Trends in Intelligent Manufacturing Systems

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Abstract—A lot of changes in the manufacturing sector will occur in the future and it is important to transform the actual production systems to evolvable production systems. Fractal, bionic and holonic manufacturing systems are three concepts that have been proposed due their characteristics of flexibility and intelligence. This generation of manufacturing systems is known as intelligent manufacturing systems (IMS).

Agent-based software is a technology that can make actions of control or supervision, endowing mechatronics devices with some intelligence. The use of multi-agent based software in operation and control of distributed systems is offering new distributed intelligent control functions (cooperation, planning, scheduling) over wired or wireless networked systems.

In this paper, underlying principles of the construction of an IMS are concisely presented.

I. INTRODUCTION

In the manufacturing sector a lot of changes in the next years will be done [1], [2], [17]. Customers participate increasingly in the production processes through the imposition of personal specifications and exigency for products with higher quality and lower sized batches and smaller delivery times. Classical systems are no longer appropriate since they are characterized by high volume and low variety of production, low flexibility and high replacements costs. To increase the competitiveness, the enterprises should reduce batches sizes, product-life cycles, delivery times and increase the product variety to answer to the consumers wills. This would make a drastic decrease of the efficiency of a classical production system. For these reasons it is important to transform actual production systems to systems more flexible and seamlessly reconfigurable to respond the product changes and more robustness with respect to disturbances to maximize the total use of the manufacturing resources. Production systems with evolvable characteristics like modularity, standardization of electric and mechanic interfaces or open control structures that allow “plug and work” are essential to answer the needs of this new reality [26], [27].

The traditional computer integrated manufacturing (CIM) is a concept created to deal with this new challenges, including lack of flexibility and integration [5]. It’s a concept that typically involves not only the aspects related with the production activities but also sales, stocks and personal administration.

CIM is the designation used to describe the complete automation of the factory by integration of business and manufacturing functions through application of technology. All of the processes and activities are controlled in a hierarchy of computer systems and the information that circulates is exclusively in the digital form. However the planning and scheduling of tasks are centralized, and the production are almost sequential. A CIM system implicates high investments, long lead times and complex structures that can take us to the generation of rigid systems [14], [16]. Loss of flexibility and reconfiguration capabilities in dynamic environments are some of the aspects that put problems to the progress of enterprises and a small change always means new and high costs.

Many concepts have been proposed to solve the problems of quick changes in producing new products with new specifications. Fractal, bionic and holonic manufacturing are three concepts frequently referred and studied as the new generation of manufacturing systems [10], [11], [14], [15], [18]. This generation of manufacturing systems known as intelligent manufacturing systems (IMS) should have capabilities of flexibility, adaptability, intelligence, etc.

The control system of IMS will be distributed, and new intelligent embedded devices, information and communication concepts are emerging ([3], [6], [7], [9], [12], [13]) as new technologies that can be implemented.

The American Committee on Visionary Manufacturing Challenges established 10 strategic technology areas as the most important for meeting the grand challenges. Some these technology areas are listed below [2]:

- adaptable, integrated equipment, processes, and systems that can be readily reconfigured;
- processes that minimize waste and energy consumption;
- system synthesis, modeling, and simulation for all manufacturing operations;
- technologies to convert information into knowledge for effective decision making;
- product and process design methods that address a broad range of product requirements;
- software for intelligent collaboration systems.

To have a flexible and robust manufacturing system it is necessary an intelligent control system that makes an efficient use of the flexibility [21] and agent-based software is the technology that can deal with the control and supervision of intelligent mechatronics components. The use of multi-agent based software in operation and control of distributed systems can offer distributed intelligent control functions and cover the mechatronic and production specifications.

Many and new mechatronics components (e.g. intelligent sensors and actuators) are appearing at the markets with functionalities that promise good results in the integration on...
IMS. However, agent-based control strategies are yet emerging ([4], [5], [20] - [24]) and are crucial for the distributed control needed in future manufacturing systems (see section III). As present in [4], agent-based approaches offer many advantages for distributed manufacturing process planning and scheduling systems like modularity, reconfigurability, scalability, robustness and fault recovery. The manufacturing systems reliability and flexibility will depend fundamentally by the reliability and flexibility of the embedded control system [5].

In this paper, underlying principles of the construction of an IMS are presented. The objective is give a general idea of the complexity of the future manufacturing systems, explain some concepts and definitions accepted by scientific community.

This paper is organized as follows. Section II reviews the concepts of the fractal, bionic and holonic manufacturing systems. Section III the concept of software agent and the importance of the multi-agent system (MAS) approaches in the future manufacturing processes. Section IV shows the importance of services-oriented architecture (SOA) and web services (WS) in the creation of the future intelligent devices present in future IMS. Finally, in Section V we present the paper conclusions.

