REVIEW ARTICLE

Several key problems in automatic layout design of spacecraft modules*

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Abstract Computer-aided layout design of spacecraft modules, such as satellite modules and manned spaceship modules, is of great significance and egregious complexity. It is known as a combinatorial optimization and NPC problem in mathematics, a conceptual design and complex system in engineering. The main difficulties include representation and formulation of the problem in mathematics and the solution strategy and pragmatic approaches in engineering practice. After a brief survey of the state-of-the-art in relevant fields, this paper summarizes the research work of the authors' group on automatic layout design of spacecraft modules in the last 15 years, mainly focusing on 5 key problems. They are modeling and problem-solving algorithms, interference calculation, theory and applications of layout topological pattern, decision-making in layout design, and their pragmatic approaches in engineering practice.

Keywords: spacecraft, layout, computer-aided design, conceptual design, combinatorial optimization.

Spatial layout problem concerns the placement of components in an available space such that a set of objectives can be optimized while satisfying optional spatial or performance constraints[1~3]. Cagan et al.[3] illustrated the major constituent parts for a generic layout system (Fig. 1), which consists of two sections, representation and formulation of the layout problem and optimization search algorithm. They also

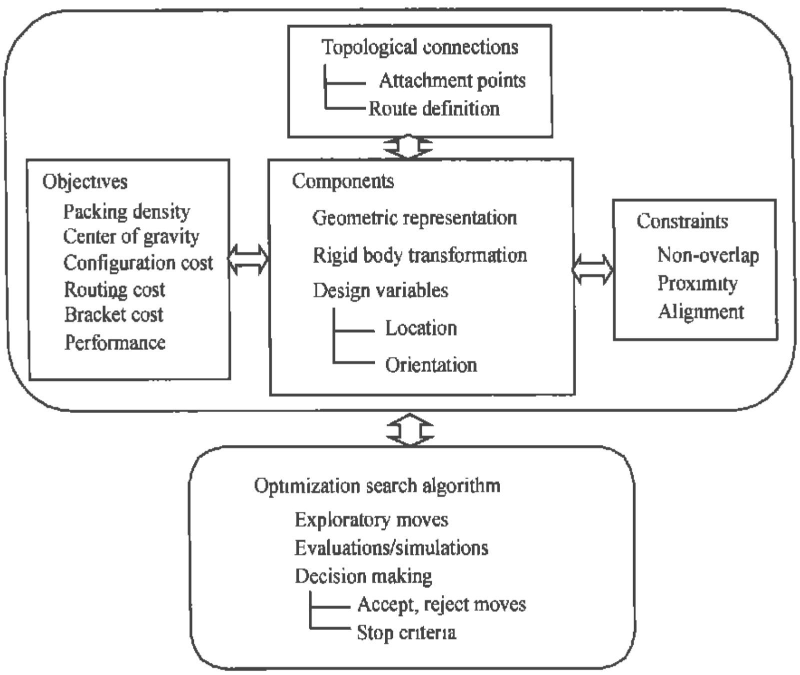

Fig. 1. Major constituent part for generic layout synthesis[3].

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pointed out that the difficulties in automating the layout process stem from: (1) the modeling of the design objectives and constraints; (2) the efficient calculation of the objectives and constraints; (3) the identification of appropriate optimization search strategies.

Layout design of a spacecraft module, taking the satellite module shown in Fig. 2 for an example, usually involves the consideration of some performance constraints, such as inertia performance, equilibrium, stability of whole system, the influence of electromagnetic interaction and thermal diffusion between components, in addition to classical constraints of non-overlap, proximity, alignment and topological connections. It directly concerns the structure, performance of the module, and the cost of its design, manufacture, assembly and maintenance. Reasonable and harmonious layout design is essentially the common property of most successful satellites.

