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SIMULATION-BASED SCHEDULING FOR PHOTO-RECONNAISSANCE SATELLITE

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ABSTRACT

A simulation-based scheduling mechanism for photo-reconnaissance satellite is presented in this paper. The satellite scheduling problem belongs to a class of single-machine scheduling problems with time window constraint. It is NP-hard in computational complexity. Based on simulation platform, a mixed integer programming model is used to formulate the problem and an advanced tabu algorithm is adopted to solve the MIP. Numerical results demonstrate that this approach is efficient in the scheduling problems.

1 INTRODUCTION

Photo-reconnaissance satellite is operated from earth to meet military image requests of certain zones. Generally, there are more image requests for satellite than that can be satisfied, the satellite scheduling is an oversubscription scheduling problem. Satellite just has limited windows of opportunity to image a given target area, its activity scheduling must meet the strict and demanding requirements. Solving the scheduling problem can make the maximum use of satellite.

The imaging request usually consists of spot targets and area targets. A spot target is a small circular or rectangle area, while an area target is a large irregular polygonal. Compared with spot target, area target is much larger. An area target requires several contiguous strips to be imaged, while a spot target can be covered by a single strip with steady posture. Although the study on satellite scheduling problems about spot target has attracted much attention for years, the study about area target is still needed to be further investigated.

The time window is a primary constraint needed to be met. In order to achieve repetitive observation under comparable light conditions, photo-reconnaissance satellite is usually launched into heliosynchronous orbit. Based on the characteristics of heliosynchronous orbit, a given target zone just have limited time windows of opportunity for being imaged.

To agile satellite whose sensor can point cross-track or along-track, it takes time to maneuver the satellite-based sensor from its previous position to the desired aspect angle for the new imaging operation. The maneuvering time, also called setup time, depends on the positions and postures of the two consecutive imaging operation. For a given imaging area, the choice of the position and posture for the satellite is not unique. There are preferences for the possible combination of positions and postures. Since the time windows are fixed, the maneuvering operation should consider the imaging time to ensure that there are enough time to image the selected target.

According to the above discussion, we conclude that the satellite imaging scheduling problem belongs to a class of single-machine scheduling problems featured by sequence-dependent setup effects and time window constraints, which is NP-hard in computational complexity.

To solve the satellite scheduling problem, this paper presents a scheduling mechanism based on simulation. The scheduling mechanism will be described in the following sections.

2 SIMULATION-BASED SCHEDULING MECHANISM

In the scheduling mechanism, simulation is the foundation of scheduling system, which fulfills the functions of preprocessing and validating. The simulation-based scheduling mechanism consists of four distinct phases: constructing scenario, processing data, scheduling and validating scheme (see the Figure 1). The roles of these phases are outlined in the following subsections.

2.1 Constructing Scenario

Constructing Scenario is the stage of establishing a scenario in simulation module while the scheduling mission is arrived. The constructed scenario includes all information about targets, satellite, satellite-based sensor, ground-station, time period, photograph weight, light constraint and other constraints. Every scenario represents a scheduling mission, which can be kept in the archives.

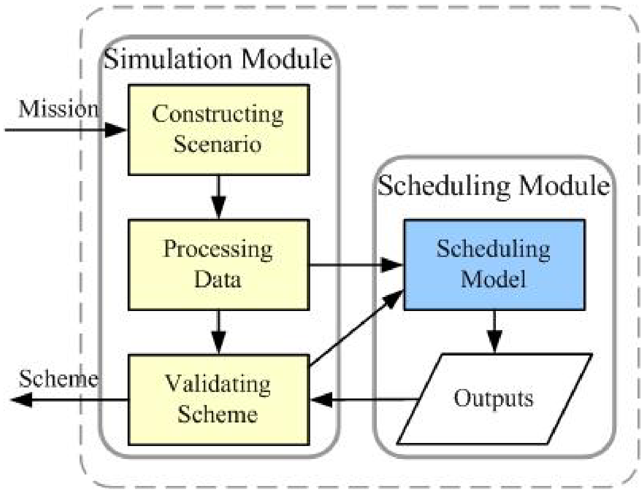

Figure 1: Simulation-based Scheduling Mechanism

2.2 Processing Data

At this stage, the simulation module will compute the time windows of imaging targets and then output data of time windows to scheduling module. Considering the characteristic of satellite-based sensor , a difference between spot target and area target is made. Let $\Re'$ denote the set of spot targets and $\Re''$ be the set of area targets. $\Re$ represents the whole targets required to be imaged, where $\Re = \Re' \cup \Re''$.

The time windows of spot target can be computed directly with the position. Compared with spot target, the computing procedure for area target is much more complicated. Simulation module will first compute the polynomial equation of satellite nadir based on the parameters of orbit, then divide area target into many segments based on the polynomial equation. The direction of every segment is parallel to the track of satellite. The size of segment has a reference to the designing characteristic of satellite-based sensor (see Figure 2). Let $\Re'''$ be the set of candidate pieces which are the divided result of area target in $\Re''$. I denote the set of all candidate tasks, which will be outputted into scheduling module, then $I = \Re' \cup \Re'''$.

