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A quasi-human strategy-based improved basin filling algorithm for the orthogonal rectangular packing problem with mass balance constraint

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ABSTRACT

Under the background of layout optimization of the satellite module, we study the orthogonal rectangle packing problem (ORPP) with mass balance constraint, which is an NP-hard problem. Based on the quasi-physical strategy, we convert the problem into an unconstrained optimization problem. The major challenge of solving this problem is that the objective function being optimized is characterized by a multitude of local minima separated by high-energy barriers. Basin filling (BF) algorithm is a new heuristic global optimization algorithm, which combines the energy landscape paving (ELP), based on Monte Carlo sampling, and local search, based on the gradient method. We use the improved basin filling (IBF) algorithm to solve the ORPP with mass balance constraint. In the IBF algorithm, in order to avoid the ELP falling into narrow and deep valleys of energy landscape, a new update mechanism of the histogram function in the ELP is proposed. In addition, a quasi-human corner-occupying strategy and a local movement strategy, based on the adaptive gradient method with retreat and acceleration, are used to update the layouts. Experimental results show that the proposed algorithm is an effective method for solving the ORPP with mass balance constraint.

1. Introduction

Given n objects and a bounded space, each given a shape and a size, the packing problem focuses on finding the best way to pack these objects into the bounded space without overlap and to improve the utilization of the container's space. The packing problem is a classical NP-hard problem and is extensively applied in logistics packing, industrial cutting, circuit layout, spacecraft equipment loading, and other fields (Birgin, MartiNez, & Ronconi, 2005; Lodi, Martello, & Monaci, 2002). The solution to this problem is multi-optional, for example, the problem can be two-dimensional or three-dimensional, the container can be circular, rectangular, or polygonal, the way of placing objects can be orthogonal or arbitrary, and the constraints can include mass balance, inertia, and stability. In recent years, scholars have done research on the orthogonal rectangular packing problem (ORPP) and put forward algorithms to solve it, including exact algorithms such as the graph theory method (Macedo, Alves, & Carvalho, 2010), the dynamic planning algorithm (Birgin, Lobato, & Morabito, 2012), the branch-and-bound method (Clautiaux, Jouglet, Carlier, & Moukrim, 2008; Cui, Yang, Cheng, & Song, 2008; Hifi, 1998; Lesh, Marks, McMahon, & Mitzenmacher, 2004), heuristic methods such as the method based on the action space (He & Huang, 2014; He, Huang, & Jin, 2012; He, Jin, & Huang, 2013; Wang & Yin, 2015) and other heuristics (Chan, Alvelos, Silva, & Valério, 2013; Charalambous & Fleszar, 2011; Liu, Zhang, Yao, Xue, & Guan, 2016; Martello & Monaci, 2015; Polyakovsky & M'Hallah, 2009), *meta*-heuristic algorithms such as evolutionary approaches (Khebbache, Prins, & Yalaoui, 2008; Li & Dong, 2011), the energy landscape paving method (Liu, Huang et al., 2016), the Wang-Landau sampling method (Liu, Hao et al., 2016), hybrid approaches (Bortfeldt, 2013).

This article studies the ORPP with mass balance constraint (Feng, Wang, Wang, & Teng, 1999), which differs from the general rectangular packing problem. Besides the requirement of non-overlapping and high space utilization, this packing problem requires the packing system to satisfy the constraint of mass balance. It has a profound background of satellite module layout design (Fig. 1(a)), where some given objects, including various instruments and devices, are allocated into the spinning satellite module such that the resulting layout satisfies the following constraints (Tang & Teng, 1999): (1) There is no overlap between any

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two different objects or between the objects and the module; (2) All objects get highly centralized on the center of the container; (3) The static non-equilibrium value of the system is as small as possible. Optimization of the satellite payload design plays a very important role in optimizing satellite performance, saving resources, reducing production costs, and achieving high economic efficiency. The layout of the satellite module will directly affect dynamic performance, control performance, and service life of the satellite in orbit. A reasonable payload layout is very important for the satellite to receive and collect all kinds of data and information (Sun & Teng, 2010). Suppose that all objects in the satellite module are cubes (Fig. 1(a)) and are allocated to the upside and downside of the supporting board which is perpendicular to the central axis of the module. To simplify the solution to this problem, the dimensionality reduction method is generally applied. Given that cubes can be projected into rectangles in a plane, the satellite module layout design is reduced to the ORPP with mass balance constraint (Fig. 1(b)). The layout technique of solving the ORPP with mass balance constraint is not only helpful to study satellite payload layouts but also can be generalized to other industrial fields, such as industrial cutting and circuit layout. However, the ORPP with mass balance constraint is an NP-hard problem. With the enlargement of layout scale, it is increasingly necessary to find an effective algorithm for this problem.

