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Agent-based distributed manufacturing control: A state-of-the-art survey

Paulo Leitão *

Polytechnic Institute of Bragança, Quinta Sta Apolónia, Apartado 1134, 5301-857 Bragança, Portugal

A R T I C L E I N F O

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A B S T R A C T

Manufacturing has faced significant changes during the last years, namely the move from a local economy towards a global and competitive economy, with markets demanding for highly customized products of high quality at lower costs, and with short life cycles. In this environment, manufacturing enterprises, to remain competitive, must respond closely to customer demands by improving their flexibility and agility, while maintaining their productivity and quality. Dynamic response to emergence is becoming a key issue in manufacturing field because traditional manufacturing control systems are built upon rigid control architectures, which cannot respond efficiently and effectively to dynamic change. In these circumstances, the current challenge is to develop manufacturing control systems that exhibit intelligence, robustness and adaptation to the environment changes and disturbances. The introduction of multi-agent systems and holonic manufacturing systems paradigms addresses these requirements, bringing the advantages of modularity, decentralization, autonomy, scalability and re-usability. This paper surveys the literature in manufacturing control systems using distributed artificial intelligence techniques, namely multi-agent systems and holonic manufacturing systems principles. The paper also discusses the reasons for the weak adoption of these approaches by industry and points out the challenges and research opportunities for the future.

1. Introduction

The manufacturing industry is and will continue to be in the future one of the main wealth generators of the world economy (CMV, 1998). According to a report elaborated by the European Commission (EC, 2004), which makes a vision of the manufacturing sector for 2020, there are 26 millions of enterprises in the European Union (EU), being 10% related to the manufacturing domain and representing approximately 22% of the EU National Gross Product. This data reflects clearly the importance of the manufacturing activity in the world economy, and explains the attention devoted to the adequacy of methods and technologies, to improve the productivity and competitiveness vectors.

In the last decades world has moved towards a global economy, with markets demanding for products with high quality at lower costs, highly customized and with short life cycles, imposing new requirements on manufacturing enterprises, namely in terms of quality, response, agility and flexibility, that are crucial for an enterprise staying in the business. In this worldwide market competition environment, the companies can no longer be seen acting standalone, being forced to reconsider the way they are organized to increase their competitiveness. On one hand the companies tend to divide into small sub-companies, each one having a specific core business, focusing on the production of a few specialized ranges of products. On the other hand, the companies tend to share skills and knowledge, networking together to achieve global production. This situation provides the opportunity for small and medium enterprises (SME) to improve their competitiveness within the global economy, participating in supply chains or forming virtual enterprises and e-alliances to fulfill specific customer demands.

The traditional manufacturing control systems are not designed to exhibit these capabilities of responsiveness, flexibility, robustness and re-configurability, since they are built upon centralized and hierarchical control structures that present good production optimization, but a weak response to change due to the rigidity and centralization of their control structures. Such centralized hierarchical organization normally leads to situations where the whole system is shutting down by single failures at one point of the system hierarchy (Colombo et al., 2006). In these circumstances, the current challenge is to develop collaborative and reconfigurable manufacturing control systems that support efficiently small batches, product diversity, high quality and low costs, by introducing innovative characteristics of adaptation, agility and modularization. Information and communication technologies, and especially artificial intelligence techniques, have been used for more than two decades addressing this challenge. Namely, agent-based and holonic manufacturing control seem to

* Tel.: +351 273303003; fax: +351 273313051.
E-mail address: pleitao@ipb.pt

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be suitable to face these requirements, since they present decentralization of control over distributed structures, modularity, scalability, autonomy and re-usability. When properly designed and implemented, agent-based control systems result in a performance that is flexible, robust, adaptive and fully tolerant, which are key factors for manufacturing success in the increasingly global marketplace.

This paper presents the state-of-the-art in intelligent and distributed manufacturing control systems using emerging paradigms, such as multi-agent systems and holonic manufacturing systems (HMSs), and surveys the applications of agent-based manufacturing control systems, including the real implementations in industry. The objective of this paper is not to provide an exhaustive survey of the application of multi-agent systems and holonic manufacturing principles to manufacturing environment, but to focus on the manufacturing control applications. Earlier surveys of multi-agent systems for intelligent manufacturing systems (IMSs) can be found in Shen and Norrie (1999), Monostori et al. (2006), Marik and Lazansky (2007) and for the development of holonic manufacturing applications can be found in Babiceanu and Chen (2006), and McFarlane and Bussmann (2000).

This paper also tries to understand why these distributed and intelligent control solutions are not currently more adopted by industry. For this purpose, the possible reasons are identified and discussed, being the challenges and trends in agent-based manufacturing control systems pointed out to increase their performance and adoption.

The paper is organized as follows. Section 2 reviews the concepts associated with manufacturing control systems, describing the traditional approaches and the distributed and intelligent ones, namely the agent-based and holonic manufacturing control systems, which address agility, flexibility and adaptability requirements. Section 3 surveys the existing applications of multi-agent systems and HMSs in manufacturing control, and Section 4 identifies the reasons for the weak adoption of these emergent control solutions by industry. Section 5 points out the trends, challenges and research opportunities in agent-based agile manufacturing control systems. Finally, Section 6 rounds up the paper with conclusions.

2. Manufacturing control systems

Manufacturing systems involve activities related to the production of goods using manufacturing resources and knowledge, according to the external demands and subject to the environmental context, e.g. social and economic aspects. A manufacturing system is of few utility without the presence of an appropriate supervisory control system. Additionally, the confidence degree and flexibility of the manufacturing system is not only conditioned by its components (e.g. workstations, robots or conveyors) but is also dependent on the associated control system.

Diltis et al. (1991) consider four basic types of control architectures: centralized, hierarchical, modified hierarchical and heterarchical. The centralized architecture is characterized by a single decision node, where all the planning and processing information functions are concentrated (Diltis et al., 1991). This architecture presents better control optimization but some important disadvantages, in terms of speed of response, tolerance to faults and expansibility, especially for large systems. The hierarchical architecture is characterized by the existence of several control levels, allowing the distribution of decision-making among hierarchical levels, introducing better robustness, predictability and efficiency. However, the appearance of disturbances in the system reduces significantly its performance. The modified hierarchical architecture tries to improve the response to disturbances, maintaining all the features of hierarchical architecture and adding the interaction between modules at the same hierarchical level. The expansibility of the system is easier than the hierarchical architecture due to the interaction at same control level feature.

In the heterarchical architecture the client–server structure with fixed relations is no more applied (Diltis et al., 1991), allowing a high performance against disturbances, being the global optimization reduced, because the decision-making is local and autonomous, without a global view of the system. The expansibility of the system is an easier task, because it is enough to modify only the functioning of some modules or add new modules to the control system.

2.1. Traditional approach to manufacturing control problem

The manufacturing control is concerned with managing and controlling the physical activities in the factory aiming to execute the manufacturing plans, provided by the manufacturing planning activity, and to monitor the progress of the product as it is being processed, assembled, moved, and inspected in the factory. Algorithms at this level are used to decide what to produce, how much to produce, when production is to be finished, how and when to use the resources or make them available, when to release jobs into the factory, which jobs to release, job routing, and job/operation sequencing (Baker, 1998).

Due to its complexity, especially the high number of interactions between the different components and the variety of functions executed, manufacturing control systems are traditionally implemented using centralized or hierarchical control approaches, comprising, as illustrated in Fig. 1, the following main components: planning, scheduling, execution (i.e. dispatching, monitoring, diagnosis and error recovery) and machine/device control. Each one of these components operates in a specific temporal horizon, ranging from weeks at the strategic level to seconds at the shop floor.

