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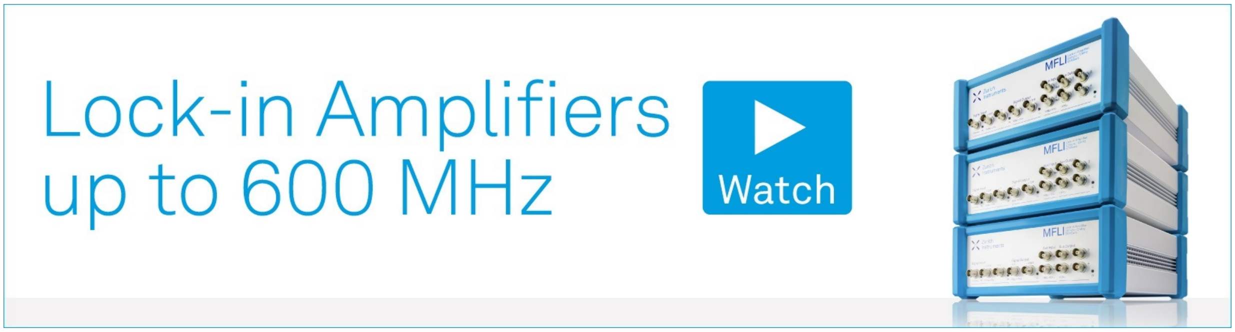

Application of Constraint-Based Satellite Mission Planning Model in Forest Fire Monitoring

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Abstract. In this paper, a constraint-based satellite mission planning model is established based on the thought of constraint satisfaction. It includes target, request, observation, satellite, payload and other elements, with constraints linked up. The optimization goal of the model is to make full use of time and resources, and improve the efficiency of target observation. Greedy algorithm is used in the model solving to make observation plan and data transmission plan. Two simulation experiments are designed and carried out, which are routine monitoring of global forest fire and emergency monitoring of forest fires in Australia. The simulation results proved that the model and algorithm perform well. And the model is of good emergency response capability. Efficient and reasonable plan can be worked out to meet users' needs under complex cases of multiple payloads, multiple targets and variable priorities with this model.

Key words: Forest Fire; Remote Sensing Satellite; Mission Planning; Constraint Satisfaction; Greedy Algorithm.

INTRODUCTION

There are a large number of forest fires occur each year all over the world, resulting in many affected area, posing a serious threat to forest resources and the safety of human life and property. Satellite remote sensing has become an important means to guide the prevention and rescue of forest fires, because of its wide coverage, fast information updating and rapid response compared to traditional monitoring methods. It is becoming more and more popular in forest fire monitoring.

The process of satellite's earth observation is complex. Satellite observation planning and data transmission planning are integrated with time, resources and many other constraints.[1] In the face of complex constraints and a great number of demands, manual planning is of low efficiency and difficult to guarantee the quality of planning. To take full advantage of the limited time and resources and meet users' needs, it is necessary to study and apply satellite mission planning technology. [2]

MODEL

Model Structure

Constraint satisfaction problem (CSP) is a basic problem in the field of artificial intelligence, and it has been used in many fields, like resource scheduling, computer vision and temporal reasoning. [3] Constraint satisfaction problem can be described as follows: given a set of variables, and each variable has its own range. The value of the

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variable is limited by a set of constraints at the same time. The task of a CSP is to take values in the range of the variables and achieve a desired effect with these constraints satisfied.

The task of satellite mission planning is essentially a kind of CSP. Based on the thought of constraint satisfaction, it is possible to extract several sets including observation targets, observation requests, observation, data downlink and so on. Then we can establish the satellite mission planning model with these sets and use constraints to link the them up. [4]The constraints set is composed of multiple constraints, such as time, resource and image. The resource set constraints satellite, payload and so on. Fig.1 is the structure of the model.

