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A hybrid online scheduling mechanism with revision and progressive techniques for autonomous Earth observation satellite

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A R T I C L E I N F O

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A B S T R A C T

The autonomicity of self-scheduling on Earth observation satellite and the increasing scale of satellite network attract much attention from researchers in the last decades. In reality, the limited onboard computational resource presents challenge for the online scheduling algorithm. This study considered online scheduling problem for a single autonomous Earth observation satellite within satellite network environment. It especially addressed that the urgent tasks arrive stochastically during the scheduling horizon. We described the problem and proposed a hybrid online scheduling mechanism with revision and progressive techniques to solve this problem. The mechanism includes two decision policies, a when-to-schedule policy combining periodic scheduling and critical cumulative number-based event-driven rescheduling, and a how-to-schedule policy combining progressive and revision approaches to accommodate two categories of task: normal tasks and urgent tasks. Thus, we developed two heuristic (re)scheduling algorithms and compared them with other generally used techniques. Computational experiments indicated that the into-scheduling percentage of urgent tasks in the proposed mechanism is much higher than that in periodic scheduling mechanism, and the specific performance is highly dependent on some mechanism-relevant and task-relevant factors. For the online scheduling, the modified weighted shortest imaging time first and dynamic profit system benefit heuristics outperformed the others on total profit and the percentage of successfully scheduled urgent tasks.

1. Introduction

1.1. Earth observation satellite scheduling

Earth observation Satellite Missions involve satellites that fly in low orbit and use different earth-observation payloads to gather information about the Earth (land, water, ice, and atmosphere) using a variety of measurement principles (spatial, spectral, and temporal resolution).

Bidot et al. [1] defined scheduling as the search for a sequence of precise start times at which precise resources are allocated to allow the completion of a given set of tasks satisfying the temporal and resource constraints.

In contrast to traditional scheduling problems in manufacturing, the scheduling of an Earth observation satellite is restricted because the tasks can only be executed at specific times (called time windows). Furthermore, it constitutes an over-constrained problem because it might not be possible for all requests to be scheduled within the specified horizons; thus, conflicts must be resolved [2]. The observation time window for a task is always longer than the required imaging time, and the time windows for different targets may overlap with each other. A solution to the problem of Earth observation satellite scheduling involves not only selecting those tasks to perform but also determining the precise start time of a task within a specific time window [3].

1.2. Online scheduling for autonomous earth observation satellite

Planning and Scheduling for autonomous systems often requires to take into account uncertainties about the system and environment state, unexpected events, and new request arrivals. Autonomous systems must also make decisions continuously (repeatedly) over a potentially long-term mission horizon.

Unlike a traditional Earth observation satellite, an autonomous satellite has the autonomy of self-scheduling and self-reparation. Self-scheduling is the process of autonomously determining the task to be performed next and the time at which it should be executed, based on operational goals and knowledge of the system and its environment. Self-reparation is the process of rescheduling tasks based on performance degradation or urgency.

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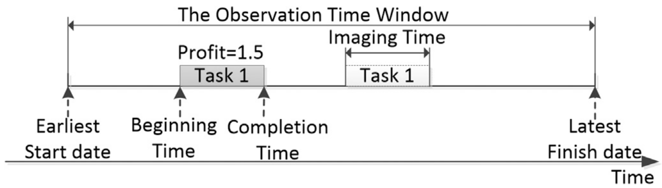

Fig. 1. Schematic of a normal Earth observation task.

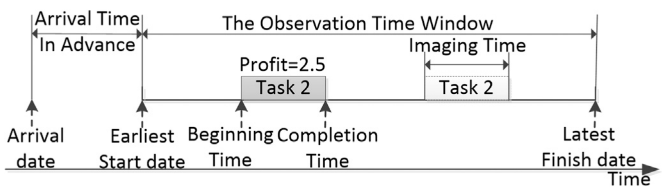

Fig. 2. Schematic of an urgent Earth observation task.

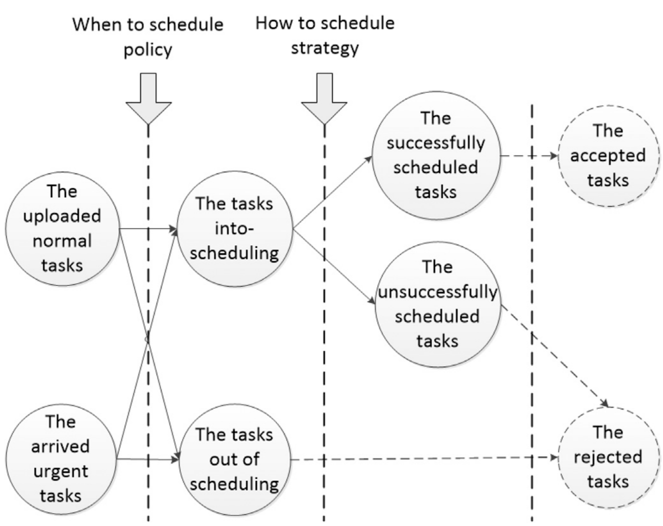

Fig. 3. The task state transforming flow.