The production plans are passed to the scheduling component by the production planning, which have a temporal horizon of days and weeks. The scheduling is concerned with the assignment of operation to resources, within a shorter temporal horizon and respecting a specific criterion, e.g. the due date or priority. Scheduling can be defined as the optimal allocation of resources over the time to jobs, where these assignments must obey to a set of constraints that reflect the temporal relationships between jobs and the capacity limitations of the resources. The manufacturing scheduling is a complex combinatorial problem, more specifically a non-polynomial (NP) problem, widely studied and reported in the literature, mainly due to its highly combinatorial aspects, its dynamic nature and its applicability in manufacturing systems (Shen and Norrie, 1998). The scheduling methods range from simple heuristics, such as earliest due date (EDD) or shortest processing time (SPT), to more elaborated computational techniques, such as constraint satisfaction techniques, neighborhood search techniques and genetic algorithms.

The execution is related to performing the final assignment of orders to the resources based on the current state of the manufacturing system and on the schedule plan. A dispatching algorithm decides how to use a manufacturing resource only upon the availability of the factory plant resources, taking into account the current status of the production system (Bauer et al., 1991). The dispatching rule determines which job a resource will work on next. This sequencing decision can be based on the job's due date, the customer priority, minimization of set-ups, the SPT, or any other possible rule or heuristic. An important aspect of the

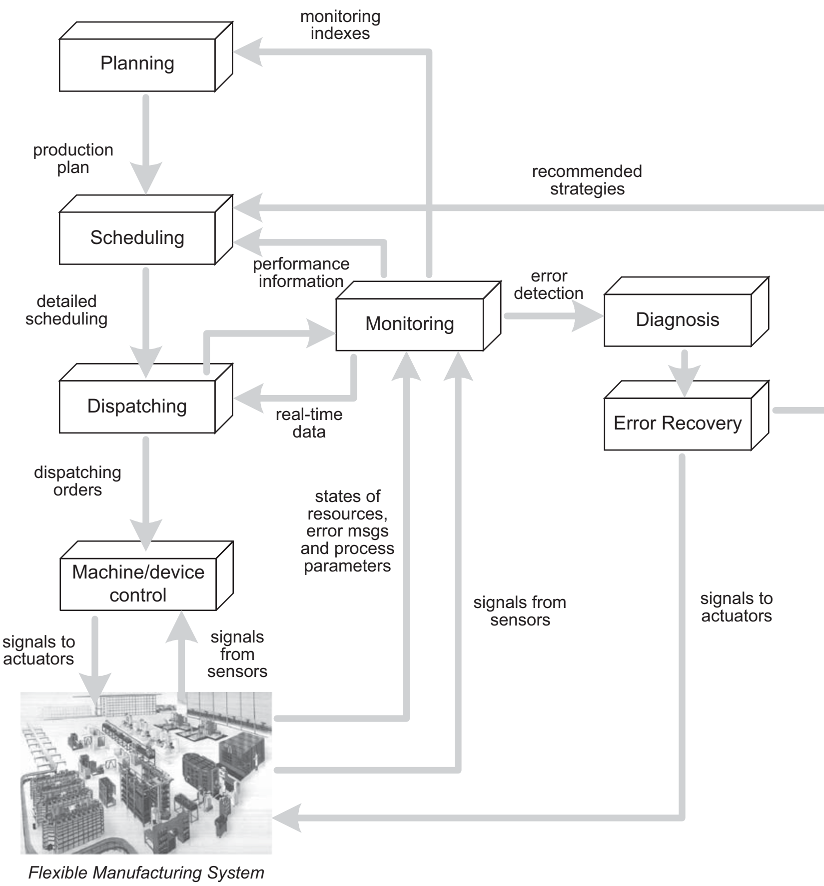

Fig. 1. Traditional approach to manufacturing control systems (adapted from MESA International, 1995 and Colombo, 1998).

factory operation is to have a detailed and up-to-minute knowledge about the work in progress and the status of the process. The execution of manufacturing plans is subjected to deviations, e.g. due to machine failures, operators' absenteeism, rush orders or parts delayed by suppliers, which implies the decrease of the system productivity. In this case, the system should respond dynamically and quickly to the disturbance, taking proper corrective actions to complete the production orders on time and to minimize the impact of the disturbances, for example by reformulating the plans or executing corrective maintenance. The monitoring component also provides information about the progress of the plans execution to the upper-level components, which can, if necessary, reformulate their plans. In case of error detection it is necessary to perform some kind of diagnostics that help to identify the source of malfunctions and unreliable operation conditions. The treatment of disturbances during the execution of the production plans makes the manufacturing control interesting and complex.

Machine/device control is the lowest level of control hierarchy and involves the initiation, coordination and monitoring of the different machine functions.

The traditional approach to manufacturing control systems based on centralized or hierarchical control structures, presents good characteristics in terms of productivity, essentially due to its intrinsic optimization capabilities. However, dynamic and adaptive response to change is, currently, the key to competitiveness, and the traditional approaches to manufacturing control typically fall into large monolithic and centralized software packages that are developed and adapted case by case, requiring a huge and expensive effort to implement, maintain or re-configure the control application. In conclusion, they are not adequate because they do not support efficiently the current requirements imposed to manufacturing systems, namely in terms of flexibility, expansibility, agility and re-configurability.

A new class of intelligent and distributed manufacturing control systems is then required to fulfill the gap left by the centralized approaches, in which (Leitão and Colombo, 2006):

- Using a distributed approach, a complex problem can be divided into several small problems, each one mapped on an intelligent building block, i.e. control unit;
- Each control unit is autonomous having its own objectives, knowledge and skills, and encapsulating intelligent functions; however, none of them has a global view of the system;
- The global control decisions (e.g. the scheduling, monitoring and diagnosis) are determined by more than one control unit, i.e. the control units need to work together, interacting in a collaborative way to reach a production decision;
- Some control units are connected to physical automation devices, such as robots and CNC machines;
- Control units should exhibit several important features such as re-configurability, robustness, plugability, learning and re-usability.

A manufacturing control system that satisfies the above requirements operates in a totally different way when compared with the traditional centralized control systems. The change from the traditional centralized approach to the new distributed and intelligent approach is illustrated in Fig. 2.

Multi-agent-based control and holonic manufacturing control are two suitable examples that address this new class of

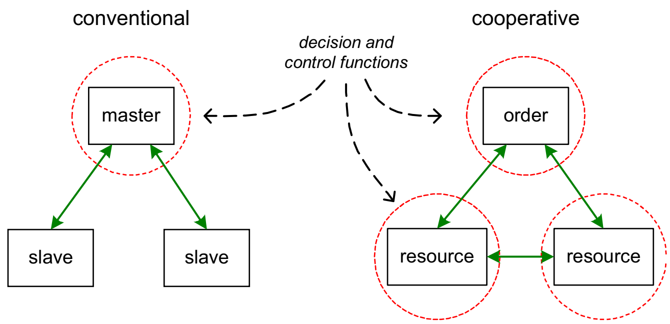

Fig. 2. Conventional and distributed approaches to decision-making (adapted from Marik and McFarlane, 2005).

distributed and intelligent manufacturing control. These paradigms, introducing artificial intelligence techniques in practice, have the capability to respond promptly and correctly to change, and differ from the conventional approaches due to their inherent capabilities to adapt to emergence without external intervention.