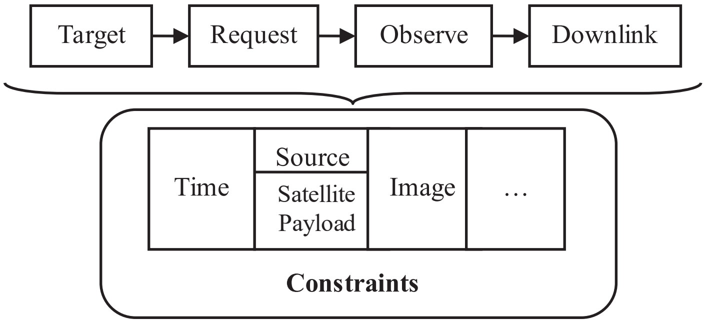


FIGURE 1. The structure of a constraint-based satellite mission planning model.

Optimization goal

Priority is an important element in satellite mission planning. There are two types of priority in the model: observation and data downlink priority. In this paper, priority is divided into 5 grades: the lowest, low, normal, high and the highest, which is respectively represented by number 1~5.

The purpose of satellite mission planning is to solve the contradictions between time, resource and demand. We should make a trade-off in the *Observe* set and maximize the priority of the final observation plan through constraint processing and object optimization. The final observation plan is a set S in which $observe_i$ is arranged by time. The optimization goal is to make the set S :

$$\max \sum observe_i . priority \tag{1}$$

Constraint analysis

There are many constraints on earth observation activities of remote sensing satellites. There are many supply difficulties when the satellite platform carries sensors in orbit. As a result, Power, data storage space and other resources for payloads to use are limited. Because the satellite turns around the earth and the earth rotates itself, satellite can only view the target area in the visual time window. The satellite coverage area is limited by satellite orbit, side swing capacity, field angle of sensors and other factors.[5] In addition, there are other constraints to limit satellite observation activities.

It is necessary to deal with these constraints in the mode to achieve optimization goals. The constraints in this model are analyzed as follows:

Symbol explanation: *Target* represents the set of observation targets, *Request* represents the set of observation request, *Observe* represents the set of observation, *Payload* represents the set of payload, and *Downlink* represents the set of data downlink. The abbreviated symbols are T , R , O , P and D .

Time Constraint

$\forall t_j \in T, \forall r_i \in R_j, \forall d_k \in D$,

$$r_i . startTime \geq t_j . startTime, \quad r_i . endTime \geq t_j . endTime \tag{2}$$

$$R_j.(r_i.startTime, r_i.endTime) \subseteq t_j.VisualTime \tag{3}$$

$$(d_i.startTime,\ d_i.endTime) \subseteq d_i.PermitTime \tag{4}$$

R_j represents the set of observation requests from target t_j, r_i represents a single request in R_j. d_i represents a single data downlink.

Constraint (2): The constraint of time range. Each observation should be within the range of observation time in the request.

Constraint (3): The constraint of visual time window. Each request from a target area should be within the visual time window.

Constraint (4): The constraint of downlink time window. $PermitTime$ represents the time window when data download is permitted. The period of data downlink should be within $PermitTime$ which relay satellite distributes to the remote sensing satellite.

Resource Constraint

$\forall o_i \in O, \forall p_j \in P, \forall d_k \in D$,

$$o_i.p_j.dataAmount \le p_j.remainAmount \tag{5}$$

$$o_i.energy \le satellite.remainEnergy \tag{6}$$

$$o_i.power \le satellite.remainPower \tag{7}$$

$$d_k.dataAmount \le D.permitAmount \tag{8}$$

Constraint (5): Storage constraint. When the observation mode is "playback", data collected by a payload is temporarily stored in the on-board memory. The capacity of memory is limited, and it allocates the maximum storage space for each payload. So there is a constraint: the data produced by each payload cannot exceed the remaining storage amount for it.

Constraint (6): Energy constraint. The energy on the satellite is mainly from the solar energy collected by solar arrays. However, the satellite can only collect solar energy when facing sunlight. Its ability to collect and convert solar energy is also limited. So the energy consumption of each observation cannot exceed the remaining energy.

Constraint (7): Power constraint. Payloads' normal work need to take up power, while the total power provided by the satellite is certain. So the power required for earth observation cannot exceed the remaining power.

Constraint (8): The constraint of downlink data volume. Because of the Limited storage space on the relay satellite, the amount of downlink data should not exceed the storage capacity.