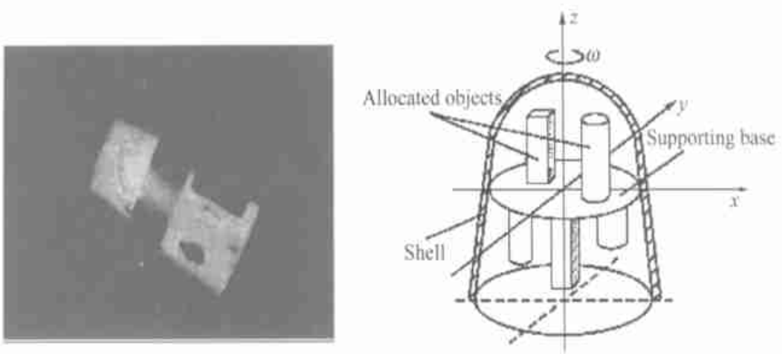

Fig. 2. Layout sketch of a satellite module. (a) Appearance of the satellite; (b) objects located on a supporting base in the module.

As far as we know, theoretical researches on layout problems with performance constraints began in the 1970s. Pereira[4] used artificial intelligence (AI) techniques to solve a layout problem of a set of plane rectangles with preconcerted adjacent and un-adjacent relation constraints in 1978. Available approaches up to now include heuristic algorithms[5~7], evolutionary algorithms (such as GA)[8,9], AI approaches (expert system, instance-based reasoning, and agent techniques, for example)[4,10], graph theory[11,12], collaborative design and multi-level optimization method[13,14], and virtual design approach[15].

Recently researches on layout design of spacecraft have been greatly strengthened with substantial progresses, while still little literature is available. A multilevel collaborative approach[13] was adopted in spatial layout design of launch vehicle, which manipulated the layout design of each subspace in turn. But the order of subspaces to be handled depended on a set of heuristics and the problem itself. Kamaran et al.[16] proposed a FARAGAM algorithm to solve the arrangement of functional subassemblies of the satellite ZS3-SAT. On the basis of the partition of functional modules and a reference layout scheme, they iteratively added subassemblies to a satellite module by composite design method and human-computer interactive techniques, which might be a practical approach in engineering. But the partition of functional subassemblies, the setting of weighting factors and the alternative of semi-layout scheme are all problem-dependent. Toshiharu[17] and Linden[18] used evolutionary algorithms to solve the geometrical layout of a spacecraft and the arrangement of wire antennas in a satellite structure. Their main idea is to modify the structure, shape and placement of subassemblies generation by generation to meet the requirements of their operational environment. This process involves the detailed design of functional components and subassemblies. Qian et al.[19] summarized the frequently used algorithms in layout design of spacecraft modules with applications, and indicated that it is essentially the absence of theory and pragmatic approaches of modeling, solving and decision-making in complex engineering problems that chokes automatic layout design of spacecraft modules.

Against the background of layout design of spacecraft modules, our group focus on the research and application of theory and method of complex layout design and have the great honor of the strong support of 7 granted projects from the National Natural Science Foundation of China (NSFC) since 1987. This paper summarizes our work on automatic layout design in the last 15 years, mainly focusing on 5 key problems, representation and formulation of complex layout problems and problem-solving algorithms, interference calculation, layout pattern theory, decision-making in layout design and their pragmatic approaches in engineering practice.

1 Modeling and algorithms

1.1 Modeling

Computer-aided layout design primarily depends on digital models, including the nonlinear optimization model in operations research, knowledge- or case-based symbol model in artificial intelligence, and visualization model of geometrical, mechanistic, and kinetic simulation. Some mathematicians give the above three models a joint name, "mathematical model"; some specialists in artificial intelligence named them "composite knowledge model"[20], while those in automation technology entitled them "digital model". The combination of above three models is of great importance in engineering practice, and several remarkable points are as the following.

First, the three digital models mentioned above should complement each other in layout modeling, and the mutual transformations or communications between them is a challenging issue.

