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Distributed control of production systems

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ABSTRACT

This editorial introduces the special issue of the Elsevier journal, Engineering Application of Artificial Intelligence, on Distributed control of production systems. The current technology in communication and embedded systems allows products and production resources to play a more active role in the production process. This new active capacity will generate major changes in organizations and information systems (e.g., Enterprise Resource Planning (ERP) and Manufacturing Execution Systems (MES)). New approaches are now required for modelling, testing and assessing the features made possible by the decisional and informational capabilities of these new active entities. One among the many possibilities is to use agents and holons, since agent and holon-based approaches assume interaction between intelligent entities to facilitate the emergence of a global behavior. This special issue thus focuses on the possible applications of distributed approaches for the design, evaluation and implementation of new control architectures for production systems. Both fundamental and applied research papers are presented.

1. Introduction

This editorial introduces the special issue of the Elsevier journal, *Engineering Application of Artificial Intelligence*, on *Distributed control of production systems*. The current technology in communication and embedded systems allows products and production resources to play a more active role in the production process. This new active capacity will generate major changes in organizations and information systems (e.g., Enterprise Resource Planning (ERP) and Manufacturing Execution Systems (MES)). New approaches are now required for modelling, testing and assessing the features made possible by the decisional and informational capabilities of these new active entities. One among the many possibilities is to use agents and holons, since agent- and holon-based approaches assume interaction between intelligent entities to facilitate the emergence of a global behavior. This special issue thus focuses on the possible applications of distributed approaches for the design, evaluation and implementation of new control architectures for production systems. Both fundamental and applied research papers are presented.

This editorial is structured as follows. The concepts of control and distributed control of production systems are first presented. Then, the evolution of industrial needs is introduced, highlighting the expected advantages of distributed control systems but also presenting the challenges that are addressed in each of the papers in this special issue. The last section offers conclusions about the direction that future advances will take.

2. Control and distributed control of production systems

In this paper, the term "control" includes what is generally accepted as the whole loop that allows a process or a system to be controlled, from sensors to actuators. As a result, a closed loop can then be defined as something that exists between a system that controls and a system that is controlled (Wiener, 1948). In this context, Baker (1998) proposed a block-diagram model of manufacturing control (Fig. 1).

Due to the difficulty of a single central factory controller to deal with production system complexity (e.g., data management complexity, uncertainty related to demand and resource availability, the lag between events and relevant information processing) while at the same time considering real-time constraints (i.e., reactivity), one widely used solution has been to distribute decisional capabilities to decisional entities, leading to non-centralized control systems. In this special issue, it is assumed that distribution of control means the division of a global control process based on a splitting criterion (e.g., geographical, functional) into several decisional sub-activities that are assigned to sub-systems, called decisional entities. These decisional entities are systems that are able to support a decision process, which is composed of a triggering activity, problem formulation, problem

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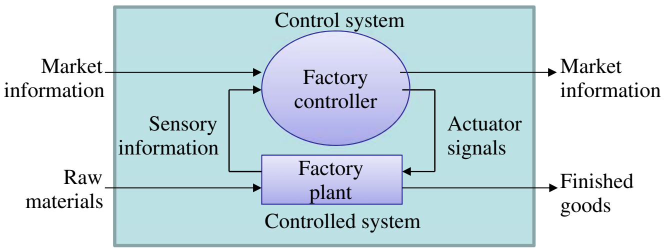

Fig. 1. Block-diagram of manufacturing control, according to Baker (1998).

solving and application of the resulting decisions through the system actuators. The triggering activity can be based on an estimation of the distance between the desired goal and the state detected by sensors. Decentralized control is thus a form of distribution in which the decisional activities that are assigned can be seen as local control activities (e.g., local control of a resource).

In the early 1970s, the first kind of control distribution was fully hierarchical and based on the Computer Integrated Manufacturing (CIM) paradigm. Splitting the global control problem into hierarchically dependent sub-problems with decreasing time ranges (i.e., strategic, tactic and operational, such as planning, scheduling and supervising) assigned to hierarchically dependent decisional entities allowed sufficient long-term optimization to be maintained (i.e., global optimality), while supporting less short-term optimization (e.g., agility, reactivity). This approach has led to the well-known Manufacturing Resources Planning (MRP2) and more recently, to Enterprise Resource Planning.