Imaging Condition Constraint

$\forall o_i \in O, \forall p_j \in P$,

$$o_i.p_j.sunAngle \le p_j.minSunAngle \tag{9}$$

$$o_i.weather.cloudLevel \ge t_i.weather.cloudLevel \tag{10}$$

$$o_i.groundResolution \ge t_i.groundResolution \tag{11}$$

Constraint (9): Solar elevation angle constraint. In order to make a payload work normally and ensure the quality of observation, a payload will not work until the sun elevation angle is greater than or equal to the minimum value it needs.

Constraints (10): Cloud coverage constraint. The cloud conditions over a target should be better than its requirements for clouds.

Constraints (11): Ground resolution constraint. The ground resolution of an observation cannot be lower than its requirements for the target.

Other Constraints

$\forall o_i \in O, \forall p_j \in P$,

$$p_j.periodWorkTime \le p_j.maxperiodWorkTime \tag{12}$$

$$p_j.periodWorkNum \le p_j.maxperiodWorkNum \tag{13}$$

$$p_j.circleWorkTime \le p_j.maxcircleWorkTime \tag{14}$$

$$p_j.circleWorkNum \le p_j.maxcircleWorkNum \tag{15}$$

$$o_i.p_j.onTime_{k+1} - o_i.p_j.offTime_k \ge p_j.minInterval \tag{16}$$

$$p_j.minWorkTime \le o_i.p_j.workTime \le p_j.maxWorkTime \tag{17}$$

Constraint (12): In a planning cycle, the length of working time of a payload cannot exceed the maximum limit.

Constraint (13): In a planning cycle, the number of times a payload works cannot exceed the maximum limit.

Constraint (14): In a cycle of the satellite, a payload's work time cannot exceed the maximum limit

Constraint (15): In a cycle of the satellite, the number of times a payload works cannot exceed the maximum limit.

Constraints (16): To avoid switching on and off frequently, we set the minimum time interval from a payload shuts down to its next booting up.

Constraint (17): The time length of a payload in working condition should be between the shortest and the longest time length.

MODEL SOLVING

Greedy algorithm

Greedy algorithm is an algorithm commonly used in optimization problems. Its strategy is to make the best choice at every step considering the current state, according to the available information. Greedy algorithm does not consider the pros and cons of a selection from the whole. Therefore, it is often a local optimal solution in some sense, but it is very efficient with excellent performance in time and has been widely used in practice. [6]

The key to the application of greedy algorithm is the determination of greedy principle. In the problem of satellite mission planning, the greedy principle is not fixed and needs to be determined according to the actual situation. In our work, we take it as the greedy principle (optimization objective function) that making full use of time and resources and trying to satisfy the high-priority request. In practice, we select the mission (observation or downlink) with the highest priority at each step and put it into the plan [7]. The algorithm is described as follows:

Symbol explanation: I represents the mission set (which includes the observation set and the downlink set) in the initial state. F Is used to store the missions selected from I.

Step 1: Sort the missions in I by priority.

Step 2: Select the mission with the highest priority in I and put it into F.

Step 3: Sort the missions in F by time and check whether they satisfy the constraints. If not, do appropriate treatment or directly remove them from F.

Step 4: Check whether I is empty. If I is not empty, go to step 2. If I is empty, go to step 5.

Step 5: Obtain the final plan based on the missions in F.

Solving procedure

Step 1: Data formatting. Format the data to meet the processing requirements of the system, including user needs, satellite, payload, and orbital data.

Step 2: Planning for payloads' work. Develop plans with greedy algorithm.

Step 3: Data storage and transmission planning. Use greedy algorithm to deal with constraints and develop plans.

Step 4: Output the plan. Output payload work plans and data transmission plans.

Fig.2 shows the procedure of the model solving.

