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Satellite observation scheduling with a novel adaptive simulated annealing algorithm and a dynamic task clustering strategy

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ABSTRACT

Efficient scheduling is significant for the effective use of scarce satellite resources. Task clustering has been demonstrated as an effective strategy for improving the efficiency of satellite scheduling. However, current task clustering strategies are static, i.e., they are integrated into the scheduling in a two-phase manner rather than in a dynamic fashion, without expressing their full potential in improving the satellite scheduling performance. In this study, we present an adaptive simulated annealing–based scheduling algorithm integrated with a dynamic task clustering strategy (ASA-DTC) for satellite observation scheduling problems (SOSPs). Firstly, we develop a formal model for the scheduling of Earth observing satellites. Secondly, we analyse the related constraints involved in the observation task clustering process. Thirdly, we detail an implementation of the dynamic task clustering strategy and the adaptive simulated annealing algorithm. The adaptive simulated annealing algorithm is efficient and contains sophisticated mechanisms, i.e., adaptive temperature control, tabu-list-based short-term revisiting avoidance mechanism and intelligent combination of neighbourhood structures. Finally, we report on experimental simulation studies to demonstrate the competitive performance of ASA-DTC. We show that ASA-DTC is particularly effective when SOSPs contain a large number of targets or when these targets are densely distributed in a certain area.

1. Introduction

Earth observing satellites (EOSs) have become indispensable tools in scientific studies, military operations and civil activities because they exhibit many evident advantages (e.g., wide field of view, without the restriction of territory) in disaster surveillance, target reconnaissance and intelligence acquisition. The accommodation capabilities of existing EOSs are generally insufficient for meeting large numbers of observation requests coming from various users. Therefore, efficient satellite observation scheduling methods are necessary to use scarce satellites resources rationally. The observation scheduling of satellites involves the reasonable arrangement of satellites, sensors, time windows and sensor-slewing angles for observation tasks to maximize the overall observation return when subject to related constraints. The satellite observation scheduling problem (SOSP) can be categorized a type of multi-dimensional knapsack problem (Bensana, Verfaillie, Agnese, Bataille, & Blumstein, 1996), which is NP-hard.

Exact algorithms, such as the acyclic graph–based path search method (Gabrel & Vanderpooten, 2002), Depth-First Branch and Bound and Russian Doll (Bensana et al., 1996), were developed at the beginning to solve SOSP. In Bensana et al. (1996), the exact methods were compared with approximate methods, including greedy search and tabu search. In general, exact algorithms are feasible in tackling small-size SOSPs while approximate algorithms are more suitable to larger-scale SOSPs. In order to tackle complex scheduling problems, approximate algorithms seeking for satisfactory solutions are becoming more popular (Asadzadeh, 2016; Roychowdhury, Allen, & Allen, 2017). Actually, many approximate algorithms have been proposed for SOSPs, such as heuristic algorithm (Wang, Dai, & Vasile, 2014), iterative algorithm (Spangelo, Cutler, Gilson, & Cohn, 2015), Lagrangian relaxation and linear search techniques (Lin, Liao, Liu, & Lee, 2005), improved greedy algorithm (Potter, Gasch, & Bauer, 1998), squeaky wheel optimization (Globus, Crawford, Lohn, & Pryor, 2004), genetic algorithm (Baek et al., 2011; Chen, Wu, Shi, Li, & Zhong, 2016; Kim & Chang, 2015; Kolici,

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Herrero, Xhafa, & Barolli, 2013; Mansour & Dessouky, 2010; Yuan, Chen, & He, 2014), particle swarm optimization (Zhang, Guo, Cai, Sun, & Wang, 2013), differential evolution (Wu, Wang, Li, Dou, & Hu, 2015), tabu search (Bianchessi, Cordeau, Desrosiers, Laporte, & Raymond, 2007; Vasquez & Hao, 2001) and ant colony optimization (Wu, Liu, Ma, & Qiu, 2013; Wu, Ma, & Zhu, 2012; Zhang, Zhang, & Feng, 2014). A partition-based method was proposed in Vasquez and Hao (2003) to obtain the tight upper bounds of SOSPs associated with Spot 5 satellites.

Wang, Reinelt, Gao, and Tan (2011) presented a nonlinear model, designed a priority-based heuristic and developed a decision support system for the satellite scheduling problem. Zhai, Niu, Tang, Wu, and Shen (2015) proposed a multi-objective optimization approach to generate robust satellite schedules in response to emergency tasks, in which both the profit and robustness of the schedule were considered simultaneously. Karapetyan, Minic, Malladi, and Punnen (2012) investigated the data downlink scheduling problem for Canada's Earth observing SAR satellite. A fast schedule generation procedure was presented and verified, which shows a clear superiority to the approach currently in use. Perea, Vazquez, and Galan-Viogue (2015) studied the swath acquisition planning problem for multiple satellites. The problem was transformed into a set covering problem. Mathematical programming methods, heuristics and metaheuristics were applied to this problem, respectively. Chen et al. (2016) investigated the integrated scheduling of both observation and data down-link tasks for electromagnetic detection satellites. In addition, a genetic algorithm was proposed to search the high-quality schedule globally. Wang, Demeulemeester, and Qiu (2016) investigated the satellite observation problem with the consideration of cloud uncertainties. A chance constraint programming model was constructed and a branch and cut algorithm was designed to solve the problem. Wu, Pedrycz, Li, Ma, and Liu (2016) first investigated the coordinated planning of heterogeneous Earth observation resources including satellites, airships and unmanned aerial vehicles.

