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Onboard mission planning for agile satellite using modified mixed-integer linear programming

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ABSTRACT

This paper investigates a new Agile Earth Observation Satellite (AEOS) mission planning algorithm. This new developed algorithm is based on Modified Mixed-Integer Linear Programming (MILP) approach, which takes the minimum slew angle and highest priority criterion. The key point of the paper lies in that the planning process is treated as a Dynamical Combinatorial Optimization (DCO) problem due to the time-varying constraint and the requirement of the problem. The design of the new algorithm is also to meet the real-time requirement of onboard mission planning. The mathematical formulation of the problem is modified to satisfy the demand of the LP solver, and a newly developed dynamic database is used to simulate the constantly changing satellite-target relative position with limited observation windows. The new mission planning model is solved by the LP method to test its reliability. Another solution with Generic Algorithm (GA) is also given to check the result. The calculation time of these two methods is compared to show that the LP approach has a better compatibility with the onboard mission planning requirement.

1. Introduction

The Agile Earth Observation Satellite (AEOS) is considered as the most promising representative of the next-generation earth observation platform [1]. The Attitude and Orbit Control System (AOCS) of AEOS is significantly improved recent years, and the observation mode is totally different from those of the traditional earth observation spacecraft. To this reason, the new mission analysis, planning and operation system must be developed to meet the more complex mission requirements [2–4].

The idea of mission management for aircraft and spacecraft is a long discussed topic, and many important works in this region have been reported. Lin addressed the issue of space station overall mission planning by use of decomposition approach [5]. Wang presented the robust gain scheduled control and optimal trajectory planning for an autonomous space rendezvous system subject to input saturation [6]. However, the onboard mission planning and self-management technology is not widely adopted yet. The most scientific observation missions still rely on the ground space cycle operation mode [7]. The newly demonstrated CASPER system is able to realize the mission planning process for EO-1 satellite considering the time-varying condition, which is one of the most convincing examples of the onboard planning technology being used in real satellite mission [8]. Whereas, CASPER's planning service only stops at the general activity level, the detailed satellite dynamic model and optimal control criterion are not considered.

In the field of earth observation satellites, the development of the onboard mission planning system is hindered by the limited onboard computing capability. The traditional earth observation satellites only have the capability of slewing along the certain fixed directions. The onboard instruments can take images only when the attitude of satellite is stable. To these reasons, the researches in the field of satellite mission planning are mainly focused on the constellation configuration and multi-satellite cooperation. Examples of such works can be found as the framework of operation strategy of space constellation proposed by Chen [9], and the software architecture design presented by Xu to improve the constellation autonomous formation flying capability [10]. With the continuous development of AOCS technology, more and more attention has been paid to the attitude control of complex structures with higher accuracy and higher angular velocity. An example of such works can be given as the flexible structure control strategy addressed by Cao [11,12].

Computational optimization is one of the major research topics in the artificial intelligence and computer science. The GA based

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combinatorial optimization algorithm was presented by Yeniay to solve the optimization problem with various constraints [13]. The advanced optimizer is also adopted in the field of aerospace control. For example, Komfeld proposed a GA based algorithm for the optimal attitude planning [14]. However, the computing capability and the strict real-time constraint of the onboard mission planning are rarely considered in the studies mentioned above. Melton presented a Maximum-Likelihood method in order to achieve the optimal attitude control, which proved that the calculation time can be reduced dramatically with the modified formulation and new developed computing algorithms from the attitude control perspective [15]. The results from the work of Melton prove the feasibility of reducing the calculation time cost to meet the real-time requirement. At the same time, this paper also presents the similar idea with the Linear Programming (LP) solver. The LP technology was firstly introduced by Orourke to solve the general optimization problem (not specified to be in aerospace area) [16]. The concept of LP continues to develop and becomes more efficient, and recent research shows that this approach can be combined with neural network and reinforcement training approaches to realize more complex and effective optimization [17]. The use of LP approach in satellite trajectory and attitude planning has also long been carried out. Coverstone-Carroll adopted the traditional LP method to realize an activity planning for a space robot considering the robot's orbit dynamics and its orientation cost criterion [18]. Richards proposed a mixed integer optimizer for satellite's trajectory planning with avoidance constraints [19]. Zhang developed a modified LP algorithm for space rendezvous mission planning, in which the problem of rendezvous and docking maneuver planning was solved by dynamical activity distribution approach [20].