Second, to what degree a layout problem should be simplified and formulated in digital models. Traditional mathematical optimization model lacks adaptability and robustness despite its constraint relaxation techniques. Generally, human's thinking frequently alternates between two procedures, from simple to complex and from complex to simple. So digital models should adapt to the different degrees a layout problem is formulated.

Third, the integration of available algorithms should adapt to special digital models. Here, we mainly concentrate on the integration of numerical algorithms for the nonlinear optimization model of a complex layout problem. The composite algorithms and the mathematical model should be constructed simultaneously so that they match each other naturally. Some researchers present an idea of the meta-system as an effective tool, but few successful paradigms are reported. Agent techniques, including human-computer cooperative agent, may be a promising approach now.

With the development of computer techniques about natural language recognition and understanding, the natural language model is likely to be a feasible tool to represent and solve a complex layout problem. It is good at qualitative representation and human-machine synergy or human-computer cooperation in nature.

1.2 Algorithms

Most layout design problems may boil down to single- or multi-objective optimization problems to a certain degree. So pursuing an efficient and convergent optimization algorithm with superior robustness is always an important direction in our work. For a complex layout problem, such as layout design of a satellite module, a feasible solution with acceptable quality, rather than a global optimal solution ideally, is a sensible aim in engineering practice. Teng et al.[7] once proposed a heuristic named simulated experimental method, which simulated the physical packing process of a satellite module with the support of sensitivity analysis and mathematical programming method. Then, against the background of layout design of spacecraft, we improved classical genetic algorithms on coding mechanism[21,22], genetic operators[22,23], and adaptive adjustment of control parameters[23]. And moreover, we also developed parallel simulate annealing/genetic algorithm1), ant algorithm[24], and parallel hybrid ant immune algorithm2). Recently, we concentrate on human-computer cooperative computational intelligence algorithms and evolutionary design method, based on which an evolutionary collaborative design method is developed under network environment. However, our collaborative design system is still simply equipped up to now.

1.3 Human-computer cooperation algorithms

Layout design of a spacecraft module usually involves a great number of objects to be located and a set of complex spatial or performance constraints. It is very difficult for algorithms alone to solve the problem completely with a satisfactory efficiency. Furthermore, the final solutions in terms of a mathematical model are possibly not acceptable in engineering practice. Man-machine synergy[25] or human-comput-

1) Miao, Y. B. Inverse perturbation method and human-computer interactive annealing genetic algorithm and their applications. Ph. D. Dissertation, Dalian University of Technology, 2001.

2) Li, G. Q. Research on the theory and methods of layout design and their applications. Ph. D. Dissertation, Dalian University of Technology, 2003.

er cooperation[26] is a promising approach to improving the efficiency of problem-solving process and the quality of final solutions. But how to realize the idea in engineering applications is still an open question.

Some work on the interactive approach between human and evolutionary algorithms was carried out recently[27, 28]. However, they mainly focused on real-timely interactive operations between a human and a computer during a run, rather than developing a communicating mechanism to benefit the exchange of information or experience on solving a problem. In our group, Qian et al.[29] proposed a human-computer cooperation genetic algorithm (HCCGA), which encoded the layout schemes designed by a human and put them into the population of GAs as artificial individuals. Artificial individuals and intrinsic individuals generated by GA randomly were combined as a new population manipulated by genetic operators. Artificial individuals were provided not only at the initialization of the population, but also real-timely during the running cycle of GA. Experts could monitor and guide the evolutionary process of GAs by a human-computer interface. Combining HCCGA with collaborative design techniques, Qian[1)] developed a collaborative layout design system based on HCCGA, which enabled a group of engineers to cooperate with each other via networks, with the support of HCCGA. Similarly, Miao[30] implemented a human-computer cooperative SA/GA with its application to layout design of a satellite module and upper structural components of a crawler crane QUY150[2)].