Previous works usually aimed at dealing with specified satellite platforms, e.g., Spot series satellites (Mansour & Dessouky, 2010; Vasquez & Hao, 2001, 2003), electromagnetic detection satellites (Li, Chen, Zhong, Jing, & Wu, 2014), SAR satellite constellation (Kim & Chang, 2015; Pang, Kumar, Goh, & Le, 2015), Pleiades constellation (Bianchessi et al., 2007), COSMO-SkyMed constellation (Bianchessi & Righini, 2008), Landsat 7 satellite (Potter et al., 1998), ROCSAT-II (Lin et al., 2005) and FORMOSAT-2 (Liao & Yang, 2007).

Recently, the scheduling of agile satellites attracts an increasing attention (Grasset-Bourdel, Verfaillie, & Flipo, 2011a, 2011b; Liu, Laporte, Chen, & He, 2017). Xu, Chen, Liang, and Wang (2016) constructed a mathematical programming model and proposed a constructive algorithm to solve the problem. Tangpattanakul, Jozefowiez, and Lopez (2015) proposed a multi-objective local search heuristic to solve the earth observation scheduling problem of agile satellites, in which total profit and fairness of resource sharing were taken as the two objectives. Wang, Chen, and Han (2016) constructed a complex network model for scheduling agile Earth observation satellites and proposed a fast approximate scheduling algorithm (FASA) to obtain the effective scheduling results.

Task clustering has been demonstrated an effective strategy for improving the scheduling efficiency of SOSPs (Wu et al., 2013). The scheduling process of SOSP with the consideration of task clustering is illustrated in Fig. 1, which shows that the solution of SOSP involves the arrangement of a sequence of observation activities for each orbit of each satellite. Task clustering strategy is based on the idea that if multiple observation tasks (each observation task corresponds to an observation target) can be executed by the same sensor of the same satellite with the same time window and sensor-slewing angle, these observation tasks can be merged and finished together by a single observation activity. For example, task t_6, t_7 and t_8 can be combined into a clustered task and can be finished by one observation activity (Fig. 1). The following are some potential advantages of task clustering strategy (Wu et al., 2013). First, it enables a satellite to finish more tasks at the cost of fewer sensor powering-on times. Second it could make some previously mutual exclusive tasks be finished simultaneously. Third it enables a satellite to finish more tasks while reducing the sensor-slewing number and range to save energy.

Considering the high complexity of both task clustering and satellite scheduling, we begin with the presentation of a two-phase-based scheduling framework. The framework has been experimentally demonstrated superior to some other state-of-the-art satellite observation scheduling algorithms (Wu et al., 2013). This framework separates the problem solving process into two phases, namely, the task clustering phase and task scheduling phase. The task clustering strategy incorporated in the two-phased-based scheduling framework is static, i.e., once the clustered tasks have been generated in the task clustering phase, the tasks will not be changed in the followed task scheduling phase. Given that clustered tasks are obtained without careful consideration of the task scheduling process, the potential of the task clustering is not fulfilled to the highest extent.

In this work, we present an adaptive simulated annealing–based algorithm integrated with a dynamic task clustering strategy (ASA-DTC) to solve SOSPs and overcome the shortcoming of the static task clustering (STC) strategy. The related dynamic task clustering strategy is embedded into the neighbourhood search processes of ASA-DTC.

The proposed novel adaptive simulated annealing (ASA) is augmented by the combination of three sophisticated mechanisms. The first mechanism is an adaptive temperature control function for realizing the annealing schedule. Second is the use of a tabu list to avoid the short-term revisiting of the same solution components. Third is an intelligent combination of two neighbourhood structures. In the solution search process, the neighbourhood structures are selected automatically according to their respective previous performance. The dynamic task clustering strategy is integrated into the neighbourhood structures. The employed mechanisms can effectively improve the performance of the "conventional" simulated annealing (SA), which may easily suffer from a premature solution or consume considerable time resources to find satisfactory solutions.

We also introduce a new task clustering constraint, namely, the resource consumption constraint. This constraint requires that if multiple tasks can be finished independently with less resource consumption, then these tasks should not be merged into a clustered task. In this study, resources are referred to as energy and memory storage. This resource consumption constraint helps to avoid useless clustered tasks, thus providing more exact guidance for the task clustering operation.

The major contributions of this paper are summarized as follows:

(1) We propose ASA-DTC for SOSPs. The integration is realized by dynamically performing task clustering operations in the neighbourhood search of the algorithm.
(2) We improve the dynamic task clustering strategy by introducing a new resource consumption constraint, which can prevent the generation of useless clustered tasks and can save resources.
(3) We incorporate three novel mechanisms into ASA-DTC, namely, the adaptive temperature control, tabu-list-based short-term revisiting avoidance technique and intelligent combination of different neighbourhood structures, to improve the performance of conventional SA algorithm. The method for the intelligent combination of different neighbourhood structures is presented first in this study.
(4) We conduct extensive experimental simulations and comparative analyses to demonstrate the efficiency of ASA-DTC.

Point targets are considered in this paper, and a point target is related to an observation task. We pay attention on the issue of dynamic task clustering and its integration with the ASA scheduling algorithm for SOSPs. The sensors of satellites considered in this study are able to slew laterally. Primary constraints, including maximum sensor