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Design of reconfiguration mechanism for holonic manufacturing systems based on formal models ☆

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ABSTRACT

One of the key design issues of holonic manufacturing systems (HMS) is to effectively respond to resource failures based on the flexible holonic architecture. The objective of this paper is to propose a viable design methodology to implement reconfiguration mechanism in HMS. A reconfiguration mechanism is developed to accommodate changes based on collaboration of holons without leading to chaos at the shop floor. To deal with resource failures in HMS, an impact function is defined to characterize the impact of resource failures on different holons in a holarchy. A collaborative reconfiguration mechanism based on an impact function is proposed to effectively reconfigure the systems to achieve minimal cost solutions. The design and implementation methodology combines contract net protocol for negotiation of holons, Petri net for the representation of individual product holons and resource holons and FIPA-compliant agent platform for publication/discovery of holons. A simulation system is developed to verify the proposed reconfiguration mechanism.

1. Introduction

Holonic manufacturing systems (HMS) (Balasubramanian et al., 2001; Wyns, 1999; Christensen, 1994) have been recognized as a paradigm to accommodate changes and meet customers' requirements flexibly based on the notion of holon (Koestler, 1967) to provide a reconfigurable, flexible and decentralized manufacturing architecture. Koestler proposed the word "holon" to describe a basic unit of organization in biological and social systems. A holon is an autonomous, co-operative and intelligent entity able to collaborate with other holon to process the tasks. Autonomy and cooperation are two important characteristics of holons. Autonomy allows holons to decide the actions needed to be taken to accomplish the objectives without consulting any supervisory entity. Cooperation makes it possible for holons to agree on common plans and mutually execute them. The distributed architecture of multi-agent systems (MAS) (Nilsson, 1998; Ferber, 1999) and the agents' characteristics of autonomy and cooperation make MAS a potential model for the analysis and implementation of HMS (Ulieru et al., 2001). However, the aggregation relation of holons allows a holon to be part of another holon in the holonic architecture (Paolucci and Sacile, 2005), which makes holonic systems different from MAS and reflects the difficulties to model and analyze HMS with an existing MAS theory. To lay a theoretical foundation for the design and analysis of HMS, a viable approach is to combine MAS architecture with suitable models.

Van Brussel et al. (1998) proposed reference architecture PROSA for HMS and paved the way for further study and design of HMS. In existing literature, surveys of multi-agent manufacturing systems can be found in Shen and Norrie (1999), Monostori et al. (2006), and Marik and Lazansky (2007). Contract net protocol (CNP) (Smith, 1980) is a well known protocol for distributing tasks in multiagent systems. Application of CNP in design of HMS can be found in Neligwa and Fletcher (2003) and Fisher (1999). Works on how to formally specify the dynamic behaviour of holonic systems appear in Leitão et al. (2003) and Hsieh (2008a, 2009a, 2010). Existing results on how to achieve global optimization in HMS can be found in Hsieh (2008a). In spite of the promising perspect and research developed by the holonic community (Bussmann and McFarlane, 1999; Brennan et al., 2002; Deen, 2003), HMS leave some important questions open (Shen et al., 2008; Marik, 2004). Key research topics of HMS include design methodologies and technologies for developing holonic control applications, optimization in holonic system architecture, disturbance handling and reconfiguration in HMS (Leitão, 2008; Hsieh, 2009b).

The special issue on distributed control of production systems in Trentesaux (2009) focuses on the possible applications of distributed approaches for the design, evaluation and implementation of new control architectures for production systems. In particular, reconfigurability is recognized as an important property that differentiates HMS from conventional manufacturing systems. Farid and McFarlane proposed an assessment tool based

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on "Design Structure Matrix" as a means of assessing the modularity of elements in a manufacturing system (Farid and McFarlane, 2006). Moreover Covanich and McFarlane compared the ease of reconfiguration of Holonic and conventional manufacturing systems (Covanich and McFarlane, 2009). It is found that HMS with conventional hardware may have little advantage over conventional manufacturing systems, while HMS with an ideal hardware appears to have significant advantage over conventional manufacturing systems. A reconfiguration process model was also proposed by Chokshi and McFarlane (Chokshi and McFarlane, 2008). To effectively deal with disturbances and accommodate changes, it relies on a proper reconfiguration mechanism. Leitão and Restivo studied how the production control structure should evolve to adapt to changes (Leitão and Restivo, 2006). Leitão and Restivo presented an agile and adaptive manufacturing control architecture that addresses the need for the fast reaction to disturbances at the shop floor level, increasing the agility and flexibility. Barata et al. (2008) addressed the design and implementation of a multiagent based control architecture to support modular reconfigurable production systems. The goal of this paper is to propose a systematic methodology to develop and implement reconfiguration mechanism based on formal models to deal with resource failures in HMS. In addition, a simulation system is developed to verify the proposed reconfiguration mechanism.