2.2. Agent-based manufacturing control

The multi-agent system paradigm derives from the distributed artificial intelligence (DAI) field, being characterized by decentralization and parallel execution of activities based on autonomous entities, called agents. The definition of agent concept is neither unique nor consensual (Russel and Norvig, 1995; Wooldridge and Jennings, 1995; Ferber, 1999; Wooldridge, 2002). Despite some definitions and interpretations for agents, a suitable definition is: "An autonomous component that represents physical or logical objects in the system, capable to act in order to achieve its goals, and being able to interact with other agents, when it does not possess knowledge and skills to reach alone its objectives". The most important properties of an agent are the autonomy, intelligence, adaptation and co-operation.

There are several agent architectures, ranging from reactive agents, operating in a stimulus–response manner, to deliberative agents characterized by their pro-active reasoning and goal-oriented behavior. A well-known deliberative and cognitive agent-type is belief–desire–intention (BDI) architecture, which origin lies in a theory of human practical reasoning, focusing particularly on the role of intentions in practical reasoning (Wooldridge, 2002). In the BDI agents, the decision-making depends on the manipulation of beliefs, desires and intentions of the agents. The development of reactive agents is simpler than the cognitive agents (Ferber, 1999), easier to understand and more robust and fault-tolerant than the other agent types (Nwana, 1996). However, reactive agents are incapable of foreseeing what is going to happen and thus of anticipating the future by planning what action to take (Ferber, 1999).

A multi-agent system can be defined as a set of agents that represent the objects of a system, capable of interacting, in order to achieve their individual goals, when they have not enough knowledge and/or skills to achieve individually their objectives. Agents organize themselves into a heterarchical structure characterized by the high-level of autonomy and co-operation, being the client–server structure with fixed relations no more applied (Diltis et al., 1991). These features allow a high performance against disturbances, being the global optimization reduced, because the decision-making is local and autonomous, without a global view of the system. The expansibility of the system is easier, being only enough to modify the functioning of some agents or add new agents to the control system.

Multi-agents systems allow a new approach to the problems, both in the design and implementation phases, introducing functionalities that support efficiently the distributed manufacturing system needs, such as modularity, decentralization and dynamic and complex structures characteristics, for what agents are well suited to solve (Parunak, 1998). Additionally, the required software to develop agents is shorter and simpler than the software required by the centralized approach, leading to easier development, debug and maintenance (Parunak, 1996).

In multi-agent systems, since each agent has a partial view of the system, the agents need to be able to communicate in order to achieve a pre-defined goal or solve a problem. The interaction between agents requires that the agents can understand themselves, using a proper agent communication language, ontologies and interaction protocols. In volatile and dynamic scenarios, where it is difficult to foresee future events, agents must learn to adapt their behavior to those dynamic environments, improving their performance. Learning capabilities contribute to the intelligence of an agent, by acquiring new knowledge and skills, which will be used in the future to take better decisions.

Agent-based approaches have been applied in many different areas, such as electronic commerce, e-business, air traffic control, process control and telecommunications, besides manufacturing. In fact, manufacturing, transport, telecommunications and healthcare are seen as the most significant domains for agent technology (AgentLink, 2005). In the automation and manufacturing domains, an agent can represent physical resources, such as machine tools, robots, auto-guided vehicles (AGVs) and products and logical objects, such as the schedulers and orders. Using the appropriate distributed control algorithms, individual machines and product agents can make their own manufacturing control decisions relating to resource allocation and coordination, using an automated form of "negotiation". The key benefit of such approach is that if production is disrupted or re-organized in some way, the same negotiation process still takes place, albeit with different machines or products making the decisions, and hence the system is relatively robust to change.

Fig. 3 illustrates, with a simple example, how the production control works using agents. This example comprises: (i) a part agent, running in an industrial personal computer (IPC), that is responsible for the supervision of the execution of operations in the part, (ii) three machine agents representing three computer numerical control (CNC) machines available at shop floor, running in the numerical controller of each machine and (iii) a transport agent representing an AGV and running in a programmable logic controller (PLC) and programmed using IEC61131-3 language.

Initially, the part agent queries the available agents that represent the factory resources, about who has skills and is available to execute a drilling operation in the part. Independently, each agent verifies its skills and availability, and answer to the part agent:

- The agent representing machine #1 replies the part agent saying that it cannot execute the operation since it is out of service.
- The agent representing machine #2 replies the part agent saying that it is overloaded.
- The agent representing machine #3 answers positively to the announcement.

At the end of the negotiation, the part agent allocates the drilling operation to the machine #3, and then negotiates with the transporter agent(s), the transportation of the part to the physical location of machine #3. It is important to notice that the control system, in the illustrated example, is independent of the number

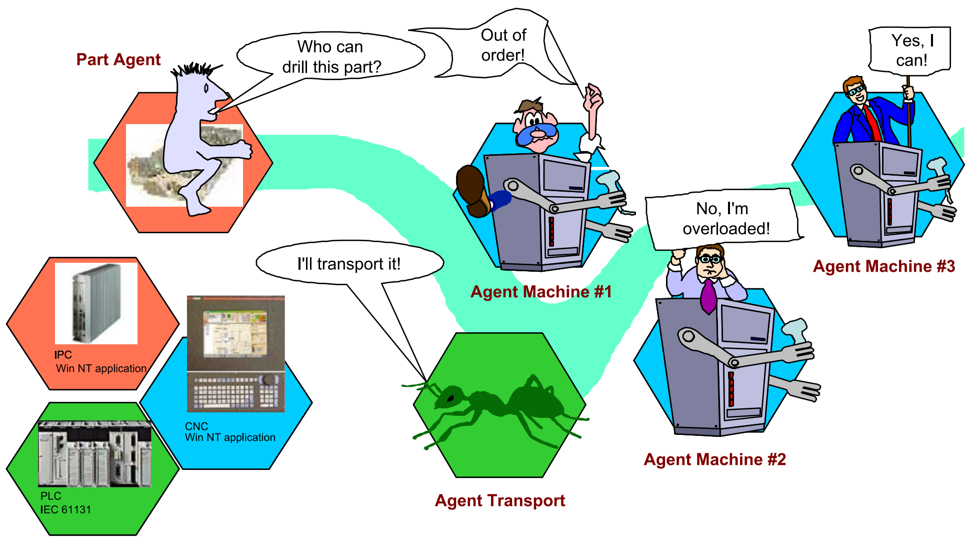

Fig. 3. Application of industrial agents in manufacturing control (Colombo, 2005).

of machines in the system, as well it does not "feel" the introduction of new machines or the remotion of machines. Additionally, the agents representing the several machines were developed using the same "piece of software", being customized for each machine according to its type, skills and behavior.

2.3. Holonic manufacturing control

To face the requirements of operating on a global scale and to meet the needs of an ever more demanding consumer market, an international collaborative research program in manufacturing, called IMS, was started in the beginning of nineties. Within the IMS programme, several paradigms for the factory of the future were developed, such as holonic, bionic and fractal manufacturing systems. These theories present similar concepts and characteristics but with different origins: mathematics for the fractal factory (Warneke, 1993), nature for bionic manufacturing systems (Okino, 1993) and social organizations for HMSs (Brussel et al., 1998). These paradigms suggest the idea that manufacturing systems will continue to need a hierarchical structure besides the increased autonomy assigned to individual entities. They also advise that hierarchy is needed in order to guarantee the inter-entities conflict resolution and to maintain the overall system coherence and objectivity resulting from the individual and autonomous attitude of the entities (Sousa et al., 1999). In spite of the similarity of concepts and characteristics, these paradigms emphasize a different set of issues and characteristics, as reviewed by Tharumarajah et al. (1996).

