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Satellite scheduling of large areal tasks for rapid response to natural disaster using a multi-objective genetic algorithm

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ABSTRACT

Earth satellite observations are very useful during the response phase of disaster management, since satellites could provide accurate, frequent and almost instantaneous data for large areas anywhere in the world. To rapidly respond to natural disasters, a key problem is how to efficiently schedule multiple earth observation satellites to acquire image data of a large stricken area by coordinating multiple different even conflicting needs of disaster relief, such as the extent of coverage over the stricken area, timeliness, and the spatial resolution. In this paper, considering two typical application scenarios during the response phase, we propose a multi-objective optimization method to solve the problem of satellite scheduling of a large area target. First, we design a decomposition method to partition a areal task into a series of observation strips. Next, the multiple satellite tasking problem is expressed as a multi-objective integer-programming model including optimizing objectives of the coverage rate, the imaging completion time, the average spatial resolution and the average slewing angle. Finally, the multi-objective genetic algorithm NSGA-II is designed to obtain optimal solutions of satellite scheduling. A real disaster scenario, i.e., 2008 Wenchuan earthquake, is revisited in terms of satellite image acquisition in the context of emergency response. To prove the advantage of NSGA-II, a comparison with state-of-the-art approaches is performed. Furthermore, we discuss the applicability of the proposed method under two kinds of situations: (1) roughly grasping the damage of affected area as soon as possible and (2) accurately assessing the damage of buildings in the worst-hit area.

1. Introduction

Natural disasters could cause serious environmental and economic losses. When a disaster does occur, it is particularly critical to provide an immediate response to the disaster aimed at protecting life and property [1]. Timeliness is critical to an efficient disaster response because the primary goal of the emergency response is to search for survivors and rescue lives [2]. As a result, rapid information acquisition during the three days after a disaster event is crucial [3]. The most efficient way to obtain this information is using earth observation satellites. Space-based monitoring has proven to be an excellent information source for emergency responses at the local, regional, and global scales because of its wide coverage, frequent and repetitive collection of data for the Earth's surface and relatively low cost per unit of coverage [4].

Although much work has been done on information extraction for disaster reduction from satellite images [5], little attention has been paid to how to efficiently schedule multiple earth observation satellites to meet multiple requirements during a natural disaster response. For remote sensing applications during the response phase, the first practical problem is the coordination and scheduling of image acquisition [3,6]. Satellite task scheduling solves this practical problem by making a desirable satellite imaging plan, based on which the image data will be captured by assigned satellites. Satellite task scheduling is to reasonably allocate satellite resources and imaging time to earth observation tasks on the precondition of satisfying complex constrains [7]. According to the size, all the earth observation tasks can be divided into two classes: spot targets and area targets [8]. As shown in Fig. 1, spot targets can be covered by a single strip of satellites, whereas the scope of area targets is large which can only be partially captured by a single satellite. We mainly focus on the imaging requirements of large area targets triggered by major disasters, which are also called areal tasks in the context.

The practical problem of satellite scheduling of a large area for an

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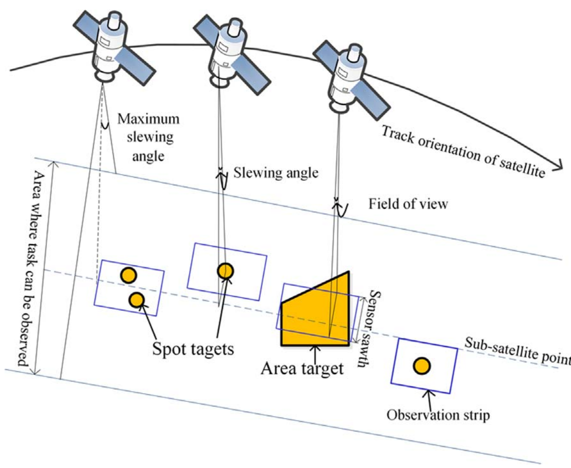

Fig. 1. Illustration of satellite observing activity.

emergency response is rather complex, since a satellite often cannot acquire the entire area in a single pass. Thus, it is necessary to coordinate multiple satellites to perform the observation, which is more complex than single satellite task scheduling. Although satellites are tied to predefined orbital paths, the slewing ability of more recently launched sensors can increase the temporal resolution and provide more frequent observation opportunities, resulting in a larger number of satellite combinations with various point angles. With so many observation opportunities, determining the best combination which can cover the entire affected area is a multi-satellite task scheduling problem. Specifically, multi-satellite task scheduling generates a “best” imaging plan to determine which satellite observation opportunities should be assigned to observe which parts of the disaster area.