A kind and favorable man-machine interface usually contributes much to the human-computer cooperation process[31, 32]. Liu[33] studied visualization techniques, including histogram of Euclidean distance and cartoon face (CF) with algorithmic emotions. He combined different statuses of the geometric representation of CF's components, such as eyebrows, eyes and mouth, to obtain a set of CF's expressions. Then a mapping was established by an artificial neural network (ANN) approach to enable CF's expressions to reflect the different statuses of GA. It has been shown in practical applications that the man-machine interface benefits experts to adjust control parameters of an algorithm during its run and guide the evolutionary process of GA.

A complex layout problem such as layout design of a spacecraft module is frequently too difficult for a human or a computer alone to solve completely. The idea of human-machine synergy and human-computer cooperation suggests the combination of human's unique power and advanced computer techniques in complex engineering applications, and is certainly an important approach to optimal layout design of spacecraft modules.

2 Interference calculation

Interference calculation is an essential issue in computer-aided layout design. It usually contains two matters, interference detection that makes a judgment on whether two geometrical components overlap each other, and interference measurement that quantifies the degree of overlap between two geometrical components if they interfere. Most interference calculation algorithms can be grouped into two categories, space decomposition approach and hierarchical bounding volume approach. The former divides a virtual space into a set of cells with the same size and detects geometry overlaps only when two components occupy the same or adjacent cells. The latter simplifies a component to an irregular-shaped geometrical object that closely envelops it and then does interference detection between irregular objects. Following the latter approach, we have developed simple and efficient interference detection algorithms of rectangle-rectangle, rectangle-circle, ellipse-ellipse, and ellipse-rectangle cases and measuring algorithm of overlapping amount between two arbitrary polygons.

No fit polygon (NFP) method, originated by Art in 1966[34], is a popular way for interference detection between two polygons. Adamowicz[35] improved it in the solution of nesting problems. Now NFP method works in the interference detection between a convex and a convex polygon[36, 37], a convex and a non-convex polygon, and a non-convex and a non-convex polygon[38], despite that its efficiency is not very satisfactory sometimes, especially for the case that contains at least one non-convex polygon.

For the high-frequency requirements of dynamic interference calculation in computer-aided layout design, we developed simple and efficient interference detection algorithms, including dynamic NFP algo-

1) Qian, Z. Q. Human-computer cooperative evolutionary design method and its application to layout scheme design of spacecraft module. Ph. D. Dissertation, Dalian University of Technology, 2001.

2) See footnote 1) on page 803.

rithm for rectangle-rectangle case[39] and non-fit boundary (NFB) algorithm for rectangle-ellipse and ellipse-ellipse case[1)]. The basic idea of Art's NFP method is, taking the no fit polygon between rectangle A_1 and A_2 shown in Fig. 3(a) as an example, to equal an overlapping judgment between the two rectangles to an enveloping judgment between the reference point of a rectangle (such as O_2, the center of A_2 in Fig. 3(a)) and the NFP. That is to say, if the point is located within or just on the polygon NFP $[A_1, A_2]$, the two rectangles overlap; otherwise, they are separate to each other. Following this idea, Teng et al.[39] presented an algorithm to calculate the dynamic NFP between two rectangles with relative motions, and Chen[1)] developed NFB algorithms for ellipse-ellipse and ellipse-rectangle case, as shown in Fig. 3(b) and (c).

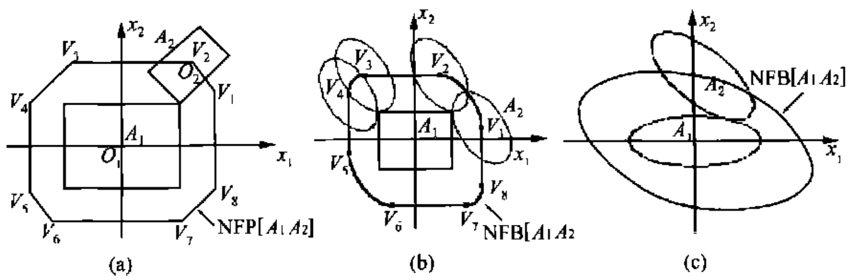

Fig. 3. No fit boundary for interference detection. (a) No fit polygon for rectangle-rectangle case; (b) no fit boundary for rectangle-ellipse case; (c) no fit boundary for ellipse-ellipse case.

