Automatica 44 (2008) 2538–2548

Contents lists available at ScienceDirect

Automatica

journal homepage: www.elsevier.com/locate/automatica

Robustness analysis of holonic assembly/disassembly processes with Petri nets☆

Fu-Shiung Hsieh

Department of Computer Science and Information Engineering, Chaoyang University of Technology, Taiwan

ARTICLE INFO

Article history:
Received 18 November 2006
Received in revised form
18 August 2007
Accepted 3 March 2008
Available online 19 September 2008

Keywords:
Holonic manufacturing systems
Fault tolerant
Liveness
Petri-nets
Robustness

ABSTRACT

Although the concept of holonic manufacturing systems (HMS) has been proposed for over a decade, several desired properties of HMS such as fault tolerance have not been quantitatively characterized and rigorously proven. This paper aims to provide a theoretical foundation for analyzing the fault tolerant properties of holonic assembly/disassembly processes in HMS. Fault tolerant analysis is concerned with the impact of resource failures on the operation and performance of HMS. The goal of fault tolerant analysis is to study the ability to retain the operation of holonic processes in the presence of resource failures. To study fault tolerant properties, we propose a collaborative Petri net (CPN) to model holonic assembly/disassembly processes and formulate an optimization problem to minimize the cost of CPN. We propose a greedy algorithm to find a nominal optimal solution. Based on the nominal solution, we analyze the effects of resource failures on the operation and performance of the holonic assembly/disassembly processes. Computational complexities are also analyzed.

1. Introduction

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, Brennan, & Norrie, 2001; Brussel, Wyns, Valckenaers, Bongaerts, & Peeters, 1998; Christensen, 1994; Wyns, 1999) aim to 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. Although there are many studies on HMS (Brennan & Norrie, 2001; Gou, Luh, & Kyoya, 1998; McFarlane & Bussmann, 2000; Neligwa & Fletcher, 2003; Ramos, 1996), few works on quantitative analysis of HMS are available due to the complexities. As a result, despite the fact that HMS has been proposed and studied extensively for over a decade, several desired properties of HMS such as fault tolerance have not been quantitatively characterized and rigorously proven.

Fault tolerance is one of the most challenging issues in the design of complex manufacturing systems (Duffie, 1990). This includes automatic detection of failure situations, diagnosis of the cause of failures, and determination and implementation of appropriate recovery actions. The potential malfunctions that could appear during the operation of a manufacturing system have been studied in Christensen (2003), Jarvis and Jarvis (2003), Johnson (2003) and Neligwa and Fletcher (2003). Ulieru and Norrie (2000) applied fuzzy modeling techniques to study the capabilities of holonic systems to recover in the event of occurring faults. In the fault tolerant HMS developed by Fletcher and Deen (2001), multiple entities use a cooperation framework for rescheduling affected tasks and recover the system from unexpected events. Fault tolerance is achieved by using error-generated information, a holon rescheduling mechanism, and a functional component failure recovery mechanism. However, quantitative characterization of the fault tolerant properties of HMS has not been addressed in Fletcher and Deen (2001). Motivated by this deficiency, the objectives of this paper are to probe into the fault tolerant properties of holonic assembly/disassembly processes and study the impact of resource failures on the operation and performance of the nominal processes.

A holonic assembly/disassembly 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 Gou et al. (1998), Neligwa and Fletcher (2003) and Ramos (1996). Formation of holonic processes in HMS based

☆ This paper was presented in the First IFAC Workshop on Applications of Large Scale Industrial Systems (ALSIS06). This paper was recommended for publication in revised form by Associate Editor Xiaohong Guan, under the direction of Editor Mituhiko Araki. This paper is supported in part by the National Science Council of Taiwan, R.O.C. under grant NSC97-2410-H-324-017-MY3.

E-mail address: fshsieh@cyut.edu.tw.

0005-1098/$ – see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.automatica.2008.03.008

on CNP has been studied in Hsieh (2004, 2006a), where Petri net (Murata, 1989) models have been proposed to capture the interactions between resource holons and product holons. Fault tolerant analysis of production processes based on Petri net models has been studied in Hsieh (2006b, 2007). These results pave the way for the study of fault tolerant properties of holonic assembly/disassembly processes. To achieve the objectives, we first formulate a nominal process optimization problem based on Petri nets and propose a greedy algorithm to find a nominal optimal solution. Based on the nominal solution, we analyze the effects of resource failures on the operation and performance of holonic assembly/disassembly processes. The computational complexity to test whether a certain type of resource failures is tolerable is also analyzed.

This paper differs from Ulieru and Norrie (2000) in that resource failures and holons are modeled with Petri nets instead of fuzzy approach. This paper is differentiated from the failure recovery mechanism presented in Fletcher and Deen (2001) as we focus on characterizing the tolerable resource failures in HMS. The problem considered in this paper is more general than that of Hsieh (2006a) as the holonic assembly/disassembly process considered is more general than the holonic sequential processes. Moreover, the fault tolerant properties studied in this paper have not been addressed in Hsieh (2006a).

The remainder of this paper is organized as follows. In Section 2, we briefly review the formation of holonic assembly/disassembly processes. In Section 3, we propose a collaborative Petri net model and formulate an optimization problem for this class of systems. In Section 4, we study the condition for the existence of an optimal solution to the optimization problem and propose a greedy algorithm for solving the optimization problem. In Section 5, we present a nominal supervisory control algorithm. Robustness of the nominal solution is analyzed in Section 6. Section 7 concludes this paper.