The mission planning for agile satellite is a relatively new research topic [21]. Lemaitre proposed a mission selecting and scheduling algorithm using image processing and area target regrouping approach, which mainly focused on the ground area target analysis and the Field of View (FOV) scanning direction planning of onboard instrument [22]. Based on the discussion above, it is clear that more improvements can be made in this research area. The aim of this paper is to propose a new onboard mission planning method for agile satellite using modified mixed-integer linear programming. The rest of this paper is organized as follows. Section 2 describes the detailed formulation of the onboard mission planning problem of agile satellites. In Section 3, the new model is solved by the LP method to test its reliability, and the solution obtained by Generic Algorithm (GA) is also given to conduct comparative analysis. And finally a conclusion is drawn in Section 4.

2. Formulation of the problem

2.1. Coordinate system definition

The earth observation satellites usually operate on the sun-synchronized orbit with the inclination of 97 degree and the altitude of 500 km. This kind of orbit enables the satellite to have global earth coverage and relative low altitude to obtain clear images [23,24]. The detailed mission scenario and related parameters in this paper are set in Table 1.

The standard observation interval defined in Table 1 is obtained according to the fact that the average access time of a target point on ground to a satellite flying in the orbit of 500 km altitude is about 700 s. Since the aim of the paper is more focused on the mission planning level, the simplified dynamic model of satellite is adopted. It is also assumed that the satellite is able to slew with a constant angular velocity in any direction. The acceleration and deceleration processes at the beginning and end of slew maneuver are neglected.

Table 1
Related parameters of mission scenario.

Related parameters	Value
Standard observation sequence interval	700 s
Onboard mission planning interval	5 min before the beginning of observation sequence
Observation pointing constraint	Anti-sun pointing
Observation interval constraint	Target area during day time
Standard slew angular velocity	6°/s

In order to conduct the earth observation mission, the AEOS satellite needs to slew frequently in engineering practice. To properly describe and define the movement and the attitude of the satellite, the following coordinate systems are defined:

1) The earth-centered earth-fixed coordinate system o_f–$X_fY_fZ_f$: This coordinate system is to define the orientation of satellite and the positions of all the ground targets. The satellite's orientation is presented in the quaternion form, while the ground targets are presented in a two-dimensional coordinate system: $\mathbf{p}_{ti} = [\lambda_i \ \varphi_i]$ with λ_i and φ_i denoting the target's longitude and latitude, respectively. For simplicity, the coordinate system is named as the earth fixed coordinate thereafter.
2) The satellite body coordinate system $o_b - X_bY_bZ_b$: This coordinate system is defined to calculate the pointing direction of the instrument in the inertial space. The center of the coordinate locates at the center of mass of the satellite: The z direction is defined by the bore sight of the instrument. The y direction is defined by the rotational axis of spacecraft's solar panel and the x direction completes the right hand rule.
3) The earth J2000 inertial coordination system $o_j - X_jY_jZ_j$: The definition of this coordination system is traditional. It can be used to calculate the orbit of satellite. From the orbit information, one can determine the observation window of all targets. The coordinate system is named as the earth inertial coordinate for simplicity.
4) The orbit coordinate system $o_o - X_oY_oZ_o$: This coordinate system is used to describe the position of satellite in orbit. The z axis is collinear to the satellite position vector in the earth J2000 coordinate system. The x axis is perpendicular to z axis and points to the satellite's velocity direction and the y axis completes the right-hand rule.

Fig. 1 shows the relative position between the earth, the satellite and the ground targets. It also demonstrates all the coordinate systems and the concept of scanning path of the satellite's instrument during the observation.

With the definition of the coordinate systems, the following relative positions can be easily obtained:

$$\mathbf{d}_{tf} = \begin{bmatrix} x_{tf} \\ y_{tf} \\ z_{tf} \end{bmatrix} = r_e \cdot \begin{bmatrix} \cos(\varphi_i)\cdot\cos(\lambda_i) \\ \sin(\varphi_i)\cdot\cos(\lambda_i) \\ \sin(\lambda_i) \end{bmatrix} \tag{1}$$

$$\mathbf{r}_{sat}^i = \begin{bmatrix} x_{sat}^i \\ y_{sat}^i \\ z_{sat}^i \end{bmatrix} \tag{2}$$

$$\mathbf{r}_{sat}^f = \begin{bmatrix} x_{sat}^f \\ y_{sat}^f \\ z_{sat}^f \end{bmatrix} = \mathbf{\Xi}(t) \cdot \begin{bmatrix} x_{sat}^i \\ y_{sat}^i \\ z_{sat}^i \end{bmatrix} \tag{3}$$

$$\mathbf{r}_{rel}^f = \mathbf{d}_{tf} - \mathbf{r}_{sat}^f \tag{4}$$

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