For interference measurement, we usually take an overlapping area as the metric object between 2D geometrical components. Liu et al.[40] and Wang et al.[41] developed an efficient algorithm separately to calculate the overlapping area between two triangles, based on which an algorithm for two arbitrary polygons was then proposed. Simple and efficient interference algorithm for 3D case is still an open question.

Interference algorithms mentioned above mainly deal with simple and regular-shaped components. Interference calculation between simple 3D components can usually be inverted to a series of 2D cases by relevant projections. Complex interference calculations should be performed on a platform of CAD software, such as Pro/Engineer.

3 Theory and applications of layout topological pattern

As mentioned above, a layout problem is an NP-complete problem in terms of computational complexity. To relax the serious combinatorial explosion in layout optimization and understand the essence of layout design problems, many researchers pay their attention to the layout pattern theory that concentrates on the relative position relationship between objects in a layout scheme. There is not an acknowledged and rigorous definition about the relative position relationship between spatial objects up to now. To meet practical requirements, Leung[42] and Goetschalckx[43] determined the adjacent position relationship by finding the maximum-weight planar sub-graph of a complete graph. Yan[44] proposed RECGRAPH theory to describe spatial position relationship of planar layout (e.g. adjacency, accessibility, visibility). Wang et al.[11,45] introduced a normal-constraint-graph model and a hierarchical-constraint-graph model. Because a vertex was allowed to correspond with object boundary in these models, they could be used to represent the detailed spatial position relationship and constraints in layout design. In our group, by virtue of group theory and equivalence relation, Feng et al.[12] presented some properties of the isomorphism and equivalent class for layout schemes based on the relative position relationship between objects. They also introduced a global layout optimization algorithm in theory. Teng[46,47], Liu et al.[48], Li et al.[49,2)] presented the definitions of homeomorphic and non-homeomorphic layout patterns separately and proposed a set of methods to construct homeomorphic and non-homeomorphic layout patterns. However, we have to say that we find subsequently that these definitions are not perfect or rigorous.

1) Chen, Y. et al. No fit boundary algorithm for ellipse-ellipse and ellipse-rectangle (in Chinese). Journal of Dalian University of Technology (to be published).

2) Li, G. Q. et al. Homeomorphic and non-homeomorphic layout patterns. Chinese Journal of Computers (in Chinese) (to be published).

A layout topological pattern (LTP) refers to the relative position relationship (neighborhood relationship) between a set of objects. If two LTPs have the same relative position relationship between objects, they are homeomorphic; otherwise they are non-homeomorphic. A key problem here is how to definitely formulate the relative position relationship between objects.

Li et al.[49] used relation matrix and pattern matrix as tools to present the definitions of homeomorphic and non-homeomorphic layout topological patterns and developed relation matrix transformation, model-changing iteration (MCI) method, and centroid exchange method to generate non-homeomorphic initial layout patterns for further improvements. Some mathematical programming methods and HCC-GA in Section 1.3 have been adopted to do layout optimization from a set of non-homeomorphic initial layout patterns. Limited numerical examples demonstrated that, for some mathematical programming methods with deterministic search rules, taking non-homeomorphic layout patterns as starting points for layout optimization is beneficial to reduce redundant repeated computations. But these numerical verifications are far from competent for a generic conclusion.

4 Decision-making in layout design

Computer-aided layout design is a multidisciplinary project. Decision-making in layout design directly dominates the efficiency of layout design process and the quality of a final layout scheme. After a deep analysis and full comparisons between classical decision-making methods including analytic hierarchy process (AHP), fuzzy decision, gray system theory, matter-element analysis, cluster analysis, value engineering method, and neural network approach[50~52], we once developed a fuzzy decision making system for layout design of spacecraft modules[1)]. Recently, we mainly concentrate on a human-computer cooperative AHP system, which quantifies the evaluations made by experts via a human-computer interface and then integrates them with those made by a decision-making algorithm to make a final decision. We are developing a generic software framework for our decision-making system and it is certainly an indispensable constituent part to our layout design system.