The HMS is a paradigm that translates into the manufacturing world the concepts developed by Arthur Koestler to living organisms and social organizations. In middle of sixties, Koestler introduced the word holon to describe the basic unit of organization in living organisms and social organizations, based on Herbert Simon theories and on his observations (Koestler, 1969). Simon observed that complex systems are hierarchical systems formed by intermediate stable forms, which do not exist as auto-sufficient and non-interactive elements but, on the contrary, they are simultaneously a part and a whole. Koestler concluded that parts and wholes do not exist in domain of life, and proposed the word holon to represent this hybrid nature, being a combination of the Greek word holos, which means whole, and the suffix on, which means particle. Koestler (1969) also identified two important characteristics of a holon:

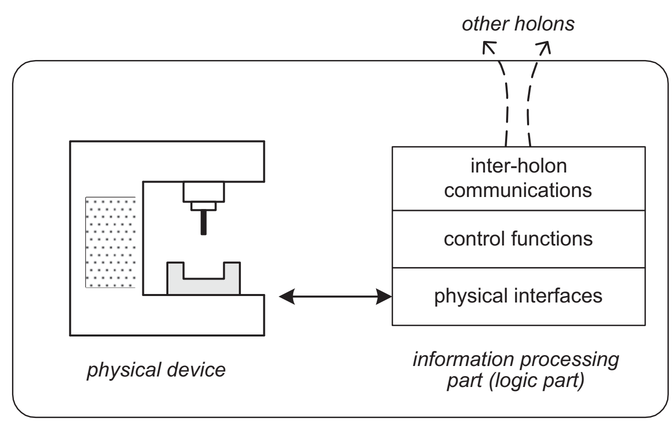

Fig. 4. A physical holon.

- *Autonomy*, where the stability of the holons result from their ability to act autonomously in case of unpredictable circumstances;
- *Co-operation*, which is the ability to have holons cooperating, transforming these holons into effective components of bigger wholes.

A holon can represent a physical or logical activity, such as a robot, a machine, an order, a flexible manufacturing system or even an human operator. The holon has information about itself and the environment, containing an information processing part and a physical processing part when the holon represents a physical device (Winkler and Mey, 1994), such as an industrial robot, as illustrated in Fig. 4.

A holarchy is defined as a system of holons, organized in a hierarchical structure, cooperating to achieve the system goals, by combining their individual skills and knowledge. Each holarchy has fixed rules and directives, and a holon can dynamically belong to multiple holarchies at the same time, which is an important difference to the traditional concept of hierarchies. The holons can integrate themselves into a holarchy and, at the same time, to preserve their autonomy and individuality.

A HMS is a holarchy that integrates the entire range of manufacturing activities from order booking through design, production and marketing to realize the agile manufacturing enterprise (Christensen, 1994). In HMS, the holon's behaviors and activities are determined through co-operation with other holons, as opposed to being determined by a centralized mechanism. Applying these concepts, HMS can be used to implement control structures that combine the advantages of hierarchical and heterarchical approaches, showing the reactivity against disturbances presented in heterarchical control, and the high and predictable performance presented in hierarchical control (Bongaerts, 1998).

According to the Janus effect, i.e. that holons combine the whole and the part, being simultaneously self-contained wholes to their subordinated parts and dependent parts when seen from higher levels, it is possible to decompose a holon into several others holons, which in turn can be broken into further holons, allowing the reduction of the problem complexity. This feature allows the structural development of production control systems through the encapsulation of manufacturing functions and components.

The implementation of the holonic manufacturing concepts can be done using the agent technology, which is appropriate to implement modularity, decentralization, reuse and complex structures characteristics. The use of agent technology addresses mainly the high-level of abstraction (Marík et al., 2002), as illustrated in Fig. 5.

At the lowest real-time control level, the interconnection with physical devices is required, making it able to read data from sensors and to send actions to actuators. Currently, the lowest real-time control is usually carried out by industrial PLCs running in a classical scan-based manner that ensures the real-time responsiveness of the control system and provides natural I/O connectivity to the real manufacturing process. The control programs here are developed using IEC 61131-3 standard programming languages, particularly the ladder logic. A possible alternative is to use the IEC 61499 function blocks standard that is an extension of the IEC 61131-3 function block diagrams. IEC 61499 defines a new way to model the control and execution of algorithms in distributed control systems, by encapsulating and reusing software modules (Lewis, 2001).

2.4. Comparative analysis

Agent-based and holonic manufacturing paradigms were developed under the same fundamental principles of autonomy and co-operation, exploring the distribution and decentralization of entities and functions. Although the similarity of the holon and agent concepts, some discussion is carried out to identify their differences, such as that described in Marík et al. (2002). Three main distinctions are identified.

In terms of origin, the agents have their roots in the computer science (namely the artificial intelligence area) and the holons in the computer integrated manufacturing (CIM) domain, focusing on the problems associated with the flexible manufacturing systems. In conceptual terms, the holon is a concept and an agent is both a concept and a technology, being possible to implement the holon concept and HMSs using agent technology. Exploring the principle that a holon can represent simultaneously a whole and a part of the whole, the holon can be composed by several lower-level holons, in contrast with an agent. In terms of modeling, agents normally represent software components and the focus is not the integration of physical devices. In the manufacturing world this issue is critical and the holon concept supports the integration of physical devices, based on the feature that a holon comprises logical and physical components. As well, an agent cannot guarantee the real-time constraints, while the holons must meet the hard real-time constraints required to achieve reliable system operation. Summarizing, a holon can be seen as a reactive agent that operates under hard real-time constraints and has connection with physical devices.

The application of multi-agent systems and/or HMSs in the development of manufacturing control systems provides several important benefits, namely robustness, re-configurability and

Table 1
Comparison between traditional and distributed approaches

Traditional control solution (e.g. CIM)	Distributed and intelligent control solution (e.g. agent-based and HMS)
Centralized solution for each individual control function	Distributed solution with cooperation between nodes and focusing on more than one control function
Rigid and static architecture	Flexible, programmable and dynamic architecture
Client–server relations	Holon–holon relations
Top-down approach	Bottom-up approach
Communications one for many (1-N)	Communications many for many (N–M)
Intelligence centered in the top levels	Intelligence distributed by the control levels
Efficiency through the specialization	Efficiency through the flexibility
Weak response to disturbances	High response to disturbances
Operators are replaced by automation technologies (removed from production process)	Operators are complemented with automation technologies (increasing the skills of the operators that stay in the production process)
More efficient for high volume and low variability	More adequate for high–low volume and medium–high variability

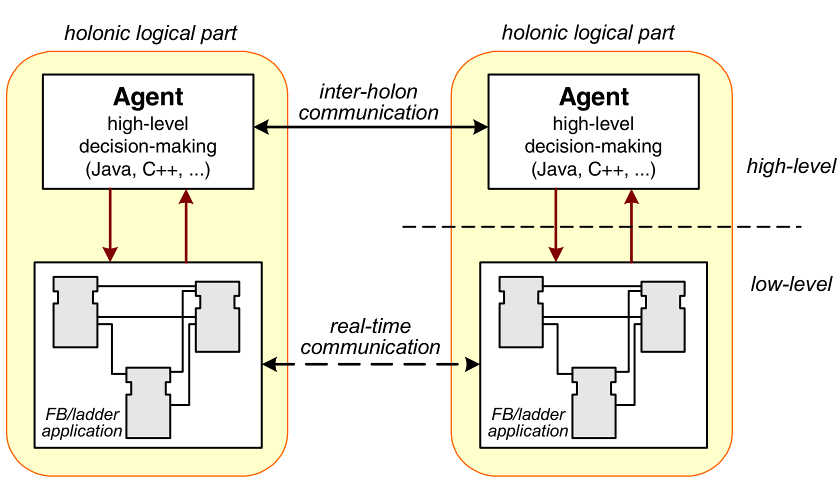

Fig. 5. Decision-making levels in the holonic logic part (adapted from Marik and McFarlane, 2005).

re-usability. Table 1 summarizes some fundamental differences between distributed and intelligent approaches and conventional centralized and top-down approaches for manufacturing control systems (e.g. CIM).

