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Dynamic composition of holonic processes to satisfy timing constraints with minimal costs ☆

Fu-Shiung Hsieh

Department of Computer Science and Information Engineering, Chaoyang University of Technology, 168 Jifong East Road, Wufong Township, Taichung County, 41349 Taiwan

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ABSTRACT

The flexible architecture provided by holonic manufacturing systems (HMS) poses challenges in planning and control of production processes. The challenges are due, in part, to the loosely coupled structure of holons and also to the complex interactions among holons. Development of new methodologies is required to optimize the holonic processes in HMS to achieve the objectives. In this paper, we concentrate on the development of method for the composition of holonic processes. We consider the holonic processes composition (HPC) problem to synthesize processes with minimal costs while meeting the timing constraints in HMS. We formulate this problem based on a hybrid model in which contract net protocol is adopted as the negotiation protocol and timed Petri net is used to analyze the timing and resource constraints. To specify the costs of operations, we augment the timed Petri net with a cost function. We formulate an optimization problem to minimize the cost while meeting the timing constraints based on the Petri net models. A solution to HPC can be represented by a collaborative Petri net. Our methodologies include a condition to check whether the timing constraints can be met, a condition for the existence of an optimal solution to the HPC problem and a multi-layer contract net protocol to find the minimal cost solution.

1. Introduction

The manufacturing sector has been facing major challenges as it undergoes revolutionary changes fuelled by new and sophisticated demands from customers, global competition, distribution of manufacturing and marketing activities and technological advances. Due to the dynamically changing characteristics of manufacturing environments, static control structures are not suitable anymore. Bousbia and Trentesaux (2002) reviewed state-of-the-art and future trends of self-organization in distributed manufacturing control. The increasing versatility in product demands calls for a system architecture able to evolve in time (Trentesaux and Tahon, 1995). In order to address these challenges, manufacturing enterprises need to change the way they do business and adopt innovative organizational forms, technologies and solutions to increase their responsiveness and production efficiency. To cope with the increased rate of changes that was affecting the entire business world, the idea of using the holonic concept in the design of manufacturing systems emerged in the early 1990s (Agility Forum, 1997). Holonic manufacturing systems (HMS) (Balasubramanian et al., 2001; Wyns, 1999; Brussel et al., 1998; Christensen, 1994) provide a reconfigurable, flexible and decentralized manufacturing environment to accommodate changes and meet customers' requirements dynamically based on the notion of holon (Koestler, 1967), an autonomous, co-operative and intelligent entity able to collaborate with other holons to process the tasks.

In HMS, a holon can be part of another holon and a system of holons that can autonomously cooperate to achieve a goal forms a holarchy. A challenge is to design a mechanism to guide the holons such that the decisions made by the individual holons as a whole composite a holarchy that achieves the objectives such as meeting customers' demands and due dates. In existing literature, there are many studies on HMS (McFarlane and Bussmann, 2000; Gou et al., 1998; Ramos, 1996; Brennan and Norrie, 2001; Wullink et al., 2002; Giebels et al., 2001; Neligwa and Fletcher, 2003; Leitão et al., 2003; Hsieh, 2006, 2008; Leitão and Restivo, 2006). There are many works on planning and optimization in HMS. Giebels et al. (2001) (Wullink et al., 2002) proposed the system architecture of a flexible manufacturing planning and control system, named EtoPlan, for concurrent manufacturing planning and control of activities and groups of resources in a manufacture-to-order environment based on multiple and holarchies. Existing works on how to specify formally the dynamic behaviour of holonic systems appear in Leitão et al. (2003), Johnson (2003) and Hsieh (2006). In Karageorgos et al. (2003), the authors present an approach based on agent negotiation with an extended

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E-mail addresses: fshsieh@cyut.edu.tw, apistech@ms14.hinet.net (F.-S. Hsieh).

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contracting protocol for supporting logistics and production planning, taking into account not only availability but also cost of logistic service providers. Studies on how should the production control structure evolve to adapt to changes have been made by Leitão and Restivo (2006). Leitão and Restivo (2006) present 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 of the enterprise. Existing results on how to achieve global optimisation in decentralised systems can be found in Hsieh (2008).

In a real-world manufacturing environment, finding the right sequences and associated schedules with resource, precedence and timing constraints is a difficult task. One approach to overcome the limitations of classical scheduling is the use of distributed schemes such as agent or holonic-based control architectures (Babiceanu et al., 2005). Babiceanu et al. (2005) presents a solution for scheduling using the holonic control approach in which a feasible solution emerges from the combination of individual material handling holons' solutions. Leitão and Restivo (2007) presents a holonic approach to manufacturing scheduling, where the scheduling functions are distributed by several entities, combining their calculation power and local optimization capability.

In Hsieh (2008), the author defined a holarchy formation problem to lay a foundation to propose models and develop collaborative algorithms to guide the holons to form a holarchy that coherently moves toward the desired goal state with minimal costs. However, timing constraints have not been taken into acoount in Hsieh (2008). In this paper, we will concentrate on the development of methodology to compose holonic processes with minimal costs while satisfying timing constraints. Instead of applying the complex and optimized scheduling algorithms found in traditional approaches, we extend the distributed collaborative mechanism proposed in Hsieh (2008).