2. Holonic assembly/disassembly processes

Holonic processes are production processes dynamically created based on the collaboration of resource holons and product holons in HMS. To process a task, at least one product holon and a set of resource holons form a collaborative network called a holarchy in HMS. One way to form collaborative networks is based on the contract net protocol (CNP). Formation of holonic processes in HMS based on CNP has been studied in Hsieh (2006a), where CNP is applied to form a collaborative network base on establishment of contracts between holons. In this paper, we consider holonic assembly/disassembly processes, where execution of a task τ requires collaboration of a set of product holons and resource holons. Table 1 lists the notations used in this paper.

To describe the collaborative network for a task τ, we use an oval to represent a product holon. To describe the inputs or outputs of a product holon, we use a set of circles called interface nodes. The output interface node of a product holon may connect to the input interface node of another product holon. The dependency between product holons is represented by a digraph $g(N, E)$.

Definition 2.1. The dependency between product holons is described by a digraph $g(N, E)$, where $N = H \bigcup I$ is a set of nodes, E is a set of arcs, a node in H denotes a holon and a node in I denotes an interface between holons. An arc connecting node $h \in H$ to node $i \in I$ means that holon h will provides its outputs to other holons via interface node i. An arc connecting node $i \in I$ to node $h \in H$ means that holon h may accept the outputs from other holons via interface node i.

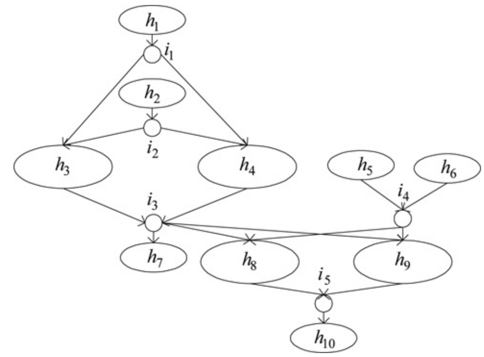

Fig. 1. Dependency digraph $g(N, E)$.

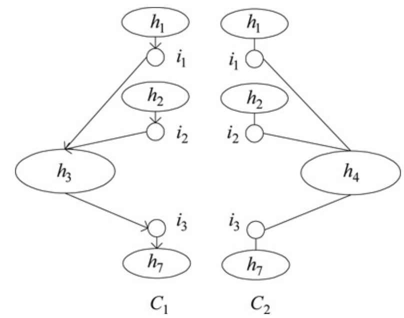

Fig. 2. Two Collaborative Networks: C_1 and C_2.

Fig. 1 shows a dependency digraph $g(N, E)$, where $H = \{h_1, h_2, \ldots, h_{10}\}$ and $I = \{i_1, i_2, \ldots, i_5\}$. In Fig. 1, product holons h_3 and h_4 provide two alternative ways to provide intermediate parts for h_7, h_8 or h_9. The outputs of h_3 or h_4 are used by h_7. Similarly, h_5 and h_6 provide two alternative ways to produce another type of intermediate parts for h_8 or h_9. Holons h_8 and h_9 process the two types of parts from i_3 and i_4.

In a given digraph $g(N, E)$, the number of outgoing arcs of a holon node h is called the out-degree of h. A product holon node h with zero out-degree is called a final product holon. In Fig. 1, h_7 and h_{10} are final product holons. We use $\text{Out}(h)$ and $\text{In}(h)$ to denote the set of output interface nodes and the set of input interface nodes of product holon h, respectively. To describe the collaborative network for a task τ, let h_τ denote the product holon that contains the final operation of task τ.

Definition 2.2. A collaborative network for product holon h is described by a digraph $C(N_C, E_C) \subseteq g(N, E)$, where N_C is a finite set of nodes and E_C is a finite set of arcs. $N_C = H_C \bigcup I_C$, $H_C \subseteq H$, $I_C \subseteq I$, $h \in H_C$, and for each $h \in H_C$, there exists $h' \in H_C$ connecting to i for each $i \in \text{In}(h)$. If there is exactly one incoming arc and one outgoing arc for each interface node in I_C, $C(N_C, E_C)$ is called a minimal collaborative network for product holon h.

Fig. 2 shows two minimal collaborative networks C_1 and C_2 to perform the task ending with final product holon h_7, where $H_{C_1} = \{h_1, h_2, h_3, h_7\}$ and $H_{C_2} = \{h_1, h_2, h_4, h_7\}$. There are eight minimal collaborative networks $C_3 \sim C_{10}$, where

$$
\begin{aligned}
&H_{C_3} = \{h_1, h_2, h_3, h_5, h_8, h_{10}\}, && H_{C_4} = \{h_1, h_2, h_3, h_6, h_8, h_{10}\},\\
&H_{C_5} = \{h_1, h_2, h_3, h_5, h_9, h_{10}\}, && H_{C_6} = \{h_1, h_2, h_3, h_6, h_9, h_{10}\},\\
&H_{C_7} = \{h_1, h_2, h_4, h_5, h_8, h_{10}\}, && H_{C_8} = \{h_1, h_2, h_4, h_6, h_8, h_{10}\},\\
&H_{C_9} = \{h_1, h_2, h_4, h_5, h_9, h_{10}\}, && H_{C_{10}} = \{h_1, h_2, h_4, h_6, h_9, h_{10}\}
\end{aligned}
$$

to perform the task ending with product holon h_{10} in Fig. 1.

In general, there may be numerous minimal collaborative networks that can perform a given task. The existence of multiple