HMS systems are not based on centralized and rigid hierarchies, presenting among others, better re-configurability and agility, and provide a bottom-up approach, because the manufacturing control is developed through the integration of autonomous manufacturing components, the agents or holons, which contrast with the conventional top-down approach, characterized by the centralization of the planning, scheduling and control functions.

Using a distributed approach, a complex control problem can be divided into several smaller simple problems, being each control unit self-contained, possessing its goals, skills, knowledge and a set of rules that regulates its behavior. In this way, the control system is developed using a bottom-up approach, being simplified when compared with traditional approaches that use centralized and hierarchical architectures, leading also to a better simplicity in the debug and maintenance of the system. In this type of approach, it is necessary to develop independently each component of the control system and the interaction between them.

The robustness of the control system is essentially achieved since this approach does not consider a central decision element, which means that the loss of one decision component will not cause any fatal failure of any other decision component. In fact, if the production is dismembered or re-organized, the same negotiation process continues to be executed, in spite of the presence of different machines and products, making the system robust to the change. Consequently, the treatment of disturbances only requires a change in a production plan or schedule through a dynamic re-scheduling mechanism, without stopping or re-initializing the process.

Agent-based and HMSs are pluggable systems, allowing changes in production facility, e.g. the addition, remotion and modification of hardware equipment as well as software modules, on the fly, without the need to stop, reprogram and re-initialize the system. This feature is crucial to support the current requirements imposed by customized demanding, allowing the dynamic system re-configurability to face the variability of the demand. The migration or update of old technologies or systems by new ones can also be performed in a smooth way without the need to stop the system (Marik and McFarlane, 2005).

Using the emergent approaches, new control systems can be developed by reusing previous agent-based solutions or components. As well, individual control components can be re-used to develop other individual control components, or to deploy a holon class in several tens or hundreds of holons instances (e.g., a resource holon class can be used to represent all resource components of the factory, being only necessary to customize each instance). Additionally, the same agent-based approach can be applied on different control levels, i.e. real-time control, production planning and scheduling and networked enterprises.

3. Survey of agent-based manufacturing control approaches

The application of multi-agent systems and HMSs in manufacturing domain, as described in previous section, allows the development of modular and distributed applications to support the manufacturing systems complexity, flexibility and re-configurability. Interesting issues are the application of emergent theories to several manufacturing applications domains, ranging from enterprise integration, to manufacturing scheduling and control, passing by materials handling, machine controllers and assembly systems. This section surveys the literature concerning on applying multi-agent systems and HMSs to develop reconfigurable manufacturing control systems.

3.1. Architectures and approaches

Duffie and Piper (1986) were the first ones to discuss and to introduce the heterarchical control approach, using agents to represent physical resources, parts and human operators, and implementing scheduling oriented to the parts. CORTES (Sadeh and Fox, 1989) uses micro-opportunistic techniques to solve the scheduling problems and Constrained Heuristic Search techniques for the decision-making related to the scheduling. The agents execute scheduling and monitoring for a set of resources. The IFCF (Lin and Solberg, 1992) uses a market-based control model to implement resource allocation and distributed scheduling. The market-based mechanism uses multiple step negotiation, allowing the real-time coordination of agents. The agents represent physical resources, parts, databases and communication processes.

Yet another manufacturing system (YAMS) (Parunak, 1998) applies a contract net technique to a hierarchical model of manufacturing system, including agents to represent the shop floor. The autonomous agents at Rock Island Arsenal (AARIA) intends to control a production system to fulfill incoming tasks in due time, focusing on the dynamic scheduling, dynamic reconfiguration and in the control of manufacturing systems that fulfill the deliver dates (Parunak et al., 1998). The manufacturing resources, process and operations are encapsulated as agents using an autonomous agent approach.

Holonic or agent-based scheduling differs from the traditional scheduling in terms of the distribution of the computation and decision-making functions, bringing benefits in terms of reaction to disturbances and the parallel computation. Here the dominant interchange mechanism used to support distributed problem solving is the Contract Net Protocol (Smith, 1980). Sousa and Ramos (1999) propose a dynamic scheduling system supported by a holonic approach, using forward and backward influence in the negotiation leading to the task allocation, to handle the temporal constraints and to solve conflicts. The architecture is composed by holons to represent resources, tasks, planning systems, etc. Gou et al. (1998) define a scheduling algorithm based on Lagrange relaxation concepts. It requires a centralized coordination that guides the individual holons to improve their schedule. Markus et al. (1996) proposed a market model to solve dynamic order processing and scheduling problems, such as conflicts between local scheduling agents, resolved by negotiation simple terms of tasks, due dates and prices. Heikkilä et al. (1997) proposed a holonic approach for manufacturing scheduling and control in a manufacturing cell. Sugimura et al. (1996) modelled the manufacturing operations using an object-oriented approach and propose a real-time scheduling mechanism for assembly lines. Cheung et al. (2000) describes a holonic system where series of prototype holons are implemented for real-time scheduling tasks in an existing FMS. The ADDYMS (Butler and Ohtsubo, 1992) developed a dynamic scheduling mechanism for local resource allocation at the local work-cell level, using agents to represent physical resources.

The product-resource-order-staff architecture (PROSA) (Brussel et al., 1998) is a holonic reference architecture for manufacturing systems, which uses holons to represent products, resources, orders and logical activities. This architecture is based on three types of basic holons: product, order and resource. The resource holon contains the resource and an information processing part that controls the resource. The product holon holds the process and product knowledge, and contains all information about the product. The order holon represents the tasks in manufacturing systems. Additionally, the architecture defines staff holons, whose mission is to assist and advise the basic other holons.

Under the MASCADA project, manufacturing control mechanisms were developed to support the production change and disturbance, safeguarding and/or maximizing the production systems throughput, where the disturbances reduce the effectiveness of the plans/schedules that are generated initially (Valckenaers et al., 1999). The approach uses a pro-active disturbance handling mechanism and uses autonomous and intelligent agents to represent the factory components. Bruckner et al. (1998) described the application of a PROSA-based system, developed under the MASCADA project, in a car body painting at the Daimler–Benz plant in Sindelfingen, Germany. Liu et al. (2000) used the PROSA reference architecture to develop a control architecture for an AGV system capable of being robust in the presence of disturbances. A PROSA-based agent system for production control of semiconductor wafer fabrication facilities entitled FABMAS is reported by Monch et al. (2003), where the agents represents work cells, work areas, lots and tools. The discrete event simulator AutoSched AP is used to simulate the behavior of the wafer fabrication shop floor.