II. THREE ORGANIZATIONAL MODELS

Different distributed manufacturing system (DMS) concepts are being studied to cope with the growing customers demands. They have the ability to answer quickly and correctly to changes of the environment, and they differ from conventional approaches because they can adapt to changes without external interventions.

A. Fractal Manufacturing Systems (FMS)

The fractal concepts have origins in mathematics and theory of chaos and indicate new ideas to handle with the inflexibility and rigidity of the actual organizations [10], [11]. The fractal manufacturing system is an open system, and the main characteristic is the self-similarity between their small components, known as fractal entities or fractal units. A fractal unit has the following features [10], [11], [14], [15]:

- self-organization, because don’t need external mediation to reorganize. Each unit arranges its internal structure based on previously assigned criteria;
- self-similarity, one fractal unit is identical to another fractal unit but the internal structure can be different (Fig. 1);
- self-optimized, which means that it continuously search for its best performance.

Fractals act as independent units to accomplish their own goals (e.g. production of an output). However, for the overall goal of the manufacturing system be accomplish, goal coherence should be maintained by cooperation and iteration with other units. In a fractal manufacturing system a predefined organization doesn’t exist. Any fractal unit has its own resources with static capabilities and an efficient information system that provides data required to manufacture products and allocate operating resources. These characteristics allow a great dynamic environment inside the unit that make possible to work with constant changes in the enterprise structure and react quickly to external requirements.

![Self-similarity properties between fractal units](image)

B. Bionic Manufacturing Systems (BMS)

The word ‘bionic’ is a portmanteau formed from biology and electronic. Bionics is the application of methods and systems found in nature to the new technology systems [38].

The biological life originate the bionic theory applied to the manufacturing systems [10], [14]. The structures and behavior observed in live beings from the cell level to the biological beings (plants, animal, etc) it is applicable to enterprises. The BMS make a parallelism among these biological characteristics and the essential needs for the futures production systems. For example, the productions units (also called work cells) can be compared to cells in the biological systems.

A biological cell is an entity inserted in a chemical environment. It is constituted by one internal chemical environment (cytoplasm), the nucleus that is the core of the cell (carry the genetic information (DNA) and regulate the chemical reactions inside the cell) and organelles (part of a cell with a specific function) which creates the cell functions. Cells operate through the change of chemical information with both inside and outside environments. It is this change of chemical information that will change the behavior of other cells and of their own. The coordination between cells is executed by enzymes (protein which catalyzes chemical processes). The overall goal of a group of cells in cooperation is make their associate organs work (e.g. a heart). The overall goal of a group of organs is to make organisms living(e.g. a human). Living organisms have their own societies. This hierarchical order is the ascending steps of life-form [14], [39].

The production units (work cells) are inserted in a enterprise, as productive internally resources (workers, machines, etc.) with distinct capabilities but, with cooperation, they can achieve the overall goal of the unit (intermediate and finished products) changing the states if necessary. Raw material and control information circulate in predefined ways (interfaces). The processed material and information will be sent again by the corresponding interfaces to the environment where somebody (or something) will take charge of directing for the destiny (another work cell, a repository, etc.). Coordinator and supervisor units have mission of coordinate and supervise the work between the internal elements of a cell and between cells units in the manufacturing systems [11].

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The properties of the biological cells and production units above exposed have a lot of similarities. In Fig. 2 this similarities are resumed and can be compared [11], [15].

In the life forms and manufacturing systems the information come from the top to specify the tasks to be done in the lowest levels. The operations of all cells (biological or not) are reflected in the whole production system.

Other property present in the generation of life forms is the division of the cells to create organs and other forms (information of the DNA replicated in the genes of the dividing cells [14], [40]). Similarly, manufacturing system can be divided into minor functional sections through the top-down propagation of information (tasks).

The BMS theory begin with the basic element called modelon, which is composed of lower level modelons (sub-modelons), forming a hierarchical structure as shown in Fig. 3.

Communication systems ensure the correct exchange of information inside and between modelons. The information propagation needs to be made by a self-organized process, where higher levels modelons pass information (similar to DNA information) to the modelons in the lowest levels.

Finally, supervisors or operators entities (similar to enzymes) have the responsibility of regulating and controlling the children and parents modelons interactions. They impose organizational and structural rules (self-division or aggregation) between modelons in order that, with cooperation, they execute tasks and achieve the goals of the entire system [25].

