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Optimal design of a reconfigurable machine tool considering machine configurations and configuration changes

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Abstract

A reconfigurable machine tool (RMT) is used as a group of machines by changing its configurations for different machining functions such as milling and turning. An optimization approach is introduced in this research for the design of a RMT based on evaluations to both the different machine configurations and the reconfiguration processes to change between machine configurations. In this research, different design candidates, machine configurations for each design candidate, and parameters of the machine configurations are modeled by a generic design AND-OR tree based on design requirements. A specific design solution modeled by multiple machine configurations and their parameters is created from the generic design AND-OR tree by tree-based search. For each design solution, reconfiguration process to change from one machine configuration to another configuration is modeled by a generic process AND-OR graph that is composed of operation candidates, sequential constraints among operations and operation parameters. A specific process solution is created from the generic process AND-OR graph by graph-based search. A multi-level and multi-objective optimization method is developed to obtain the optimal design that is modeled by its machine configurations, parameters of machine configurations, reconfiguration processes to change between machine configurations, and parameters of reconfiguration processes. A case study is implemented to demonstrate the effectiveness of this new optimal RMT design approach.

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Keywords: Reconfigurable machine tool; machine configurations; reconfiguration processes; optimization

1. Introduction

Among various efforts to develop reconfigurable manufacturing systems (RMSs), the recent advances in research on reconfigurable machine tools (RMTs) [1,2] have attracted the attention both in academics and industries. A RMT is usually composed of modules that can be assembled and disassembled in operation stage to obtain different configurations for satisfying different manufacturing requirements. A RMT can be used as multiple machines by sharing common and costly modules when these machines are rarely used at the same time.

Development of RMTs was started by Koren and Kota [3] in their effort to implement a patented RMT for rapid and easy reconfiguration to achieve various types of machining functions. Since then, many efforts have been devoted in development of different types of RMTs [2]. In architecture design of RMTs, modular architecture is often selected such that different modules with different functions can be added to and removed from a machine platform to change its configurations [4]. Open architecture RMTs were also considered to allow the modules developed by third-party venders to be used to extend manufacturing functions of the RMTs [5]. In configuration design and optimization for development of RMTs, Spicer et al. [6] introduced principles for configuration design of machining systems with changeable configurations. Many computer tools have been developed for supporting configuration design of RMTs [7]. Various optimization methods and tools have also been developed for identifying the optimal RMTs [8].

Despite the progress, the efforts in change of configurations during operation stage haven't been well considered for design of RMTs. To solve this problem, a new method is introduced in this research for optimal design of RMT based on evaluations to both the different machine configurations and the processes to change between these machine configurations.

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2. An optimization model for design of RMT considering machine configurations and configuration changes

In this model, a design solution for RMT is composed of multiple machine configurations, C_i *(i = 1,2,...M)*, as shown in Fig. 1. Each configuration is described by design parameters, $d_{i,1}$, $d_{i,2}$, ... *(i = 1,2,...,M)*. Change from one configuration to another configuration is described by a reconfiguration process, R_{ij} *(i = 1,2,...M; j = 1,2,...M; i ≠ j)*.

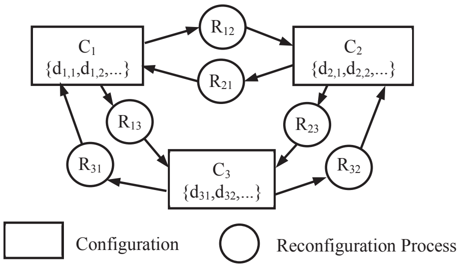

Fig. 1. Configurations and configuration changes

Since different design solutions can be identified from the same design requirements, and each of these design solutions is modeled by multiple machine configurations, parameters of these configurations, reconfiguration processes and process parameters, the optimal design is identified based on evaluations to the configurations and reconfiguration processes. If a configuration is evaluated by $I_C(C_i)$ and a reconfiguration process is evaluated by $I_R(R_{ij})$, the optimal design solution, D^*, can be identified by optimization:

$$\max_{w.r.t.\,D} \left(\sum_{i=1}^{M} I_C(C_i) + \sum_{i=1, i\neq j}^{M} \sum_{j=1}^{M} I_R(R_{ij}) \right) \qquad (1)$$