MetaMorph (Maturana and Norrie, 1996) uses an agent federation centered in the mediator approach, supporting the change of form, structure and activity, in order to adapt dynamically to emerging tasks and environment change. Agents represent manufacturing devices and products, and the mediators are used to coordinate the interactions between agents. The approach supports dynamic clustering and cloning, and learning. Tönshoff and Winkler (1996) introduced the holonic concepts for the shop floor control and Chirn and McFarlane (2000) presented a specific holonic control system architecture, holonic component-based architecture (HCBA), introducing resource and product holons, to enable a smooth migration between the available standard control hardware and the system needed to implement holonic control.

The ADACOR (ADAptive holonic COntrol aRchitecture for distributed manufacturing systems) (Leitão and Restivo, 2006) holonic manufacturing control architecture addresses the agile reaction to emergence and change, increasing the agility and flexibility of the enterprise when it works in volatile environments, characterized by the frequent occurrence of disturbances. For this purpose, it introduces an adaptive control approach that evolves in time to combine the global production optimization with the agile reaction to disturbances, being the supervisor entities and the self-organization and learning capabilities associated to the holons, the key roles to support the dynamic evolution and reconfiguration of the organizational control structure.

Brennan et al. (1997) used a hybrid control architecture, designated by partial dynamic control hierarchy (PDCH), combining the hierarchical and heterarchical approaches, for manufacturing control. Later, PDCH was used with IEC 61499 function block model to achieve a general approach for dynamic and intelligent reconfiguration of real-time distributed manufacturing control systems (Brennan et al., 2002). The IntaPS project (Denkena et al., 2002) presents an approach for integrated process planning and production control, which architecture consists of two main components, which link information systems of earlier stages of product development and the resources on the shop floor. This link is realized by decentralized planning on shop floor level and by rough level process planning. Fisher (1999) uses a holonic approach for planning and control, built upon the Integration of Reactive behaviour and Rational Planning (InteRRap) hybrid agent architecture (Müller, 1996), consisting of production planning and control, shop floor control system, flexible cell control, autonomous systems and machine controller levels. The architecture uses agents to represent holonic manufacturing components, forming a multi-agent system organized in a hierarchical structure based on rules. Monostori and Kadar (1999) proposed a holonification approach of existing resources by incorporating control units for each resource and Shen et al. (2005) introduced the iShopFloor concept that focuses the implementation of distributed intelligence in the manufacturing shop floor, using intelligent agents, specifically to achieve distributed manufacturing scheduling.

Wullink et al. (2002) introduced the Engineer-to-order Planning (EtoPlan) that is a holonic architecture for manufacturing planning and control that aims to deal with large amounts of uncertainty caused by incomplete and unreliable information. The PABADIS (Sauter and Massotte, 2001) uses the concept of co-operative manufacturing units (CMUs) to provide significant functions to the production process in automation control, encapsulating residential, products and shop floor management as agents. The approach comprises centralized (for the connection with enterprise resource planning (ERP) systems) and decentralized components, being the products implemented using the mobile agent technology.

Heragu et al. (2002) presented a hybrid manufacturing control architecture, i.e. somewhere between the hierarchical and heterarchical control approaches. It defines three levels of agents: higher level with agents elaborating optimal schedules, lower level with agents responding for the individual schedules, and intermediate agents acting as coordinator of actions of lower agents. This holonic schedule and control architecture was applied in an industrial automated warehouse system for order picking and replenishing. Babiceanu et al. (2004) present a holonic control architecture for automated material handling systems that addresses reliability, real-time scheduling, fault-tolerance and material handling hardware re-configurability. Vrba and Marik (2005) described an agent-based simulation environment manufacturing agent simulation tool (MAST) for the transportation of work-pieces among different manufacturing cells using AGVs, providing the opportunity to reuse the simulation software directly on the agent control level. The platform was implemented in Java on the top of JADE and includes a library of agents representing the basic material handling components like sensors, conveyors, diverters and work cells.

McFarlane et al. (1995) apply holonic control to continuous processes such as steel manufacturing, and Albadawi et al. (2006) described the implementation of an agent-based control architectures in two manufacturing process systems, namely a linear, tuneable model for the plastic thermoforming process, and a non-linear, mathematical and rule-based model for the metal powder grinding process. In the machine controller domain, Tanaya et al. (1997) apply holonic concepts in the development of machine controllers, which are more flexible and open than traditional NC technology. This holonic behavior is supported by advanced planning, execution and monitoring actions. Barata and Camarinha-Matos (2003) focused on the shop floor re-engineering, using agents to represent the physical components which are aggregated into consortia regulated by contracts, achieving agility in the shop floor life-cycle and Lastra (2004) proposes the actor-based assembly system (ABAS) architecture to develop reconfigurable assembly systems in a easy way. Paolucci and Sacile (2005) presented PS-Bikes as a case study of a multi-agent control system for manufacturing of custom bikes using JADE framework.

Self-organization techniques have been inspiring the development of agent-based control solutions. In this field, Hadeli et al. (2004) proposes a self-organization-based coordination and control approach that uses stimergy for the communication among agents and Ueda et al. (2001) use attraction–repulsion fields to implement a production control system based on self-organization principles.

3.2. Industrial implementations

In spite of all the research described above, only few industrial/laboratorial applications were developed and reported in the literature.

Bussmann et al. (2004) and Schild and Bussmann (2007) use agent technology to design a flexible and robust production system for large series manufacturing that meet rapidly changing operations, designated by Production 2000+, in a factory plant of DaimlerChrysler, producing cylinder heads for four-cylinder diesel engines (used in the Mercedes Benz C and E class 220 CDI). The approach uses agents to represent machines and work-pieces, implementing a dynamic resource allocation, similar to the Contract Net Protocol (Smith, 1980), with the objective of continuous optimization of the throughput. The agent-based control system allows individual work-pieces to be directed dynamically around the production area, by auction off the processing steps that are due first. The built-in redundancy gives the possibility of diverting product to another machine if a breakdown or unavailability occurs. This system was probably the first full-scale industrial agent-based production system that has been brought into operation and the result was a 20% increase in productivity on average (AgentLink, 2005). The resulting prototype system was in day-to-day operation for five years up to the end of the life-cycle of the targeted product.

Schneider Electric GmbH in co-operation with DaimlerChrysler AG-Research and Technology had developed and implemented a heterogeneous agent-oriented collaborative control system, called FactoryBroker™, adequate to control widely distributed and heterogeneous devices in environments that are prone to disruptions and where hard real-time constraints are crucial (Colombo et al., 2006).

Another example of agent-based control systems is the Holomobiles (Bussmann and Sieverding, 2001) that introduced a new holonic control approach for an assembly system in the automotive industry, namely for assembling engines, which resulted in more robustness and scalability. Holomobiles implemented a control holon for each docking station, engine buffer, machine station and AGV. It uses, as the P2000+ control system, a Contract Net Protocol to request resources, such as machine stations or AGVs. In spite of sharing common aspects with the P2000+ control system, they present significant differences in terms of system design (Bussmann et al., 2004), namely derived from the nature of the production processes (the production of cylinder heads is different from the assembly of engines) and the requirements expected for each production process (flexibility and robustness for the P2000+ system and robustness and scalability for the Holomobiles system).