For each imaging task $i \in I$, we use the simulation module to compute time windows with the constraint of scenario time period. Note TW^i represents the set of candidate time windows about task i, where $TW^i = \left\{TW_1^i, \cdots, TW_{N_i}^i\right\}$, $TW_n^i = [ws_n^i, we_n^i]$, $n \in \left\{1, \cdots, N_i\right\}$. N_i is the number of time windows which correspond to target i. ws_n^i and we_n^i are the time frames available for processing task i.

In this scheduling problem, we define every target $r\left(r \in \Re\right)$ with the weight W_r, which is related to the priority and acreage of target. While an area target $r\left(r \in \Re''\right)$ is divided into $\mathrm{M}_r\left(\mathrm{M}_r \geq 2\right)$ pieces of segment, the weight of task $i\left(i \in \Re'''\right)$ which is derived from target r can be calculated with equation W_r / M_r.

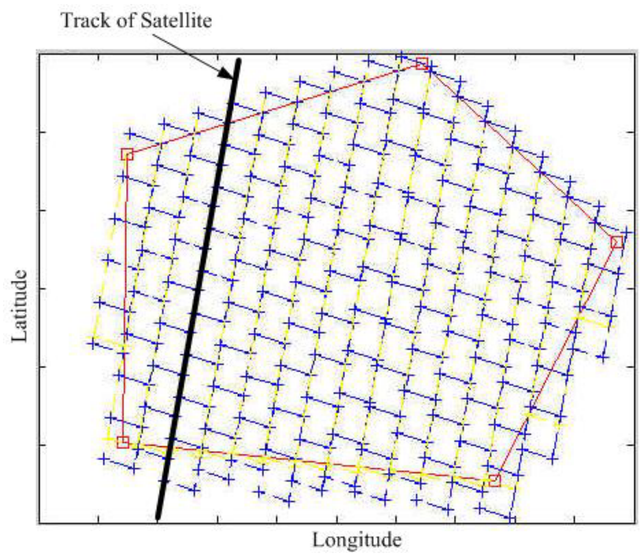

Figure 2: The cutting up of an area target into segments of constant size. The area target is represented by a red line, and the resulting images by blue lines

2.3 Scheduling

We construct a mixed integer programming (MIP) model to formulate the scheduling problem of photo-reconnaissance satellite. We assume there is a fictive task o, which begins and ends the selected sequence (with no time and no visibility constraints). We define set $I^+ = I \cup \{o\}$.

Let us define some notations first.

p_i : processing time of task i, $i \in I^+$;

w_i : the weight of candidate imaging task i;

$s_{i,j}$: setup time from processing task i to j, $i, j \in I^+$;

In this article, three sets of decision variables are used:

X : the set of order in selected sequence. If the task i is followed by task j in the selected sequence, $x_{i,j} = 1$, otherwise $x_{i,j} = 0$;

T : the set of imaging starting time of tasks, where $T = \{t_0, t_1, \cdots, t_M\}$, M is the amount of task in set I^+. For any candidate task $i \in I$, if i is selected, t_i is the imaging starting time of task i, otherwise $t_i = 0$. There is $t_0 = 0$;

Y : the set of using state of time window. If the task i utilize time window TW_n^i, $y_n^i = 1$, otherwise $y_n^i = 0,\ n \in \{1, \cdots, N_i\}$.

The problem can be formulated as follows:

$$\max \sum_{i \in I^+} w_i \left(\sum_{j \in (I^+ - i)} x_{i,j} \right) \tag{1}$$

$$\text{s.t.} \quad \sum_{j \in (I^+ - i)} x_{i,j} \le 1 \quad \forall i \in I \tag{2}$$

$$\sum_{i \in I} x_{0,i} = 1 \tag{3}$$

$$\sum_{j \in (I^+ - i)} x_{i,j} - \sum_{j \in (I^+ - i)} x_{j,i} = 0 \quad \forall i \in I^+ \tag{4}$$

$$\sum_{j \in (I^+ - i)} x_{i,j} - \sum_{n=1}^{N_i} y_n^i = 0 \quad \forall i \in I^+ \tag{5}$$

$$\sum_{n=1}^{N_i} y_n^i ws_n^i \le t_i \quad \forall i \in I \tag{6}$$

$$\sum_{n=1}^{N_i} y_n^i \left(we_n^i - p_i \right) \ge t_i \quad \forall i \in I \tag{7}$$

$$(t_i + p_i) \sum_{j \in (I^+ - i)} x_{i,j} + \sum_{j \in (I^+ - i)} s_{i,j} x_{i,j} \le \sum_{j \in (I^+ - i)} t_j x_{i,j} \tag{8}$$