This traditional CIM-based approach is known to provide near-optimal solutions when some hard assumptions are met, for example, the long-term availability and reliability of the supply and demand, the optimal behavior and high reliability of production systems, low product diversity, and the observability and controllability of all the possible internal variables. One of the theoretical foundations for this traditional approach was published by Mesarović et al. (1980). The term "distributed" is sometimes used in this context, not explicitly to refer to the distribution of control but rather to the distribution of resources, for example, to describe company sites that are not located at the same place. The papers by Jiao et al. (2009), and by Chung et al. (2009) address this topic. Jiao et al. (2009) focus on the coordination mechanisms within the supply chain of a multinational company. The control architecture is fully hierarchical, which means that there is no heterarchical relationship among decisional entities that must be coordinated, despite the fact that this control architecture is applied to a supply chain, which can be seen as a set of physically distributed resources. The authors formulate the product, process and supply chain coordination as a factory loading allocation problem using a constraint satisfaction approach. A decision propagation structure is extended from the constraint heuristic search to facilitate solution space exploration. In such a model, the search for static optimality is feasible if a global criterion can be expressed. Chung et al. (2009) propose a supervisory genetic algorithm approach to deal with distributed production scheduling that takes maintenance tasks into account. The aim of their approach is to minimize the makespan of the jobs. They analyze the influence of the relationship between the maintenance repair time and machine age on the performance of maintenance scheduling.

Since the 1990s, other kinds of distribution, especially based upon the distribution of control decision have also been considered. These approaches were adopted due to the emerging need for local reactivity. The main argument was that, in hierarchical control, the time spent to inform the correct controller within the hierarchy (bottom-up), and then to decide and to apply the decision (top-down) generates lags and instabilities. The idea was to permit the decisional entities to work together so as to react quickly instead of requesting control decisions from upper decisional levels, which was generating response time lags. In this new approach to distribution, interaction processes other than coordination appear, mainly, negotiation and cooperation (Mařík and Lazansky, 2007). However, negotiation and cooperation led to new problems, for example, the need to prove deadlock avoidance mechanisms and more generally, the need to prove that sufficient level of performance can be attained.

In the first studies of this approach to distribution, upper-level decisional control was forbidden. In fact, the relationship among such cooperating decisional entities can been qualified as "fully heterarchical". Heterarchy can be formalized using graph theory. A directed graph composed of nodes representing decisional entities and arcs representing the master–slave interaction of a decisional entity (master) with another entity (slave) is called "influence graph". If each node can be considered as both a master and a slave, no hierarchy can be identified, and thus the graph is considered to be strongly connected. This strong connection defines a heterarchy. This formalization is consistent with the initial heterarchy concept developed by McCulloch (1945). Fig. 2 illustrates the difference between hierarchy and heterarchy. Graphically, hierarchy can be seen as a kind of "vertical" distribution of control, while heterarchy is a kind of "horizontal" distribution of control.

In fully heterarchical control systems (one-level heterarchy, as shown in Fig. 2), long-term optimization is hard to obtain and to verify due to the difficulty of proving that a sufficient level of performance can be attained, while short-term optimization is easy to achieve. Multi-agent systems have been widely used to model such fully heterarchical control systems. Since the end of 1990s, a new paradigm has emerged: the holonic paradigm. The desire to integrate both hierarchical and heterarchical mechanisms into a distributed control system can be seen as an essential feature of the holonic paradigm, allowing users to benefit from the advantages of both approaches. Of course, it does not negate the pertinent drawbacks.

Fig. 3 summarizes the different ways to distribute control decisions from centralized control systems to design non-centralized control systems based upon two fundamental design choices: the choice of using hierarchical relationships and the choice of using heterarchical relationships. Given the different ways of distributing control decisions, it is possible to construct an architecture typology that is inspired by Dilts et al. (1991). Indeed, the desire to use hierarchical relationships when designing a control architecture led to Class I control architectures, and the desire to use heterarchical relationships led to Class III control architectures. Class II control architectures, being semi-heterarchical, fall somewhere in the middle, integrating both hierarchical or heterarchical relationships. A control architecture is Class II if its whole influence graph is not strongly connected (not a Class III) while at least one sub-graph is strongly connected (not a Class I). A typical Class II control architecture is a Class III control system with a supervisory level.

This special issue focuses on distributed systems that contain heterarchical relationships, with or without hierarchical ones. With exception of Jiao et al.'s (2009) and Chung et al.'s (2009), which deal with a Class I control system, the different control systems proposed range from fully heterarchical to semi-heterarchical (Classes II and III). For reasons of simplicity, in the rest of this paper, the control systems proposed are called "distributed". This is obviously a restriction of the definition proposed in the beginning of this paper, since the vertical distribution is also