Maturana et al. (2004) developed an agent-based control system for the chilled-water systems and the heating, ventilation and air-conditioned (HVAC) systems of the US Navy ships. The approach is developed according to the foundation of intelligent physical agents (FIPA) specifications and uses dynamic decision-making organizations based on agents to plan, commit and execute control tasks. The intelligent agents are used to represent physical devices, such as valves, T-pipe, cooling plants, water services and heat loads, and to represent specific ship functions, corresponding to the ship, chilled-water, power, material handling, heat and ventilation, and combat sub-systems. The agents reside on the PLC controller or on separate hardware, and can contact any device in the network via a job description language (JDL) message. The JDL represents planning, commitment and execution phases during the task negotiation, being used the Contract Net Protocol to establish dynamic negotiations among the agents. Initially, the automation presented in the real ship was simulated in the laboratory using MATLAB/Simulink and then implemented using physical equipment and controllers.

Fletcher et al. (2003) described the implementation of a holonic packing cell at the assembly cell of University of Cambridge, using the JACK Intelligent Agents™ platform. In this application, the holonic control system is responsible to assembly Gillete™ packages into customer-tailored gift boxes. The boxes are packed by two Fanuc M6i robots and the test bed integrates a storage system and a conveyor system. The approach considers order holons and resource holons that represent the physical components of the system. The designed agent-based system integrates radio frequency identifier (RFID) technology, by using electronic tags embedded in discrete units, replacing the traditional barcodes. This automatic identification allows to uniquely identify goods, thereby enabling decisions to be made by the order holons representing them.

4. Why these approaches are not fully adopted by industry?

In spite of the promising perspective of these emergent distributed and intelligent approaches, until now the industrial applications of control systems developed in the context of reconfigurable manufacturing systems are extremely rare and the implemented functionalities are normally restrict, being very slow the adoption of these concepts by industry, as identified by Marik and McFarlane (2005) and analyzed in the previous section. This means that real proofs about the applicability of these approaches and technologies in real industrial automation environments are missing. The pertinent question that arises is why these emergent approaches, such as HMSs and agent-based manufacturing, are not adopted by industry?

The answer is not clear and unique, but some barriers to the large-scale dissemination in industrial environments can be identified and discussed. Two groups of reasons can be identified: conceptual efficiency in the paradigms and development-related aspects.

4.1. Conceptual efficiency in the paradigms

One of the main barriers is related to the required investment to implement these emergent control approaches, which is much higher than that required to implement centralized solutions. This is mainly because the distributed and intelligent control approaches are raised in case of flexible and even redundant automation systems. Another related problem, as Hall et al. (2005) note, is the demand of customers and industry for proven technology without wanting to be the first to try it in their production processes. This requires the maturity of the technology and the proofs of its real applicability and merits. Additionally, industry is afraid of the usage of emergent terminology usually associated to these new technologies, like ontologies, self-organization, emergence, distributed thinking and learning.

In spite of these emergent theories being of distributed and modularized nature, the implemented systems became more hierarchical than a real distributed one. Namely, aiming to introduce coordination or global optimization in the system, purely distributed and decentralized solutions are rare to be found in research literature or industrial implementations. The use of these emergent distributed approaches requires a new way of thinking and approaching the problems, which is in some situations difficult to apprehend and develop. The design of such distributed systems may require high complexity of the system due to the high degree of interactions involved. The missing central component also causes some obstacles to the acceptance of these concepts by enterprise managers and directors.

Current approaches design simple reconfiguration mechanisms, normally focusing on the design phase, that are not flexible enough to replace manually reconfigurable systems. More complex and powerful reconfiguration methods are required, embodying learning and self-organization capabilities in distributed entities and also designing distributed control based on swarm intelligence theories. A step ahead is the application of evolution mechanisms that allows a system to evolve into new control structures adapting its behavior to the environmental conditions.

Interoperability is a crucial factor in the development of distributed and heterogeneous production control applications. The solution to those problems requires the use of standard platforms that support transparent communication between distributed control components or applications. Ontologies play a decisive role to support interoperability problems. However, the development of an ontology may take from a few hours up to months or even years depending on the choice of the language, the covered topics, and the level of formality and precision (Borgo and Leitão, 2006). The ontologies used in industrial applications are usually proprietary, very simple and just hierarchical structures of concepts. Even the FIPA specifications do not support the complete interoperability. Additionally, the definition of common ontologies for a specific domain is not an easy job: people with different background have different points of view over the same domain concepts.

The majority of agent-based laboratorial control applications use software agents without the need of integration of physical devices (e.g. in the supply chain case) or emulators of the physical devices when they are needed (e.g., in the manufacturing control systems). But in the reality, industrial applications require the integration of physical automation devices (normally tens or hundreds) with the software control system. The missing methodologies to support an easy, fast, transparent and re-usable integration of physical automation devices, is a barrier to the bigger industrial dissemination of these concepts. The heterogeneity of the automation devices, each one having particular and specific characteristics and providing a particularly set of services, increases the effort of integration.

4.2. Development-related aspects

The design and implementation of reconfigurable production systems and their supervisory control systems are complex tasks, requiring a formal specification methodology that formalizes the structure and the behavior of these kinds of systems, aiming to simplify their understanding and synthesis. This issue assumes a critical role, with little attention devoted to it within the agent and holonic communities. Additionally, there is an absence of industrial controllers with multi-agent systems capabilities to enable the agents running directly on controllers in parallel with the low-level control programs and not separately on a PC as it is usual today. This fact establishes a barrier for the real deployment of agent-based control systems on the factory floor and consequently a bigger industrial applicability of these concepts.

The developed laboratorial prototypes, reported in the literature, handle with dozens or hundreds of agents, but industrial applications usually require the running of thousands of agents. At the moment, current platforms cannot handle this scalability problem with the robustness required by the industry (Marik and McFarlane, 2005).

The HMSs support the fine granularity of the system, mainly due to the hybrid nature of its components, the holons. Being a holon a representation of the whole and the part, complex systems can be designed from coarse granularity to fine granularity by embedding holons within other holons. As an example, a flexible manufacturing system can be a holon that is part of a factory plant, and simultaneously the whole of a set of other holons, each one representing a physical machine. Unfortunately, this feature is not currently exploited in the development and implementation of holonic control systems.

Another important aspect that contributes to the weak adoption is that agent-based and HMSs are frequently referred as performing well in presence of disturbances but little evidence of that is reported in the literature. The evaluation and comparison of manufacturing control systems performance requires frameworks that define benchmark scenarios and normalized performance indicators, decoupling the control system performance from the performance of the other components of the manufacturing system, and from the particular implementation of the architecture concepts.

5. Trends, challenges and research opportunities

Several topics remain open and unanswered in agent-based manufacturing control and could be researched in the future as well as new and promising research windows will open related to this research domain. Naturally, some research perspectives can be found to solve the missing points referred in the previous section and which constitutes the barriers for the wide and large adoption of these concepts by the industry. This section intends to give a bird's-eye view of trends and challenges in agent-based agile manufacturing control systems, pointing out some guidelines that will characterize how manufacturing control systems will behave in the future and discussing research opportunities to improve these systems.

5.1. Re-configurability mechanisms

The demand for intelligent, distributed control systems that exhibit high degree of re-configurability and agility will obviously impose strong requirements on the way the systems are designed, installed, operated and reengineered. These requirements will not only have impact on the individual control architecture of the distributed entities but also, even more crucially, on how the system is developed, and what kind of architecture will support the society of distributed entities. Needless to say, current approaches being applied within the reconfiguration domain will not suffice. Indeed, in spite of the success of some agent-based and holonic approaches, a significant inroad in manufacturing plants in use today is still missing, as previously described. In this scenario, there is still a long way to go in the direction of new, reconfigurable and ubiquitous systems, able to integrate networked production resources to respond to the variability of production scenarios beyond those that were envisaged at design time. Self-organization and emergent behavior will be key issues to support the new generation of reconfigurable production control systems, being this dynamic and evolvable reconfiguration one step ahead of traditional re-configurability, considering also the evolution nature of the system and its components.