Moreover, multi-satellite scheduling of areal tasks can be defined as a multiple criterion decision-making problem because it includes more than one optimizing objective, such as the extent of coverage, timeliness, and the spatial resolution. These objectives may conflict to some extent. Additionally, each objective corresponds to a different optimal solution, resulting in a tradeoff between optimization objectives. One common tradeoff is between the spatial resolution and the coverage area, due to the fact that the lower altitude of imaging, the finer spatial resolution and the limited extent of coverage per swath [2]. Another tradeoff occurs between the spatial resolution and the timeliness because satellites with high spatial resolution generally do not have the overpass frequency to provide images quickly [1]. Although many methods exist to convert multiple objectives into a single objective by using predefined weights, the solution is sensitive to the weights [9]. Moreover, these single optimization methods can’t generate trade-off solutions, which is not appropriate to solve the multi-satellite scheduling problem with conflicting objectives.

In this study, we extend the satellite task scheduling problem to two kinds of application scenarios during the response phase: (1) roughly grasping the damage of affected area as soon as possible and (2) accurately assessing the damage of buildings in the worst-hit area. A multi-objective optimization model is proposed to address the problem of satellite scheduling of large area targets and applied in the two situations. In the proposed multi-objective integer-programming model, imaging requirements such as the extent of coverage, timeliness, and the spatial resolution are abstracted as optimizing objectives. Since the two scenarios have different imaging requirements, the model optimizes different objectives. To solve the model, the non-dominated sorting genetic algorithm-II (NSGA-II) is adopted and demonstrated using damaged area affected by Wenchuan earthquake. The proposed algorithm can provide a population of imaging plans without any additional user-defined weights, which is more propriate for the situation that preference of objectives is not easy to quantify by the users. Moreover, the method can provide decision-makers with multiple options so that they can compare and select the imaging plan which is most useful to them. The proposed multi-objective optimization model has certain adaptability to different application scenarios, which can incorporate in other imaging requirements of users.

The remainder of the paper is organized as follows. Related work is reviewed in Section 2. In Section 3, we present a multi-objective optimization approach, including analysis of the imaging requirements, the decomposition method, the mathematical scheduling model and the NSGA-II algorithm. Experimental results of two application scenarios for disaster emergency response are given in Section 4, and we compare the presented method with state-of-the-art algorithms for satellite scheduling. Finally, some conclusions are drawn in Section 5.

2. Related work

Over the past several decades, many methods have been proposed to solve the problem of satellite scheduling of areal tasks without specific time constraints [8,10–12]. A general approach to the problem consists of two steps. The first step is to decompose area targets into a set of small segments, which are called spot targets and each target can be photographed in one shot. The second step is to select a subset of these spot targets and allocate them to specific satellites using various models and algorithms. In other words, this approach divides the problem of satellite scheduling for large area tasks into two sub-problems, i.e., the partitioning of area targets and the optimization of scheduling models.

The methods for partitioning the target can be categorized into four groups: using the predefined Worldwide Reference System prior to scheduling [13]; translating the problem into a set covering problem [14]; segmenting an area target into a series of adjacent strips [10]; and employing the dynamic polygon partitioning method [8]. The first three types of methods are appropriate when dealing with a single satellite. In contrast, the fourth method considers the characteristics of the target and takes advantage of the available satellite imaging opportunities; thus, it considers more information. The dynamic polygon partitioning method segments an area multiple times according to the tracks of all the satellites and the fields of view (FOVs) of all the sensors. This type of decomposition method is appropriate for multi-satellite task scheduling problems.

Several models have been proposed for satellite scheduling problems, such as the integer-programming model [15–17], knapsack model [18,19], and constraint satisfying problem model [20]. However, these studies considered only a single objective. As the number of satellites increases, multi-satellite task scheduling problems have intrigued an increasing number of researchers’ interests. Because multiple users may have different imaging requirements, it is necessary to develop effective methods to coordinate multiple satellites incorporating in multiple imaging requirements. Gabrel and Vanderpooten proposed formulating daily satellite scheduling problems as selection one of a satisfactory path by multiple criteria [21]. Zhang et al. used an acyclic directed graph model to obtain the optimal path based on multiple objectives [22]. However, the exact methods used by the above two studies are suitable only for small-scale single satellite scheduling problems [23]. To solve a large-scale scheduling problem within reasonable computational time, heuristic algorithms including the tabu search algorithm [18,24], the greedy algorithm [25,26], the ant colony optimization method [27,28], the genetic algorithm [29–32], and the evolutionary algorithm [33,34] are more flexible. Bianchessi et al. used the tabu search algorithm to solve a multi-satellite scheduling problem; they measured the objective by the weighted sum of multiple normalized utility functions [24]. Mansour et al. developed a genetic algorithm (GA) to solve the SPOT5 scheduling problem for maximizing the daily profit and number of photographs taken [29]. For the multi-criteria problem, the objective function is measured as the weighted average of each objective. Globus et al. applied the evolutionary algorithm for scheduling coordinated fleets of satellites [33,34]. They evaluated the fitness using the weighted sum of multiple objectives and indicated that