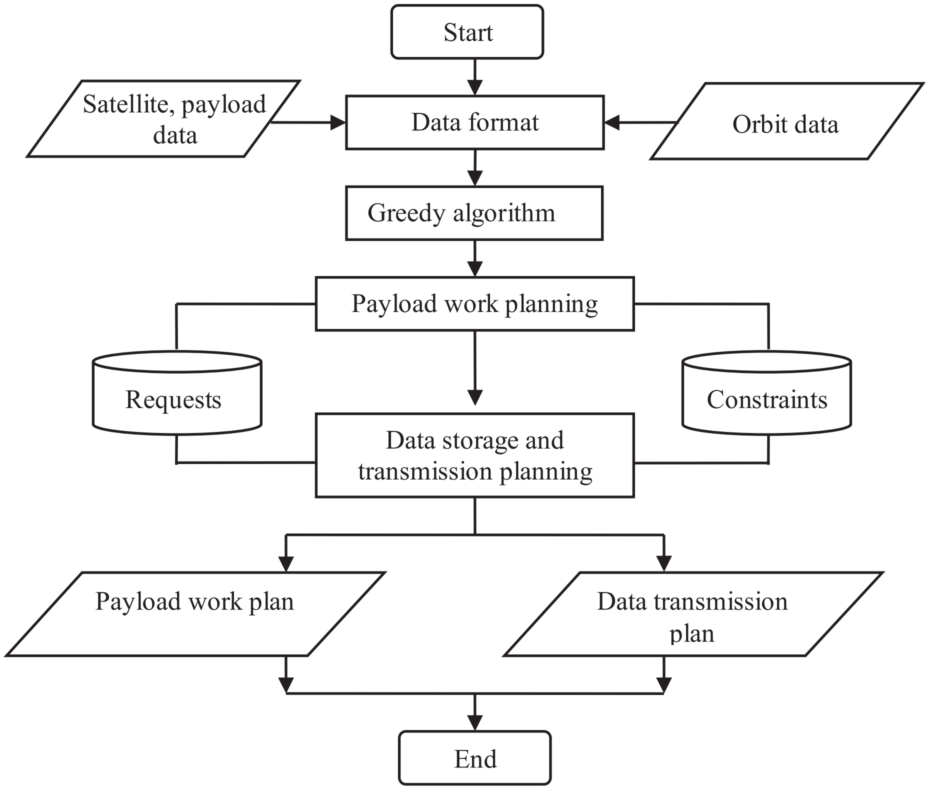


FIGURE 2. The flow chat of model solving.

SIMULATION EXAMPLES

In this section, we use the model established in section MODEL to make a routine monitoring plan of global forest fires. Then we make adjustment to the plan in time and formulate an emergency plan when forest fires occurs in somewhere.

Simulation resource

Remote Sensing Satellite

In the simulation experiment, a low earth orbit satellite is designed. The orbit elements of the satellite are shown in Table 1. The epoch is 08:00 on March 16, 2017.

TABLE 1. The orbit elements of the satellite.

Orbit Elements	Value
Semi-major Axis	6062km
Eccentricity	0.00035207346°
Inclination	42.77373796701°
Longitude of the Ascending Node	190.367190838°
Argument of Perigee	290.745915890°
Mean Anomaly	278.659836054°

Relay Satellite

According to the characteristics of this experiment, data transmission between the observation satellite and the relay satellites is chosen as the downlink mode to ensure the timeliness. The relay satellites are all in the geosynchronous orbit, with the orbit position at 176.76°E, 16.65°E and 76.4°E.

Payloads

The remote sensing satellite carries 4 earth observation payloads on board. The payloads are visible light, thermal infrared, shortwave and microwave sensors, expressed with the number 1 to 4 respectively. Thermal infrared band is sensitive to temperature and is well suited for forest fire monitoring. It is widely used in practice. Other payloads can assist in the monitoring of forest fires or undertake other observation tasks.

World Forest Fire Monitoring

Observation Target

In this simulation, 30 forest fire-prone areas are selected around the world and they make up the observation set together with the other 10 observation requests.

The 40 observation targets are distributed all over the world with different requests of payload type, observation priority and downlink priority. In addition, there are a large number of constraints to deal with. Therefore, it is a complicated planning task. Manual planning is not only inefficient, but also difficult to guarantee the quality of the plan. We should take the optimization algorithm and use computer to do the planning work.

Observation Plan

In the simulation, a planning cycle is 24 hours, from 00:00 on March 17, 2017 to 00:00 on March 18, 2017. Table 2 shows the monitoring plan of global forest fire safety. The plan is calculated with the method in section MODEL SOLVING. Fig.3 shows the satellite scanning bands in the planning cycle.

TABLE 2. The monitoring plan of global forest fire safety.

