & WE_n & \text{Continue}_n \\
\end{bmatrix}
\]

(22)

Which \(Sat\) represents the satellite number, \(Target\) represents the target point number, \(WS\) represents the observation window start time, \(WE\) represents the observation window end time, and \(Continue\) represents the observation duration. Each row of the matrix represents an executable task in the satellite resource, and the subscript \(n\) only indicates the number of tasks that can be performed in the existing satellite resources, and does not distinguish between the satellite number and the target number. In summary, the main problem solved in this paper is to select the optimal scheduling scheme with the least resource consumption and satisfying the constraint conditions in the input information (22).

Based on the coding rules of the genetic algorithm, each scheduling scheme is an individual, each of which contains \(n\) chromosomes, combined with the formula (22). The chromosome coding designed in this paper is as follows:

| Sat | Target | Task | x |
|-----|--------|------|---|

**Figure 1.** Schematic diagram of the coding structure

As shown in Figure 1, Sat represents the satellite number; Target represents the target number; Task represents the task number; \(x\) represents the decision variable, taking 0 or 1, which 0 indicates that the task is not executed and 1 indicates execution. It can be seen that each row of the formula (22) represents information of one chromosome. This kind of chromosome coding is relatively intuitive, and each chromosome represents whether the corresponding observation task is finally scheduled, and the encoding and decoding process is simple.

### 4. Satellite mission scheduling simulation

In order to verify the efficiency of the model and algorithm for point target scheduling, the following test cases are used for verification. In the example, the observation mission consists of three point targets, and the satellite resources include 10 Earth observation satellites. The coordinate information of the target is shown in Table 1:

**Table 1.** Target coordinate information table.

| Target number | longitude(°) | latitude(°) |
|---------------|--------------|-------------|
| 1             | 250          | 8           |
| 2             | 300          | 17          |
| 3             | 200          | 20          |

The initial orbital information of the 10 Earth observation satellites is shown in Table 2. The initial orbital time is 22:00:00 on January 14, 2018.

**Table 2.** Initial orbit information of 10 satellites.

| Satellite number | Semi-long axis(km) | Eccentric -ity | Inclination(°) | Argument of perigee(°) | Ascending node(°) | Mean anomaly (°) |
|------------------|--------------------|----------------|----------------|------------------------|-------------------|-----------------|
| 1                | 7029.8             | 0.022          | 100.7          | 66.2                   | 153.9             | 238.1           |
| 2                | 7843.9             | 0.033          | 104.6          | 126.7                  | 4.2               | 28.2            |
| 3                | 7025.8             | 0.021          | 99.24          | 39.14                  | 132.4             | 261.7           |
For the initial orbit data of the above 10 satellites, the orbit extrapolation for 168 hours (7 days), combined with the known target point information, can count 184 track window information that meets the user's requirements, as shown in Figure 2. The red bar indicates the No. 1 target, the green bar indicates the No. 2 target, and the blue bar indicates the No. 3 target.

![Figure 2. All orbits window information Gantt chart](image)

In summary, the simulation calculation is carried out according to the above simulation conditions, wherein the genetic algorithm parameters are set, the population number is set to 40, the crossover probability is 0.8, the mutation probability is 0.6, and the maximum iteration number is defined as 1000. Since the results obtained by the genetic algorithm are not necessarily global optimal solutions, we have carried out multiple sets of simulation experiments under the same parameters, and compared their final fitness values respectively. The simulation results show that it is going to 1000 iterations. After that, the fitness value of the population basically reached convergence.

According to the observation task requirements, the target invisible time of No.1 and No.2 is 8 hours, and the invisible time of No.3 target is 10 hours. This paper simulates the 7 days scheduling tasks, and the simulation results are as as shown in Figure 3- Figure 4.
Through the statistics of the last scheduling result, the forecasting schedule is 1 day, 28 window resources can be used before scheduling, and the total number of 8 window resources after scheduling is used, and 3 satellite resources are used. The forecasting schedule is 3 days, 81 window resources can be used before scheduling, and the total number of 26 window resources after scheduling is used, and 7 satellite resources are used. The forecasting schedule is 7 days, 181 window resources can be used before scheduling, and the total number of 59 window resources after scheduling is used, and 10 satellite resources are used.

Through the above simulation calculations and data statistics, the satellite resource scheduling model and intelligent optimization algorithm established in this paper can meet the user scheduling requirements and help solve the engineering application problems. From the income value curve and the scheduling task forecast Gantt chart, the final scheduled satellite reconnaissance mission can meet the maximum invisible duration requirement and use the least resources.

5. Conclusion
This paper describes the scheduling problem of Earth observation satellites. Under the constraints of satellite resource capability, observable time, conversion time between reconnaissance missions, energy, etc., a multi-satellite multi-target reconnaissance mission is established. Planning model. With the most resource-saving and high situational awareness uniformity as the optimization index, the
An optimized satellite reconnaissance mission planning scheme is obtained based on genetic algorithm. It is of great significance to improve the comprehensive application efficiency of spacecraft, to form uniform coverage of key areas, and to improve the uniformity of satellite resource utilization and situational awareness.

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