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Simultaneous optimization of layout and task schedule for robotic cellular manufacturing systems

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ABSTRACT

Multi-robot cellular manufacturing systems utilize several articulated industrial robots that cooperatively perform a large number of complex operations when assembling products. To enhance the system performance when designing layouts for such robotic cellular manufacturing systems, the positions of robots and other manufacturing system components must be appropriately determined by considering the sequence of tasks the robots conduct during the assembly process. This paper proposes a new multiobjective layout design optimization technique for robotic cellular manufacturing system layouts that can simultaneously determine the positions of manufacturing components and also task scheduling. First, in this paper, sequence-pair representation is used to specify layout design candidates that inherently avoid interference between assembly system components, and the use of dummy components is introduced to represent layout areas that provide necessary and appropriate spacing between manufacturing system components. In addition, task allocations for each robot are considered as discrete design variables. The design criteria for robot cellular manufacturing system layout designs are clarified and the layout design problem is formulated as a multiobjective optimization problem. To solve the optimization problem, a method based on a multiobjective genetic algorithm is proposed and numerical examples are provided to demonstrate the effectiveness of the proposed method.

1. Introduction

Robotic cellular manufacturing systems (RCMS) utilize one or more articulated industrial robots that perform a large number of complex assembly operations normally conducted by human operators in conventional cellular manufacturing systems. RCMS have advantageous features similar to those of conventional human-based cellular manufacturing systems, such as high flexibility with respect to product changes and low material handling cost. However, due to the benefits of factory automation, RCMS provide significant production advantages compared with manual assembly systems.

To fully exploit the advantageous features of RCMS, quick deployment of manufacturing systems that have efficient configurations is paramount. But since a number of articulated robots in an advanced RCMS cooperatively execute highly complex operations, RCMS design requires deep knowledge and abundant experience in the field of robotics and assembly processes, so development of effective support systems for RCMS layout design is a practical necessity.

Layout design is one of the most important decision-making processes when developing a new RCMS (Rajapakshe, Dawande, & Sriskandarajah, 2011). During the layout design process, industrial robots and other manufacturing system components are allocated at specific positions so that the assigned assembly operations can be conducted appropriately. Since the layout design process is upstream of the detailed robot motion design process, many robot motion design decisions are based on the result of the layout design process, which typically determines, and may limit, fundamental performances of the RCMS.

Numerous optimization techniques for RCMS facility layout problems have been proposed, to support decision-making at the layout design stage (Barral, Perrin, Dombre, & Liegeois, 2001; Tay & Ngoi, 1996). Unfortunately, these methods require explicit constraint handling regarding component overlapping, since component coordinates are handled as design variables, and this implementation obstructs global searching of the solution space. On the other hand, the technique of sequence-pair representation, when used in layout problems, can avoid overlapping among components and accommodate a variety of rectangle sizes that

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represent facility components (Murata, Fujiyoshi, Nakatake, & Kajitani, 1996). Several papers report that this type of representation enables very effective layout optimization in packing-type problems (Drakidis, Mack, & Massara, 2006) and facility layout problems (Liu & Meller, 2007; Meller, Chen, & Sherali, 2007).

Izui et al. (2013) proposed a layout optimization method using sequence-pair representation to assist the conceptual design of a RCMS. Practical layout design problems ordinarily have multiple metrics (Saraswat, Venkatadri, & Castillo, 2015; Emami & Nookabadi, 2013), and layout design problems should be formulated as multiobjective optimization problems rather than single objective optimization problems. Therefore, Izui et al. (2013) clarified the design criteria used at the conceptual design stage and a multiobjective genetic algorithm was employed to obtain non-dominated solutions, but it was assumed that only a single industrial robot was present. We now extend that method to handle cases in which two or more industrial robots operate simultaneously to carry out complex assembly operations.

2. Multi-robot cellular manufacturing system

A typical RCMS comprises one or more industrial robots, part boxes, tool exchangers, and an assembly table. The positions of these components are determined during the RCMS layout design process. After the component layout is set, manufacturing engineers determine detailed robot motions based on the provided layout design (Taha, Tahriri, & Zuhdi, 2011), which makes RCMS operational efficiency highly dependent on such layout design results (Gultekin, Akturk, & Ekin Karasan, 2007). Furthermore, if, due to a poorly realized layout design, it is found to be infeasible during the detailed motion design stage when the numerous tasks to be performed are assigned and choreographed, the design process must return to the layout design stage to implement design changes, causing unwelcome delays. Hence the need for a systematic layout design method that provides reasonable design solutions while considering the detailed tasks to be performed.