Number	Observation target	Payload type	Start time	End time	Integrated priority
1	Native American	1,2,3	00:25:19	00:35:26	3
2	Central South America, northern Brazil, northern Venezuela	2	00:36:39	00:52:27	3
3	Amazon rainforest	4	00:40:50	00:48:30	2
4	Kalimantan Island	2	01:27:51	01:37:51	3
5	Western Mexico, native of the United States	1,2,3	02:00:02	02:11:05	3
6	Amazon rainforest	4	02:18:59	02:21:59	2
40	Amazon rainforest	4	23:41:11	23:48:50	2

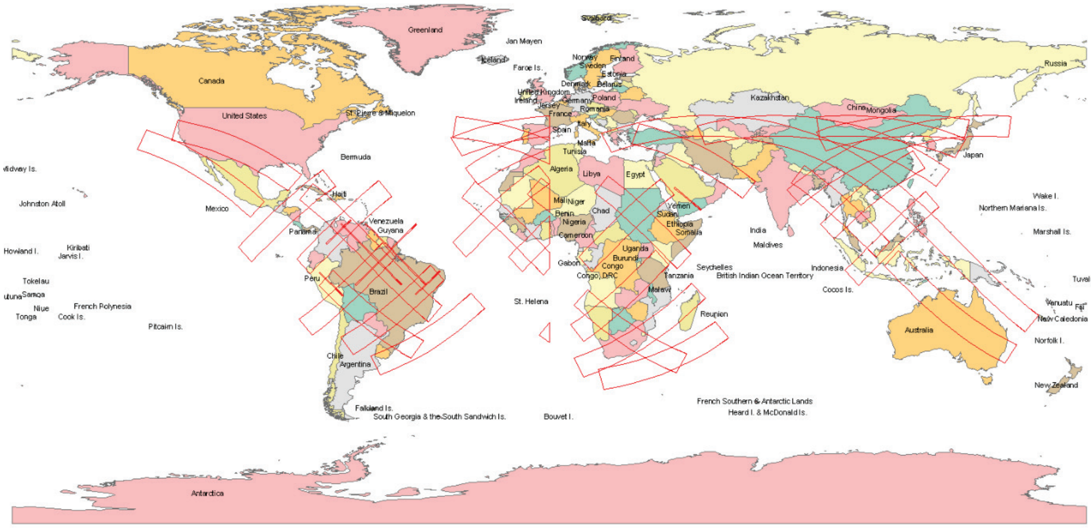


FIGURE 3. The satellite scanning bands of global forest fire safety monitoring.

Fig.4 is the Gantt chart of the observation plan. It shows the time distribution of observation modes. The mode 1 is a combination of visible light, shortwave and thermal infrared. Mode 2 is SAR and mode 3 is thermal infrared. The number of the targets in thermal infrared mode is the largest among all targets, which is related to the observation requests. Table 3 is the data downlink plan. It shows the time and volume of data transmission.

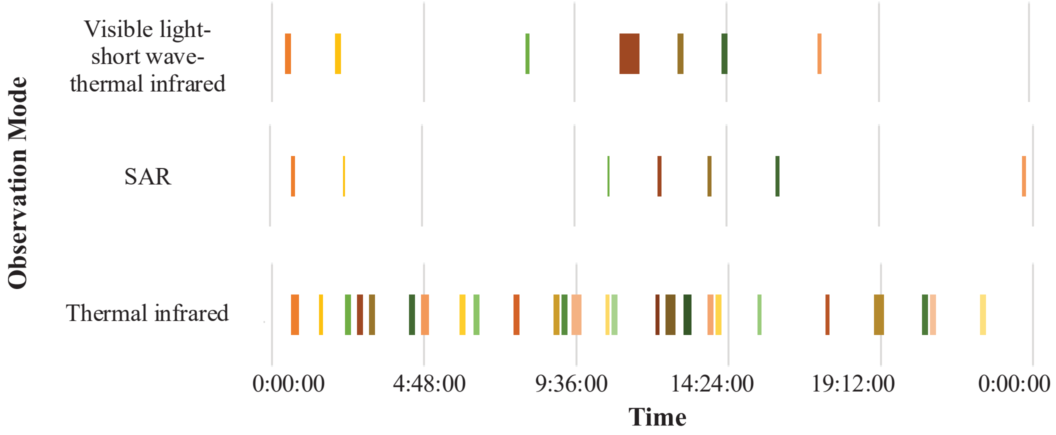


FIGURE 4. The Gantt chart of the observation plan.