5 Pragmatic approaches in engineering practice

A practical layout design problem of a spacecraft module differs from an optimization problem in mathematics, especially on the number of design variables involved and the properties of intricate factors to be considered. In fact, digital models mentioned in Section 1.1 usually are not competent to fully represent a complex layout problem in engineering practice, which often contains complex objectives or constraints that are difficult, even impossible to be formulated by mathematical method. An optimal solution in terms of a mathematical model is perhaps not a satisfactory resolution, even not a feasible resolution in engineering practice. The role of human is indispensable in many areas such as cabling and pipelining architecture design, ergonomic design, setting of weighting factors, assembly techniques, and final decision-making. Furthermore, for a mathematical model, a solution of acceptable quality often costs considerable computational resources, and the support of heuristic rules and human experience is frequently needed. So non-mathematical approach to modeling and solving a complex layout problem is an important prospective direction.

There are various work flows to realize the layout design of a satellite module, and our prophasic solution approach usually consists of three stages[7, 53, 54], 2)]. Firstly, modeling the layout container and objects to be located as geometrical objects with regular shapes, such as cuboids, cylinders, cones, and their combinations, then establishing a database of their geometrical and physical properties, and formulating the problem as a constrained single- or multi-objective optimization problem. Secondly, applying optimization search techniques to the optimization problem, ending with a set of feasible solutions within a reasonable time and cost. Lastly, reverting the container and all objects to what they really are and simulating the whole system according to the resulting feasible layout designs in previous stage on a CAD platform. Human-computer interactions are made for further improvements if necessary, with the consideration of global objectives and constraints, especially those that are not fully formulated in mathematics. Numerical simulations or physical experiments are then carried out for a final decision-mak-

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2) Ge W. H. Constrained layout optimization theory and its application to layout design of spacecraft module. Ph. D. Dissertation. Dalian University of Technology, 1995.

ing. Repeat above procedures until a satisfactory layout is obtained.

Incidentally, the following approaches are worth considering and exploring: (1) intrusive virtual design, which has been seldom used in layout design due to some practical difficulties; (2) agent techniques that have been adopted in the spacecraft design with considerable successes; (3) knowledge based engineering (KBE)[14], which is a novel hot spot and needs further developments both in theory and applications.

6 Conclusion

The automatic layout design of a spacecraft module involves a wide range of difficult problems, from solution strategies in principle, to implement methods in engineering practice. The work reported in this paper is our staged progress. Several issues remain to be further explored are as the following.

(1) Understanding the theoretical and engineering essence of layout design problems and then determining appropriate solution strategy and methods.

(2) Delving into the modeling of a layout design problem, including problem-representing modeling and problem-solving modeling. The disadvantages of traditional models consist of at least two points. On one hand, they are frequently incompetent to fully represent a layout problem so that the resulting solutions leave much to be desired. On the other hand, they usually lack sufficient adaptability and flexibility to meet existing problem-solving methods and the law of humans' thinking.

(3) Developing efficient and pragmatistic problem-solving methods. A human-computer cooperative algorithm is one of the promising efforts. The key points in its realization include: (i) asking an efficient algorithm as a solid ground; (ii) how to realize the cooperation between a human and an algorithm; (iii) developing an appropriate human-computer interface. Furthermore, the strong supports from composition algorithms, Agent, virtual design, and collaborative design techniques are also desired. We are developing a human-algorithm-knowledge based layout design method.

Research on the automatic layout design is of great significance in both academic development and engineering practice. Its application areas likely contain layout design of spacecraft, ships, engineering machines, robotics, bullet trains, and combinatory machine tools, etc.

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