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A hybrid multi-mechanism optimization approach for the payload packing design of a satellite module

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ABSTRACT

The payload packing problem of a satellite module (SM3P) belongs to a complex engineering layout and combinatorial optimization problem. SM3P can not be solved effectively by traditional exact methods. Evolutionary algorithms have shown some promise of tackling SM3P in previous work; however, the solution quality and computational efficiency are still challenges. Inspired by previous works (such as divide-and-conquer and no free lunch theorem), this study designs three-stage solution strategy in the light of the characteristics of SM3P and proposes a hybrid multi-mechanism optimization approach (HMMOA) integrating knowledge heuristic rules with two evolutionary algorithms such as ant colony optimization (ACO) and particle swarm optimization (PSO) in different stages. Firstly, the payloads to be placed are assigned to different bearing surfaces in the distribution stage. Then SM3P is decomposed into several subproblems solved by the heuristic ACO algorithm in the second stage, where a better feasible packing scheme obtained by the knowledge-based heuristic ACO is further improved by a heuristic adjustment strategy. At last, the solutions of different subproblems are combined to form a whole solution that is optimized by PSO in a way of rotation to minimize both errors of the mass center and inertia angle while other design objectives remain unchanged. The experimental results illustrate the capability of the proposed HMMOA in tackling the complex problem with better solution quality while less computational effort.

1. Introduction

Three-dimensional (3D) layout design problems are commonly encountered in many fields such as automobile industry, mechanical engineering, and aerospace industry [1–3]. As one kind of classical and complex layout design problems, the payload packing problem of a satellite module (SM3P) is discussed in this paper. The problem concerns the placement of payloads such as equipment and instruments (short for components) on different bearing surfaces in the module so that a set of design objectives can be optimized while satisfying given spatial and performance constraints [2]. Payloads packing scheme directly affects the performance, service life, structure and maintenance of the whole system. A reasonable and harmonious packing design is essentially a common property of most successful satellites. The optimization of the packing scheme is one of the key techniques to improve the global performance of a satellite [4]. However, SM3P is a nonlinear and multi-modal optimization problem that is almost impossible to be fully solved by traditional optimization techniques due to its NP-hard computational and engineering complexity.

SM3P belongs to a 3D packing problem with performance constraints on which the state-of-the-art research results were surveyed by Cagan et al. and Kicinger et al. [5,6] and can be discussed by Aladahalli et al. [7,8]. For SM3P, the existing solutions are classified into the following categories.

(1) Heuristic algorithms. For example, Teng et al. [9] established the mathematical model and proposed the sensitivity analysis approach and several heuristic rules.
(2) Evolutionary algorithms. Grignon and Fadel [10] proposed a pareto genetic algorithm to make a more informed decision on a tradeoff issue among the various design objectives and solve the configuration problem of a satellite. Cagan et al. [11] proposed an efficient annealing-based simulation algorithm to solve layout problems of the car engine and heat pump, whose idea is also useful to calculate an approximate solution of the spacecraft payload packing problem. Jacquenot et al. [12] advanced a multi-target placement algorithm for the free-form component

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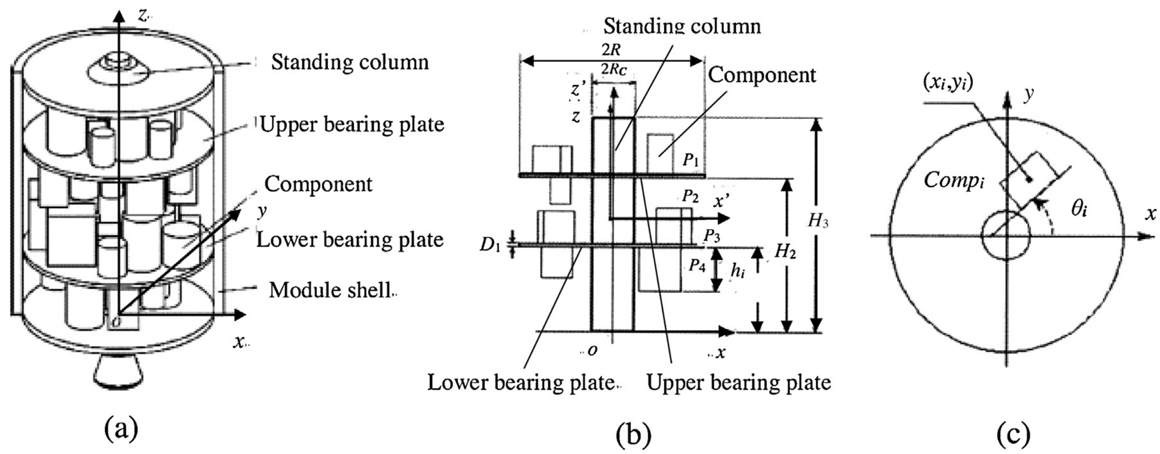

Fig. 1. Layout pattern of a simplified satellite module [2]. (a) Three-dimensional schematic diagram. (b) Projection of bearing bases. (c) Location of a component on a bearing surface.

packing problem. The algorithm in Ref. [12] can also be used in solving the multi-objective constrained spacecraft payload packing problem due to their similarity.