Optimal design of the RMT is conducted by three steps:

(1) Modeling of design solution candidates and operation configurations for each design solution candidate

The generic design descriptions considering all design solution candidates and multiple operation configurations for each design solution candidate are modeled by a generic design AND-OR tree. A specific design solution candidate is created from the generic design AND-OR tree by tree-based search, and multiple operation configurations are then created from the design solution candidate.

(2) Modeling of reconfiguration processes

Between two configurations in a design solution, the generic reconfiguration process is described by a generic process AND-OR graph composed of operation candidates, sequential constraints among operations and operation parameters. A specific reconfiguration process is created from the generic process AND-OR graph by graph-based search.

(3) Identification of the optimal design

Since the same design requirements can be satisfied by different design solutions, each of these solutions is described by multiple operation configurations, a configuration is further described by parameters, and change between two configurations can be conducted by different reconfiguration processes and process parameters, multi-level and multi-objective optimization is conducted to identify the optimal design solution and reconfiguration processes.

3. Modeling of design solution candidates and operation configurations for each design solution candidate

From the design requirements, the generic design solutions considering different design solution candidates and operation configurations for each design solution candidate are modeled by a generic AND-OR tree as shown in Fig. 2. Each design node in the AND-OR tree is either a component or an assembly with components. Each design node is associated with design parameters. When a design node is achieved by all its sub-nodes, these sub-nodes are associated with an AND relation. When a design node is achieved by only one of its sub-nodes in a design candidate, these sub-nodes are associated with an OR relation in design (OR-D). When a design node is achieved by different sub-nodes in different operation configurations of the same design candidate, these sub-nodes are associated with an OR relation in operation (OR-O).

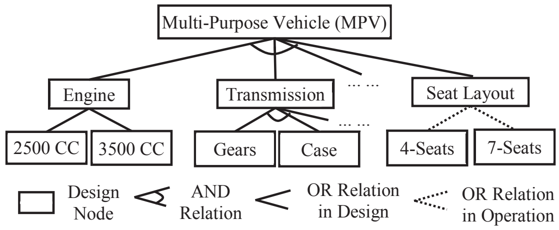

Fig. 2. A generic AND-OR tree

A specific design solution candidate is created from the generic AND-OR tree based on the following 4 rules. (1) The root node is selected first. (2) When a node is selected and all of its sub-nodes are associated with an AND relation, all these sub-nodes should be selected. (3) When a node is selected and all of its sub-nodes are associated with an OR relation in operation, all these sub-nodes should be selected. (4) When a node is selected and all of its sub-nodes are associated with an OR relation in design, only one sub-node should be selected. A specific design solution candidate created from the generic AND-OR tree shown in Fig. 2 is given in Fig. 3(a).

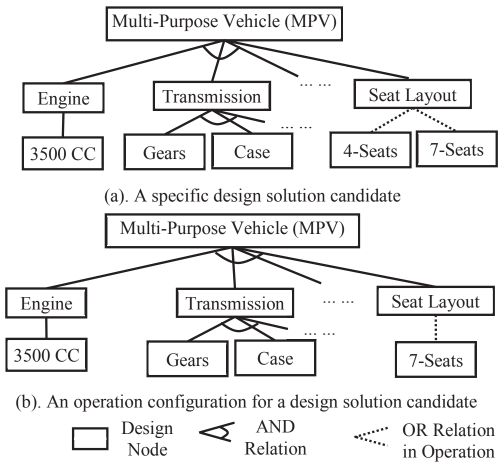

Fig. 3. Creation of a design solution candidate and operation configurations for this design solution candidate

An operation configuration for a design solution candidate is created based on the following 3 rules. (1) The root node is