The achievement of dynamic evolution and reconfiguration requires the introduction of self-organization mechanisms associated with emergent behaviors that support the evolution and reconfiguration of the system based on the self-organization of each individual control component. The reconfiguration of the control system should be done on fly, maintaining unchanged the behavior of the entire system which should continue to run smoothly after the change. Additionally, it should appear to users like ''drag-and-drop'' applications where complexity and details are hidden.

An important question in reconfigurable and evolvable manufacturing systems is related to how should the production control structure evolve to adapt to change by identifying reconfiguration and evolution opportunities, while maintaining system behavior predictable and stable. Emergence can be mapped onto the evolution of the society of agents when identifying reconfiguration opportunities and defining new complex functionalities and behavior. The introduction of learning mechanisms may support the dynamic evolution of the system allowing the evolution of the functionalities and behavior of individual control components and consequently the evolution of entire system. Indeed, learning mechanisms strongly influence the performance of the self-organization mechanism, being critical to support the identification of reconfiguration opportunities. During the reconfiguration process, some instability can appear as the result of not properly synchronized evolution processes. This implies the need to build up the reconfigurable production system from simple to self-organized and emergent reconfiguration.

5.2. Design methodologies and technologies

Currently, no structured and mature enough development methodology or tool is used in industrial practice for the agent-based control systems specification, design, verification, implementation and commissioning, as well as for reuse or reconfiguration of automation solution. The reason for this absence is the lack of proper reference models for control systems architectures, of suitable formal analysis or simulation -based verification techniques and of effectively real-time automatic code generation methods. Consequently, automation components are usually developed starting from simple graphical specifications and leaving most of the work to the control code developers, which basically only take care of the implementation details. A major drawback of this approach is that the final control solution needs a great effort in the commissioning phase (even two times the development effort!), that reliability and performance are reduced, and that the developed automation solutions are hardly reusable and reconfigurable (Leitão and Colombo, 2006). So, an important challenge is to develop formal and structured methodologies that will support the specification, design, verification and implementation of agent-based manufacturing control applications.

At last, since the agent technology is a suitable approach for the implementation of holonic and reconfigurable manufacturing control applications (and at the moment the only way to implement it) and FIPA specifications are commonly used, future research work should consider the inclusion of specific requirements to the manufacturing control systems in FIPA specifications. Examples of these specific requirements are the no preemption of operations, the event notification, the unsubscription of services, the appropriate protocols for manufacturing domain and mechanisms.

5.3. Integration of paradigms

As previously referred, multi-agent systems alone cannot solve all challenges introduced by the demand of reconfigurable production systems. In this way, agent technology must be integrated with other technologies, such as web-based technologies (including web services and Semantic Web) and grid computing for its wide and successful applications in industry in a near future (Shen et al., 2006).

A current challenge is to combine multi-agent systems with service-oriented architectures (SOA) (Jammes and Smit, 2005; Lastra and Delamer, 2006). The use of standard and open protocols, namely web technologies, e.g. web services, provides a communication platform between distributed and heterogeneous systems and applications. In such service-oriented control architectures, manufacturing resources (e.g. physical devices, software modules, intelligent units, sub-systems) provide services that encapsulate its internal behavior. The control is achieved by orchestrating the services according to a logic behavior model, providing a high-level interface for the composed process.

An unanswered problem in multi-agent systems is related to interoperability in heterogeneous environment. This requires significant efforts from the community of researchers in the area of agent-based industrial systems to develop interoperable knowledge-based systems. Semantics and ontologies seem to be the answer to this challenge. The Semantic Web is based on the idea that the data on the web can be defined and linked in such a way that it can be used for the automatic processing and integration of data by the intelligent agents (AgentLink, 2005). The Semantic Web aims to provide a common framework that would support programs to share, reuse and process data on the web, particularly when they have been designed independently.

The integration with the IEC 61499 function blocks standard (Lewis, 2001), which is a powerful modeling approach in the distributed industrial process control field, seems a suitable solution to develop agent-based real-time and distributed control application. However, in spite of the significant progress in the application of the IEC 61499 function blocks standard, at the moment, none of the major PLC vendors offer design tools and runtime support for the deployment of IEC 61499 function blocks applications.

Aiming to meet the requirements of mobility, modularity and re-configurability, new technologies supporting nomad systems, such as wireless networks, embedded systems and RFID systems, must be able to be integrated within agent-based manufacturing control systems.

5.4. Benchmarking

At the time, in spite of some research reported in the literature, such as (Cavalieri et al., 1999; Brennan and O, 2000), and the ongoing work carried out by the special interest group on benchmarking and performance measures of on-line production scheduling systems (see http://www.ims-noe.org) of the IMS network of excellence (IMS-NoE), a benchmark environment is required to provide realistic test cases for the research community test their developed systems, allowing to evaluate and compare different production control approaches. Valckenaers et al. (2006) developed a web-based benchmarking service for manufacturing control systems that contributes to evaluate and to compare the merits, in terms of performance, efficiency, agility, etc., of different manufacturing control approaches. However, some questions remain unanswered, namely the selection of proper performance indicators, especially those that allow to evaluate qualitative indicators, definition of evaluation campaign, storage of the best practices and easy connection to this service.

5.5. Prediction in disturbance handling systems

Manufacturing systems are dynamic, non-linear and often chaotic environments, subjected to the occurrence of unexpected disturbances that leads to deviations from the initial plans and usually degrades the performance of the system. The treatment of exceptions and disturbances is one major requirement to the next generation of intelligent manufacturing control systems that should be capable to treat emergency as a normal situation. In fact, innovative agent-based disturbance handling systems should integrate prediction mechanisms within the identification, diagnosis and recover of disturbances, forecasting the occurrence of future disturbances and allowing planning in advance their occurrence, minimizing their impact when they really occur. With the increase of predictability, the disturbances left to be real disturbances and became normal situations, since it is possible to plan their occurrence instead of reacting to their occurrence. This allows transforming the traditional "fail and recover" practices into "predict and prevent" practices, and consequently improving the control system performance.

6. Conclusion

Manufacturing companies at the beginning of 21th century have to face a dynamic environment where economical, technological and customer trends change rapidly, requiring the increase of flexibility and agility to react to unexpected disturbances, maintaining the productivity and quality parameters. The traditional manufacturing control systems are adapted on a case-by-case basis, requiring an expensive and huge time-consuming effort to develop, maintain or re-configure. The missing re-configurability is derived from the lack of agility to support emergency (change and unexpected disturbances).

The challenge is thus to develop innovative, agile and reconfigurable architectures for distributed manufacturing control systems, using emergent paradigms and technologies that can provide the answer to those requirements. Multi-agent systems and HMSs are two suitable paradigms to build this new class of distributed and intelligent manufacturing control systems.

In this paper, the state-of-the-art in manufacturing control systems, especially using artificial intelligence techniques to develop it, namely multi-agent systems and HMSs, was reviewed. Several approaches and architectures reported in the literature were reviewed, as well some real implementations in industry. However, the last ones are extremely rare rising doubts of the real applicability of intelligent and distributed control approaches in manufacturing systems.

From this analysis a set of challenges and trends were pointed out, namely the design methodologies that will support the easy and integrated development of such systems, supporting technologies for its implementation and benchmark frameworks for the evaluation and comparison of different solutions.

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