(3) Human-computer interactive and cooperative evolutionary design. Tanner and Fennel [13] adopted the visual human-computer interactive technology and constraint-based reasoning method to study how to place the equipment into the racks of space station freedom module. Based on an evolutionary mechanism, Potter et al. [14] proposed a cooperative co-evolutionary framework, a dynamic optimization method, where multiple cooperating subpopulations are used to co-evolve the solution components. Braun et al. [15] presented a collaborative optimization approach for the packing design problem of a single-stage-to-orbit launch vehicle. Taking the ZS3-SAT satellite as an example, Kamran et al. [16] used the configuration design and human-computer interactive technology to deal with the component packing problem of a satellite. Qian et al. [17] proposed a human-computer interactive genetic algorithm. Liu and Teng [18] put forward a human-machine cooperative evolution algorithm based on several knowledge solutions. Wang et al. [4] devised a cooperative co-evolutionary scatter search approach. Huo and Teng [19] described a co-evolutionary method based on a three-stage strategy, which includes the distribution of components among subspaces, the detailed packing design within subspaces and the packing design of the whole scheme. Huo et al. [20] designed a human-computer co-operative co-evolutionary method to find a better solution. Teng et al. [2] proposed a dual-system variable-grain cooperative co-evolutionary genetic algorithm (DVGCCGA).

(4) Hybrid algorithms. Sun and Teng [21] gave a two-stage approach where the centripetal balancing strategy and quasi traveling salesman model-based ant colony optimization (ACO) are used in the coarse packing design and detailed packing design. Zhang et al. [22] devised a hybrid method through an organism combination of the quasi-principal component analysis, genetic algorithm and particle swarm optimization (QPGP). Shi et al. [23] designed a modified artificial bee colony algorithm.

Although more and more efforts have been made on SM3P, it seems a long way to achieve a satisfying and practical engineering solution using a general-purpose approach. The open issues for further study involve how to improve the computational precision, the efficiency and the success rate. These issues stem from the following characteristics: a high dimensional real solution space larger than 2 × the number of components, the complex nonlinearity of the finess function including conflicting performance constraints and objective functions, and time-consuming calculation of the overlapping area in the finess function. These characteristics directly result in the premature convergence and low computational efficiency, even failures in the solution process, and particularly, the third one, it is a bottleneck which restricts further development of different approaches [2,4,9,17–23] in performance. Inspired by no free lunch theorem [24] and previous done work, this paper proposes a hybrid multi-mechanism optimization approach with the adjustment strategy (HMMOA). The basic strategy can be summarized as follows. (i) SM3P is decomposed into several subproblems in a way of bearing surfaces according to the divide-and-conquer idea. (ii) A heuristic ACO with an adjustment strategy is proposed to solve each subproblem to obtain better solution. (iii) The whole solution combined by the solutions of subproblems is further improved by a particle swarm optimization (PSO) search technology to minimize both errors of the mass center and inertia angle of the whole packing scheme. Four key issues of the considered HMMOA can be summarized as follows.

(a) How to obtain the packing knowledge and its mathematical representation;
(b) How to construct the knowledge-based heuristic mechanism (ordering and positioning rules);
(c) How to construct the optimized mechanism of a heuristic ACO to eliminate the bottle-neck and define the related embedding degrees for implementing the local adjustment;
(d) How to optimize both errors of the mass center and inertia angles by PSO in a way of conciseness.

The contributions of the proposed HMMOA different from approaches [2,4,9,17–23] can be stated as follows. (i) For the heuristic ACO of the considered HMMOA, it is not required to perform a time-consuming calculation of overlapping areas and the search space of the optimal packing scheme of each bearing surface is reduced by transformation from a real value space to an integer space; (ii) through the local adjustment, the marginal region of the packing scheme obtained by the heuristic ACO is further optimized to decease the moment of inertia and the enveloping radius; (iii) both the setoff amount of the mass center and inertia angles of the whole satellite module are further optimized to minimum values by the proposed PSO, while the moment of inertia and the envelope radius remain unchanged.

The rest of this paper is organized as follows. Section 2 is the problem statement and its mathematical model. Then the component distribution among bearing surfaces is described in Section