Table 3. The data downlink plan.

Downlink number	Start time	End time	Data volume (MB)
1	09:02:19	09:29:51	18477
2	10:35:51	11:10:11	22445
3	17:14:04	17:48:35	22596

Emergency Monitoring of Forest Fire in Australia

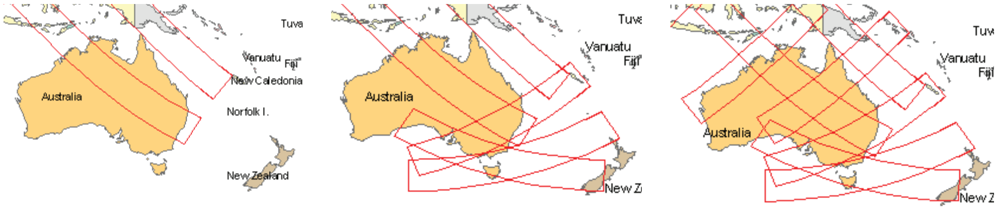
In addition to routine monitoring, the plan should adjust to emergency situations when fires occur in some regions. The affected areas should be paid more attention to, so that fire information can service in fire fighting work.

Region of Emergency Observation

Australia is a country with many forest fires each year. And in recent years, global warming is increasing the frequency and severity of forest fires in Australia. The Australian continent is located at 113 ~ 154°E, 11 ~ 39°S. Forest resources are mainly distributed in the north and east.

Emergency Observation

Assuming a forest fire occurs in a certain area in Australia, remote sensing satellite is required to monitor the forest fire urgently. In the routine monitoring, the priority of Australia is 1. There is only one observation to be carried out over part of Australia in a planning cycle (24 hours). And there is no observation of Yorkshire Peninsula where forest fires are frequent. Obviously, the original observation plan is not satisfactory when forest fires occur. In order to get more fire information, contingency planning is needed.



(a) Priority is 1 (b) Priority is 3 (c) Priority is 5

FIGURE 5. The changes of satellite scanning bands with the increase of priority.

It is mentioned when establishing the planning model that the optimization goal is to get the highest priority in the plan. So increasing observation and downlink priority of Australia is the key to the emergency plan. We did so, and Fig.5 shows the changes of satellite scanning bands with the increase of priority. When the priority is set to the highest level, 7 of the planned observations are related to Australia. Satellite scanning bands covers about 2/3 of the Australian continent (forests are scarce in other area). Yorkshire Peninsula is also monitored effectively and the forests in the northern, eastern and southeastern Australia are monitored many times.

Simulation analysis

In the routine global forest fire monitoring, a total of 40 observations are arranged in one planning cycle (24 hours). It's not a simple plan seems as every target is observed when it is visual to the satellite. Fusion and trade-offs of requests are essential to deal with a large number of constraints. Such as the second observation, it includes three targets in one observation: Central South American, northern Brazil and northern Venezuela. It avoids payloads switching on and off frequently, saves power and improves the observation efficiency. This experiment shows that the model can be used to develop efficient and reasonable plan to meet the needs of users in the complex case of multi-payload, multi-target and variable priority.

In the emergency observation of Australian forest fire, the emergency plan expands observation area, increases observation frequency and prolongs observation time, which is of great significance to master fire information and guide fire fighting work. The experiment shows that this model has good emergency response capability. It can make timely and effective adjustment to the plan according to changes in users' needs.

CONCLUSION

Satellite mission planning problem can be seen as a CSP. In this paper, we establish a constraint-based model for remote sensing satellite mission planning. The model is solved with the method of greedy algorithm to develop observation plan and data downlink plan. In the simulation. We develop routine plan for forest fire monitoring and verify the emergency response capability of the model. The simulation results are satisfactory, which shows that the model and algorithm are in good condition. Our work is of great practical value to forest fire monitoring, and it can be used to other fields. More work will be focused on the research and application of multi-satellite mission planning and intelligent algorithms.

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