A holonic process is dynamically formed by a set of product holons and resource holons based on a certain task distribution protocol such as contract net protocol (CNP) to execute a task. CNP (Smith, 1980) is a well known protocol for distributing tasks. Application of CNP for task allocation in HMS is found in Neligwa and Fletcher (2003), Gou et al. (1998) and Ramos (1996). Formation of holonic processes in HMS based on CNP has been studied in Hsieh (2008, 2006, 2004), where Petri net (Murata, 1989) models have been proposed to capture the interactions between resource holons and product holons. These results pave the way for the development of methodology for composing holonic processes that satisfy timing constraints. To achieve the objectives, we first formulate a holonic process composition problem based on Petri nets and propose a method to find an optimal solution.

This paper differs from Giebels et al. (2001) in that a formal approach based on Petri nets is adopted. Although CNP has been used in this paper, our work is differentiated from Karageorgos et al. (2003) as we focus on optimization of holonic production processes with timing constraints. This paper is differentiated from the works of Leitão et al. (Leitão et al., 2003; Leitão and Restivo, 2006) in several aspects. Although all these works intend to contribute to the development of a dynamic and adaptive control approach that improves the agility and reaction to unexpected disturbances by taking advantage of the flexibility offered by HMS without compromising the global optimisation, the approaches are different. The self-organization adaptation mechanism proposed by Leitão et al. introduces the concept of autonomy factor and a pheromone-like spreading mechanism to propagate emergence and reorganize the system. Our approach combines a multi-layer CNP with timed Petri net models augmented with costs to achieve optimization based on collaboration of holons. The problem considered in this paper is more general than that of Hsieh (2008) as the timing constraints have been considered in this work.

The remainder of this paper is organized as follows. In Section 2, we describe and state the holonic processes composition (HPC) problem. To formulate the HPC problem, we introduce timed Petri net models in Section 3. We propose a collaborative Petri net model and formulate an optimization problem for the HPC problem. In Section 4, we propose a condition for collaborative workflows to satisfy given time constraints. In Section 5, we study the condition to determine whether a holon is feasible and also the condition for the existence of an optimal solution to the optimization problem. In Section 6, we illustrate how to apply a multi-layer CNP to find the optimal solution by using an example. Section 7 concludes this paper.

2. Composition of holonic processes

An HMS consists of three types of holons: resource holons, product holons and order holons (Wyns, 1999). A resource holon consists of production resources with relevant components to control the resources. A product holon contains the production process information to manufacture products. An order holon represents an order. Individual product holons or resource holons cannot process a complex task alone. To process a task, a set of resource holons and product holons form a composite holon called a holarchy.

Fig. 1 illustrates a scenario in which a production process is to be formed in HMS with seven product holons $h_1, h_2, \ldots h_7$ and ten resource holons $r_1, r_{2,} \ldots r_{10}$ to accomplish a task with timing constraints. Holonic processes are production processes dynamically created based on the collaboration of product holons. Each product holon has an internal process flow. Execution of the internal process of a product holon may rely on the outputs from the internal processes of one or more upstream product holons. For example, product holon h_5 and h_6 depends on either h_1 or h_2 to provide the type-one parts and also depends on either h_3 or h_4 to provide the type-two parts. Product holon h_7 depends on either h_5 or h_6 to provide the type-three parts.

Execution of a task τ requires collaboration of a set of product holons and resource holons. To process a task, the internal processes of a minimal set of product holons need to be

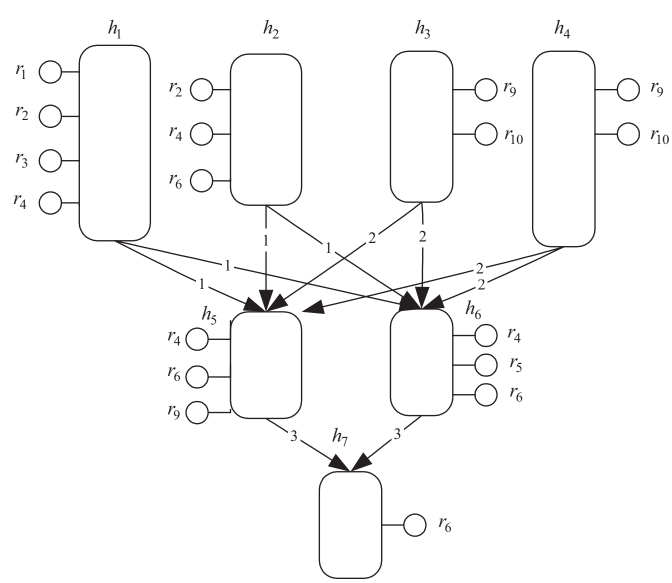

Fig. 1. Holonic process formation.