Resources may fail at any point in time, take place in any holarchy and change its characteristics and reduce the set of available resources. The effects of resource failures may propagate from one holon to another. Development of an effective method to analyze the impact of resource failures on the operation of HMS and design reconfiguration mechanism based on the analysis is a significant issue. In HMS, a set of holons that autonomously cooperate to achieve a goal forms a holarchy. For some types of tolerable resource failures, the operation of a holarchy may still be maintained without reconfiguration. Hsieh quantitatively characterized the fault tolerant properties of HMS (Hsieh, 2008b). As long as the fault tolerant condition is satisfied, the operation of HMS can be maintained without reconfiguration. Hsieh also studied how to design and analyze reconfiguration mechanisms by taking advantage of the holonic system architecture (Hsieh, 2009b). To study the reconfiguration mechanism, Hsieh defined a holarchy reconfiguration problem (HRP) and an impact function to characterize the impact of resource failures on a holarchy and studied the condition for the existence of a solution to HRP. A solution methodology that combines CNP (Smith, 1980) with Petri nets (Murata, 1989) for HRP was proposed. However, implementation issue has not been addressed in Hsieh (2009b). The aforementioned results pave the way for the development of an effective reconfiguration mechanism.

Finding a solution from scratch at the point resource failures occur is not an appropriate approach as it may lead to chaos at the shop floor. An effective reconfiguration mechanism must be based on the nominal solution so that the impact on the operation of the existing activities can be significantly reduced. To achieve an effective reconfiguration in HMS, a viable reconfiguration mechanism based on the interactions and cooperation between holons is proposed. Although this paper focuses on the development of reconfiguration mechanism to deal with removal of holons, the algorithm can be tailored for addition of holons.

As the proposed implementation of reconfiguration mechanism is based on the theoretical results proposed in Hsieh (2009b), the solution methodology combines CNP (Smith, 1980) with Petri nets (Murata, 1989). The first requirement for the implementation of our reconfiguration mechanism is the infrastructure for publishing and discovering services of holons and the support of CNP. The holonic reconfiguration mechanism can be implemented using the agent technology (Nilsson, 1998; Ferber, 1999), which is appropriate to implement modularity, decentralization, reuse and complex structures characteristics (Marík et al., 2002). The Foundation for Intelligent Physical Agents (FIPA) (http://www.fipa.org) is a standards organization that promotes agent-based technology and the interoperability of its standards with other technologies. Java Agent Development Framework (JADE), which is a FIPA-Compliant (http://www.fipa.org) agent platform that supports services publication and discovery, is adopted in this paper. Another requirement in implementation is the representation of Petri nets of individual product holons and resource holons. Petri Net Markup Language (PNML) (Weber and Kindler, 2003) is a standard for representing Petri nets. PNML is adopted to represent the Petri nets of individual product holons and resource holons. The behaviours of holons in JADE is based on composition of the PNML files of individual product holons and resource holons and parsing it to the corresponding Petri net model.

The remainder of this paper is organized as follows. In Section 2, the holarchy formation problem in HMS is introduced. In Section 3, a problem solving architecture for the holarchy reconfiguration problem is proposed. Petri net models of holarchies are introduced in Section 4. In Section 5, holarchy reconfiguration problem is studied. In Section 6, a reconfiguration mechanism is proposed and a simulation system is developed to verify reconfiguration mechanism. Section 7 concludes this paper.

2. Holarchy formation

The dynamics and behaviours of HMS are determined by the interactions of resource holons, product holons, and order holons. A resource holon consists of a production resource with relevant components to control the resource. A product holon contains the production process information to manufacture products. An order holon represents an order. In HMS, a holon can be part of another holon A holon that consists of a set of holons is called a composite holon. A system of composite holons that can autonomously cooperate to achieve a goal forms a holarchy. Individual product holons or resource holons cannot process a complex task alone. To process an order, a set of resource holons and product holons form a holarchy.

Fig. 1 illustrates an example in which three order holons negotiate with the product holons and resource holons in a HMS. The results of negotiation are represented by a number of holarchies.

Fig. 2 illustrates a holarchy formed by Order holon 1, Product holon 1, Product holon 3, Product holon 4, Product holon 6, Product holon 9, Resource holon 1, Resource holon 2, Resource holon 3, Resource holon 6, Resource holon 8, Resource holon 9, Resource holon 10 and Resource holon 11 to meet the order requirements.

Holarchy formation problem has been studied in (Hsieh, 2008a), where Hsieh proposed models and developed collaborative algorithms to guide the holons to form a holarchy that coherently move toward the desired goal state ultimately. However, implementation of the collaborative algorithms proposed in (Hsieh, 2008a) require further study. The objective of this paper is to propose an architecture for the development of a problem solver for holarchy reconfiguration in HMS based on the theoretical study in Hsieh (2008a, 2009b). A methodology to design a problem solving environment based on FIPA-compliant platforms is proposed in this paper.