For the ORPP with mass balance constraint, some related research has been done by scholars during the past decades. Feng et al. (1999) put forward a mathematical model of rectangular layouts in a circular container and proposed a theoretical global optimization algorithm by using graph theory and group theory. Xu, Xiao, and Amos (2007) adopted a gradient method to acquire a feasible initial layout and subsequently proposed a compaction algorithm with the particle swarm local search (CA-PSLS) to optimize the layout. The compaction algorithm first moved the objects to get a layout without overlap, then reduced the radius of the container, and lastly searched once again for a feasible layout. In order to obtain a compacted layout, this process was continued until the algorithm could not find a feasible layout within a container of a smaller radius. Xu, Dong, Liu, and Xiao (2010) combined a positioning strategy of constructing a feasible solution and a genetic algorithm and proposed a heuristic layout optimization algorithm. By combining a dynamic matching heuristic algorithm, a compression strategy, and a particle swarm optimization (PSO) algorithm, Huang and Xiao (2011) put forward a hybrid layout algorithm. Zeng and Zhang (2012) used a heuristic strategy to divide the circular container into four sub-regions and put forward a glowworm swarm optimization algorithm. Yoon, Ahn, and Kang (2013) proposed an improved best-first branch-and-bound algorithm. Li, Wang, Tan, and Wang (2014) defined two embedded degree functions between two orthogonal rectangles and between an orthogonal rectangle and the container and constructed an extruded resultant force formula; then they came up with an effective layout method based on the quasi-physical strategy and the dynamic adjustment method. Recently, by incorporating heuristic configuration updating strategies, a local search strategy based on the gradient method and a simulated annealing algorithm, Liu, Zhang, Xue, Liu, and Jiang (2015) proposed a heuristic simulated annealing algorithm for solving the ORPP with mass balance constraint.

Basin filling (BF) algorithm (Liu & Li, 2010) is a new heuristic global optimization algorithm, which combines the energy landscape paving (ELP) (Hansmann & Wille, 2002; Schug, Wenzel, & Hansmann, 2005) and the local search based on the gradient method, where the ELP method is mainly used to execute global search and the gradient method is introduced to explore the neighbors of newly generated layouts. The core idea of the ELP method is to perform low-temperature Monte Carlo (MC) simulations, which obtain numerical results by repeating random sampling. A modified energy expression based on the histogram is used to steer the search away from the regions that have already been explored. The ELP method is an improved MC method that is one of the well-known stochastic sampling techniques and bears some similarities to Tabu search (TS) (Cvijovic & Klinowski, 1995), in which the recently visited regions recorded by a so-called Tabu list are not likely to be revisited immediately. However, revisiting moves in the ELP method are not completely forbidden but have lower sampling weight than the moves that go to the regions with comparable energy, which have been explored less. In this article, we further improve the BF algorithm and use the improved BF (IBF) to solve the ORPP with mass balance constraint. In the IBF algorithm, in order to avoid the ELP algorithm falling into narrow and deep valleys of energy landscape, a new update mechanism of the histogram function in the ELP algorithm is put forward. In addition, a quasi-human corner-occupying strategy and a local movement strategy, based on the adaptive gradient method with retreat and acceleration, are used to update the layouts. Experimental results show that the proposed algorithm is an effective method for solving the ORPP with mass balance constraint.

The rest of this article is organized as follows. Section 2 describes the mathematical model of the ORPP with mass balance constraint. The ideas for solving this problem and the detailed search strategies are presented in Sections 3. The experimental

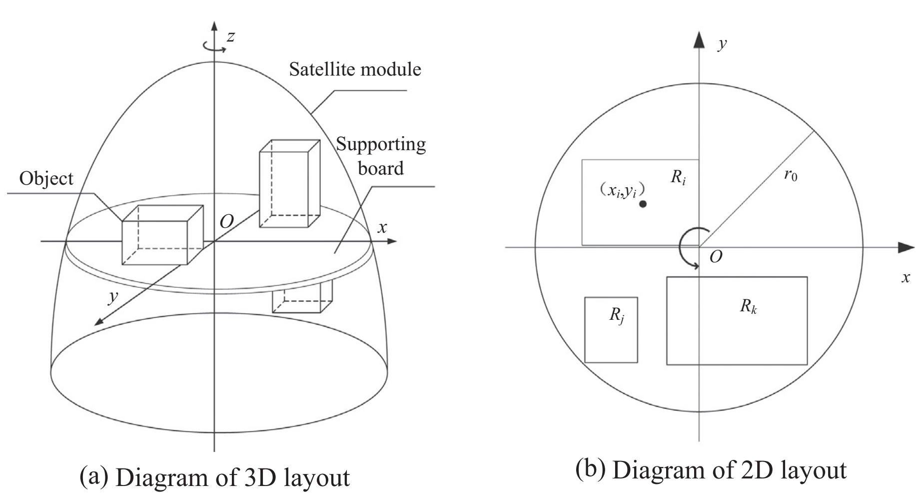

Fig. 1. Diagrams of layout optimization of the simplified satellite module.