$$x_{i,j} \in \{0,1\} \quad i, j \in I^+ \tag{9}$$

$$y_n^i \in \{0,1\} \quad i \in I^+,\ n \in \{1, \cdots, N_i\} \tag{10}$$

The objective (1) of the mathematical model considers the weight sum of selected tasks, which ensures that the selected sequence will achieve the maximum efficiency of satellite. Constraint (2) expresses that an imaging task can be selected once at most. Constraint (3) forces that the fictive imaging task o must be selected. Constraint (4) sates that if an imaging task is selected, the amount of images preceding it must be equal to that of images following it. If an imaging task is not selected, it has no preceding and no following selected image. Constraint (5) states that if an imaging task is selected, it must occupy a time window. If an imaging task i is not selected, none of the time window will be utilized. Constraints (6) and (7) force each selected imaging task must be completed within one time window. Constraints (8) states the time constraint between two selected imaging tasks, while task i is followed by task j, the imaging of i should end before the starting of imaging j.

The scheduling problem formulated above is a mixed integer programming problem of NP-hard computational complexity. To solve this NP-hard problem, we adopt an advanced tabu search (TS) algorithm.

Tabu search is a method to search the optimum solution for combinatorial optimization problems, which is proposed by Glover (1989,1990). Its power has been shown in solving many hard problems including the maximal satisfiability and graph-coloring problem. TS has three phases: preliminary search, intensification, and diversification. During the first step, TS is similar to some other optimization methods. That is whatever point x in the input space is focused currently, the criterion function f at all neighbors N of x is evaluated to find the new point x' even if it is worse than x. But this idea creates the possibility of endlessly cycling back and forth between x and x'; to avoid this TS uses a tabu list of forbidden moves. However, it is difficult to evaluate the length of tabu list while the topological of search space is not clear. To solve the problem of tabu list we adopt a tabu search algorithm with varying neighborhood (VNTS) for the satellite scheduling problem. The neighborhood used can be changed with the process of the algorithm, so that not only the scale of the neighborhood is small, but also the reachability can be kept. The computational results of different scenarios show that the VNTS algorithm has high efficiency and has a more steady performance.

The main procedure of VNTS is shown in Figure 3.

Here N_1 and N_2 are the iterative upper bounds. The $TSprocess(\ )$ is a tabu search process, which searches a better solution in neighborhood H with a tabu list of length L. S_0 is the initial solution of mathematical model. S' represents the best solution got within neighborhood H.

2.4 Validating Scheme

At this stage, simulation module will simulate whole imaging process of photo-reconnaissance satellite based on the scheme, include flying, imaging, and adjusting satellite-based sensor. The results of simulation will be passed back to the scheduling module. If a scheme is found incompatible with imaging activities, simulation module will make the scheduling module re-compute until a feasible scheme is produced.

The simulation module fulfils the function of feedback which causes the schedule module amend its scheme to close to feasible solution.

3 NUMERICAL EXPERIMENTS

Numerical experimentation is used to verify the feasibility and optimality of the proposed simulation-based scheduling mechanism.

Experiments are done on several cases. Each case includes tens of spot targets and two area targets, those targets are produced randomly by a target producing module. Those experiments are conducted in an Intel *P*4 1.6*G* PC with memory size of 128MB. The time period of the satellite scheduling is 86400 seconds (24 hours). Those experiments show that our simulation-based scheduling system could effectively solve the problem of mixed imaging mission which includes both spot targets and area targets.

```
VNTS algorithm
begin
  bestValue ← 0
  S_0 ← Initial solution
  S_k ← S_0
  repeat
    loopParam ← 0
    H ← H_1 //set neighbourhood to be H_1
    L ← L_1 //set length of tabu list to be L_1
    while (loopParam ≤ N) do
      TSprocess(bestValue, H, L, S_0, S′)
      loopParam ← loopParam + 1
    end while
    //change the neighborhood
    S_0 ← S_k
    loopParam ← 0
    H ← H_2 //set neighbourhood to be H_2
    L ← L_2 //set length of tabu list to be L_1
    while (loopParam ≤ M) do
      TSprocess(bestValue, H, L, S_0, S′)
      loopParam ← loopParam + 1
    end while
  until reach the condition of ending
  output(bestValue, S′)
end
```

Figure 3: The procedure of VNTS

4 CONCLUSIONS

In this paper, we present the simulation-based scheduling mechanism for an photo-reconnaissance satellite. The satellite scheduling problem belongs to single-machine scheduling problem with time window constraint. We utilize simulation module to construct scenario, process data, and validate scheme. We formulate the scheduling problem with a MIP mathematical model, and adopt a varying neighborhood Tabu search algorithm to solve the scheduling problem. We also utilize numerical experiments to assess the optimality of the scheduling mechanism.

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