In cases where multiple robots are used, the design process becomes far more complex because the robots typically carry out their assigned tasks in parallel. Multiple assembly operation tasks must be allocated to each robot and the usual procedure is to iteratively conduct the RCMS layout design process, based on the results of task allocations considering the need to avoid robot collisions during task operations (Barral, Perrin, Dombre, & Liegeois, 1999).

In any case, task allocation and layout design results are interdependent (Wanghui, Zhenyu, & Jianrong, 2009); choices made during the layout design and task allocation affect each other. Therefore, obtaining efficient manufacturing systems requires that decision-making for both layout design and task allocation be conducted simultaneously (Ripon, Glette, Hovin, & Torresen, 2012). We therefore propose an optimization technique for multi-robot cellular manufacturing systems that simultaneously deals with both task allocation and manufacturing layout design.

In the following sections, the design variables for task allocation and layout design are codified, the RCMS design criteria are clarified, and an optimization procedure employing a multiobjective genetic algorithm is then presented.

3. Design variables for task allocation and component positioning

3.1. RCMS layout design problem assumptions

In this paper, we propose a design optimization technique for the layout of a RCMS in which multiple robots carry out assembly operations. We assume that the list of assembly operations that the robots will perform is preassigned, and the performances and sizes of manufacturing system components such as the robots and the assembly base are also given in advance. During the layout design process, design engineers must determine which robot will conduct each assembly operation and also determine the position of each manufacturing system component, decision-making tasks that are interrelated. For instance, since the time to complete a single task by a given robot depends on the robot's posture as it completes various tasks, different component layouts will result in unique optimal task sequences. Moreover, to avoid collisions between robots, task allocations and component locations must be appropriately adjusted during the creation of a layout design. Design variable encoding techniques for determining task allocations and component locations are explained next.

3.2. Encoding technique for task allocation

The total operation time required to complete all allocated tasks must be computed to evaluate a layout solution candidate. Operational tasks performed by robots can be classified into three categories: assembly tasks, part acquisition tasks, and tool changing tasks. Furthermore, the time required for each of these tasks is considered to be the sum of the time required to carry out the actual operation and the time required for robot movement. Moreover, when multiple robots are used in a RCMS, robot idling time must also be considered. To obtain highly efficient RCMS design solutions, the allocation of the various operational tasks must consider these factors for each robot. Although the time required to conduct a task operation can be easily estimated, robot movement time and idling time depend on both the task allocation and the layout design, so these two aspects must be simultaneously optimized.

Consider that a total of N_p operational tasks are allocated to N_r industrial robots. A single end-effector of a given robot is seldom appropriate for performing all tasks, so industrial robots usually need to change their configuration to match the particular operational task that must be performed. We assume that there are K_p types of task, *i.e.*, N_p operational tasks can be classified into K_p types of task. In the following, the $\mathbf{A}$ vector represents a sequence of tasks and the required operational task types, where the i-th element of the vector represents the i-th task.

$$\mathbf{A} = [A_1, A_2, \dots, A_{N_p}] \tag{1}$$

We use vector $\mathbf{\Phi}$ to represent integer design variables for allocated tasks, as follows:

$$\mathbf{\Phi} = [\phi_1, \phi_2, \dots, \phi_{N_p}], \tag{2}$$

$$\phi_i \in \{1, 2, \dots, N_r\}, \tag{3}$$

where ϕ_i indicates the robot number that is to perform the i-th task.

Using the above vectors, we can now construct task allocation vectors $\mathbf{B}^l$ for the l-th robot, as follows:

$$\mathbf{B}^l = \left[B_1^l, B_2^l, \dots, B_{N_p}^l\right], \tag{4}$$

$$B_i^l = \begin{cases} A_i & \text{if } \phi_i = l \\ 0 & \text{if } \phi_i \neq l, \end{cases}$$

where $B_i^l = 0$ means that the l-th robot does not have an i-th task, a condition that may cause an idling state.

Each operational task indicated by A_i is now separated into assembly tasks, part acquisition tasks, and tool changing tasks. In this paper, these separate tasks are denoted as detailed tasks, and the detailed tasks of task X assigned to robot l are represented as X_A^l, X_T^l and X_P^l, with the subscripts A, T and P denoting Assembly,