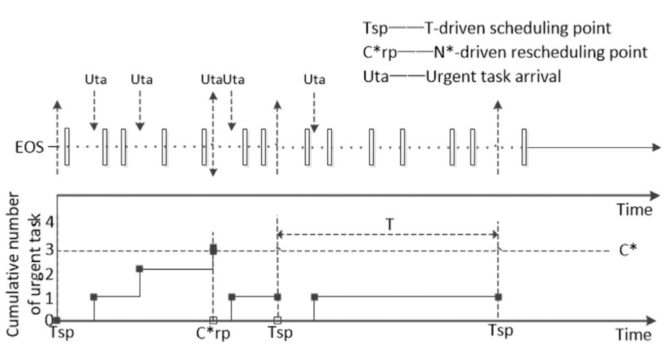

Fig. 4. Schematic of hybrid when-to-schedule policy.

With the scale of satellite network increasing rapidly, new observation tasks are generated onboard more frequently than before. So how to manage these urgent tasks on board is a realistic problem to face. One example is NASA's Sensor Web. The time between two successive visibility windows between a given Low Earth Orbit(LEO) satellite and a given Ground Station depends on the station latitude, but is very irregular along time: from 100 min (one revolution) to more than 15 h

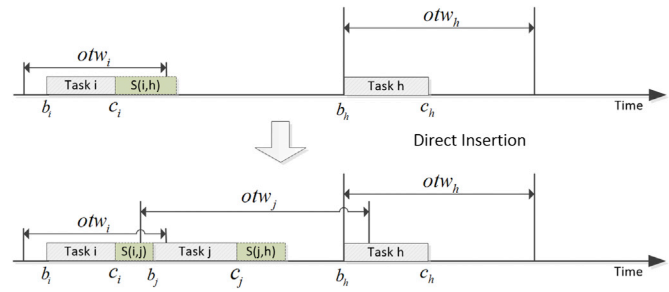

Fig. 5. The illustration of direct insertion.

[4], so a ground-based scheduler cannot react sufficiently quickly. This means the onboard scheduling system is required to respond to urgent events observed by the remote sensor and then to (re-)schedule the arrived urgent tasks as soon as possible. Once a relevant natural disaster or cloud coverage is detected by one node satellite, a new observation task related to the event will be generated and sent to itself' and other node satellites' on-board task scheduling systems. Current application of the Sensor Web primarily includes flooding, volcanic eruptions, ice breakup, forest fire monitoring and repeated observation tasks based on clouds monitoring.

When considering one node satellite in the Sensor Web, urgent tasks arrive stochastically. Furthermore, because of the different rolling angles required for different observation targets on Earth, the setup time between two observation tasks is sequence-dependent. Therefore, given the above, the scheduling for a single autonomous Earth observation satellite within satellite network environment is an online scheduling problem with stochastic task arrivals and sequence-dependent setup times. From the aspect of scheduling, some novel mechanisms and methods are needed to tackle this problem.

The remainder of this paper is organized as follows. Section 2 comprises a literature review that appraises autonomous Earth observation satellite scheduling, general dynamic scheduling methods and heuristic techniques. We define the online scheduling problem for an autonomous Earth observation satellite and illustrate the mechanism scheme in Section 3. In Section 4 we propose a hybrid when-to-schedule policy. In Section 5, we formulate the optimization problem in any scheduling point as a mixed integer linear programming (MILP) model and develop two heuristic (re)scheduling algorithms to solve this problem. The computational experiments and results are presented in Section 6. In this section, we first present the effects of relevant factors on the whole performance, and then address the results of the computational experiments comparing the performance of the developed heuristic algorithms. Finally, Section 7 provides conclusions.

2. Related work

2.1. Review of autonomous Earth observation satellite onboard scheduling

Compared with other optimization problems, the Earth observation satellite scheduling problem has received limited attention [5–11].

Romain et al. [12] discussed the problem of offline replanning using the ground-based scheduler when urgent observation requests are received during the execution of a plan with reference to the management of MUSIS (Multinational Space-based Imaging System for Surveillance, Reconnaissance, and Observation) agile satellites. In this case, the data incorporated in the replanning comprise not only the current activity plan, which could involve hundreds of observations, but also some (at most some tens) urgent observation requests. The goal is to build a new plan quickly (efficiency), optimally (optimality), and robustly (stability) for the remainder of the observation period.

Wörle et al. [13] published an account of the Verification of Autonomous Mission Planning Onboard a Spacecraft (VAMOS) system. This is