A Hierarchical and Distributed Approach to the Design of Intelligent Manufacturing Systems

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INTRODUCTION

Traditionally, the use of PLC (Programmable Logic Controllers) interconnected by a communication network and corresponding programming software became a standard in industrial automation, but PLC-driven systems are mainly centralized, providing limited reconfiguration capabilities to respond to the market needs. Decentralized manufacturing systems are considered to be able to deal with the rapid changes in the manufacturing environment better than the traditional centralized architectures by matching agility and efficiency (Leitao, et al., 2009). Two advanced decentralized approaches, Bionic Manufacturing Systems and Holonic Manufacturing Systems, are commonly characterized by a set of autonomous and collaborative components and their environmental rules. In collaborative automation, each autonomous device should provide one or more services that match its functionalities, such as device configuration management, multiple operations execution, events sending. To participate in collaborative activities, it should also include an interaction agent to communicate to others and request different services.

The Bionic Manufacturing System proposes essential concepts for realizing future manufacturing systems by drawing parallels with biological systems (Okino, 1993). A biological system exhibits many features including autonomous and spontaneous behavior, and social harmony within hierarchically ordered layers composed of cells; tissues, organs, body organisms, and social organizations. Cells are basically similar, but differentiated by function, and are capable of multiple operations. Cells act as building blocks to make up the hierarchical layers in organisms. Thus, tissues are formed by cells with similar function and shape. Different tissues combine to form organs with a particular function. Organs, in turn, group together to form body subsystems, and the subsystems make up complex organisms. These features reveal the self-organizing emergence of hierarchical and distributed control functions in the whole system. In parallel with the above, the manufacturing units can act similar to cells as building blocks to derive hierarchical control structures, such as workcells, shops, lines, factories and companies. In such structures, each layer in the hierarchy supports and is supported by the adjacent layers. Manufacturing units obtain the needed inputs from the factory floor environment, collaborate with other units, perform operations, and outputs of these operations flow back to the environment. Local coordinators may act to preserve the harmony like enzymes. Also, regulatory schemes similar to hormones may include policies or strategies that have a longer term effect on the environment.

The Holonic Manufacturing Systems has been proposed by translating the concepts developed for living and social organisms into a manufacturing setting. A holon is an autonomous and cooperative building block of a manufacturing system for transforming, transporting, storing and/or validating information and physical objects. The holon consists of an information processing part and often a physical processing part. In addition a holon is part of another holon. The autonomy means the capability of an entity to create and control the execution of its own plans and/or strategies. The cooperation means a process whereby a set of entities develops mutually acceptable plans and executes these plans. A holarchy is a system of holons that can cooperate to achieve a goal or objective. The holarchy defines the basic rules for cooperation of the holons. Based on the above definitions, it is natural that holonic manufacturing systems can be a unified way to approach the hierarchical and distributed control of any

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manufacturing unit from the elementary manufacturing process level to the whole company level.

Advanced large and complex manufacturing systems have a holonic or self-organizing and self-adaptive hierarchical structure like bionic systems, and the controllers are locally distributed according to their physical structure. So it is natural to realize the hierarchical and distributed control of overall hardware structures. When specification is given at the top-layer, it passes down layer-by-layer to the bottom and finally as primitive actions. In a bottom-up process, the actions of units cumulate and manifest in an operation of the whole system. The key solution for such advanced distributed systems is to realize the cooperation, which is different from generic management and control systems. Currently, the distributed system modeling and analysis meet with difficulties related to the cooperation problem (Celaya, et al., 2009; Kotb, 2007).

This article discusses the specification problem for real-time monitoring and control of different manufacturing processes involved with distributed manufacturing systems. Manufacturing systems are composed of different intelligent elements such as machining centers, parts feeders, handling robots, transporting mobile robots, etc. These elements have the capabilities to work independently and cooperatively with each other. Independent processes of these elements can be characterized as discrete, asynchronous, sequential, and concurrent. Therefore, based on the asynchronous concurrency, the interaction among these elements, such as the process synchronization, mutual exclusion, and deadlock avoidance, should be considered as the main issues in the design of control specification, in parallel with the biological systems. According to the characterization of discrete manufacturing system as a discrete event system, techniques derived from the Petri net are adopted for system modeling and analysis. A systematical approach is presented for the specification of the manufacturing tasks based on the high-level, compact, modular representation of task flows in manufacturing systems as an extension to the original ordinary Petri net formalism.

BACKGROUND

Petri nets can provide a structural design methodology in manufacturing systems through a top-down and/or bottom-up relationship between abstract specification and practical implementation, (Ramaswamy, et al., 1994; Zurawski, et al., 1994). One of the major advantages of using Petri net models is that the same model can be used for the analysis of behavioral properties and performance evolution, as well as for the systematic construction of discrete event simulators and controllers. Due to locality of states and actions, system monitoring can be efficiently provided in real time. By selecting an appropriate detail level with adequate representation of essential features of a system, Petri net models can be constructed applying top-down and bottom-up approaches (Gomes, et al., 2005). Net objects of different meaning can be associated and interpreted according to the purpose of the modeling. As a graphical tool, effective visual representation improves the communication between designers and customers, avoiding complex specifications, ambiguous textual description, or specific mathematical notation which are generally difficult to understand. Because ordinary Petri nets suffer from the lack of high-level constructs, which affects the readability of the final net model, to construct more concise graphs that include information flow, Predicate/Transition nets and their improvement called Colored Petri nets were introduced by attaching data values, called colors, using variables in arc expressions, and attaching Boolean expressions to transitions (Jensen, 1991). In Colored Petri nets information attached to each token as a token color can be inspected and modified when a transition fires. In this way it is also possible to fold several similar subnets into a single net. Hierarchical net modeling allows the system modeler to describe a set of sub-models which all contribute to a much larger model by interacting with each other in a well-defined way.

As a typical manufacturing task, assembly/disassembly planning is associated with the determination of a sequence of operations to be done in order to assemble/assemble a product (Zhang, 1998). High-level Petri nets were used for assembly planning, such that transitions and places represent the assembly operations and the corresponding preconditions and results, respectively. Task planning deals with the translation of an assembly plan into the robot operations that may allow the successful execution of the task. The robot operations involve the planning of sensory operations, gross-motion planning with collision avoidance, and fine-motion planning with contact motions (Zha, 1999; Zhang, et al., 2005). Petri nets can be used to capture the contact states and the transitions between them

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