C. Holonic Manufacturing Systems (HMS)

The holonic manufacturing theory grew from concepts developed by the philosopher Arthur Koestler when trying to define the hybrid nature of the structures of living organisms and social groups [5], [10], [11], [15], [41]. He proposed the term holon based on the Greek word holos (whole) and the suffix on (part). The center of the HMS theory it is the holon concept. In the domain of life, each system has its own parts and is a part of something bigger. A holon is a whole because it is constituted by subunits (other holons) and at the same time it is a subunit from a larger system (other holon). The whole/part opposing properties are reflected in the autonomous and cooperation attributes of the holons. Every system can be considered a holon, from a particle to the universe. Even at a non physical level (e.g. words) everything can be identified as part of something and can be viewed as having parts of its own [41]. In other words, any unit in a system or organization is made of by basic units (e.g. a biological organ is constituted by cells) and at the same time are a part from a whole (e.g. an organ as part of a body). In Fig. 4 is schematically represented the concept of holonic system.

Another concept that is relevant is the holarchy notion. An holarchy is a system of holons located in a the entire system goals. The holons autonomy and the level of cooperation is governed by strategies and fixed rules inside the holarchy. Moreover, a holon can be part of several holarchies and himself is a holarchy. Finally, a HMS is a holarchy that integrates the entire range of manufacturing activities.

To study and develop the next generation of manufacturing and processing technologies, an international research and development program was created (the IMS Program [30]). The HMS Consortium [32] created under the IMS Program, as developed a glossary with definitions for several concepts above presented:

- **Holon**: 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. A holon can be part of another holon.
- **Autonomy**: The capability of an entity to create and control the execution of its own plans and/or strategies.
- **Cooperation**: A process whereby a set of entities develops mutually acceptable plans and executes these plans.
- **Holarchy**: A system of holons that can cooperate to achieve a goal or objective. The holarchy defines the basic rules for cooperation between the holons.
- **HMS**: A holarchy that integrates the entire range of manufacturing activities from order booking through design, production, and marketing to realize the agile manufacturing enterprise.
- **Holonic attributes**: Attributes of a holon. The minimum set is autonomy and cooperativeness.

According to [32], the HMS concept combines the best fea-
atures of hierarchical (“top down”) and heterarchical (“bottom up”, “cooperative”) organizational structures as the situation dictates. This concept can preserve the stability of hierarchy while providing the dynamic flexibility of heterarchies.

III. SOFTWARE AGENTS

A. What is an Agent?

Because the definition of agent it was not consensual, in 1996, Franklin [19] tried to fix a definition for autonomous agent. However, he admitted that the definition it is very general because it could include undesirable entities.

Silva [11], Leitão [10] and Colombo [5] have definitions with more practical usefulness when they are looked from the point of view of a DMS. Thus, we present the main characteristics of an autonomous agents based in a mix from the definitions of these three authors. Therefore, an agent is a software entity that:

- is autonomous;
- can represent physical resources (e.g. robots);
- can represent logical objects (e.g. schedulers, orders);
- has intelligence to make own decisions and act in order to achieved its goals (process planning, scheduling, etc);
- has the capability to interact with other agents (also with humans) and cooperate if it doesn’t possess knowledge and skills to reach alone its objectives;
- can interact in the environment where is inserted (e.g. production environment) feeling and changing it based on the knowledge that it contains;
- reacts to context incentives and defines actuation plans based in his knowledge;
- can to decide if it accepts or rejects a service requested by other agent, based in its knowledge and skills.
- has capacity to acquire and to memorize new knowledge.

B. Classifying Agents

Several dimensions to classify existing software agents can be used. This section is based in the work made by Nwana [29] and in the notion that agents can be classified in agreement with their characteristics.

An agent can move around the environment where it is inserted (some network) or be caught to some resource (e.g. a machine). Therefore an agent can be classified by its mobility: static or mobile agents. An agent can possess an internal reasoning model and autonomously make his own decisions (or negotiate with others agents to achieve the goals) or it cannot possess an internal reasoning model and can only react to external stimulus from other agents or from the environment (state of). Hence, agents can be classified as deliberative or reactive. Information or internet agents control and administer the high flows of information in area networks (e.g. internet). Hybrid agents combine two or more agent characteristics in a single agent [29].

Nwana [29] also classified the agents by three minimal characteristics that agents should exhibit: autonomy, learning and cooperation. He used this three minimal characteristics to identify four types of agents: collaborative agents, collaborative learning agents, interface agents and smart agents (see Fig. 5). However, he emphasizes that these distinctions are not definitive with an example: “with collaborative agents, there is more emphasis on cooperation and autonomy than on learning; hence, we do not imply that collaborative agents never learn. Likewise, for interface agents, there is more emphasis on autonomy and learning than on cooperation”.

Finally, Nwana identify the Collaborative, Interface, Mobile, Information/Internet, Reactive, Hybrid and Smart agents as the seven main types of agents (with some degree of arbitrary) as the most investigated [29].

Other attributes, characteristics and types of agents can be seen in [29] and the references therein.

C. Why Multi-Agent Systems (MAS) in a IMS?

In the DMS organizational models referred in section II some basic features between entities are always present: autonomy, cooperation, flexibility, adaptability, intelligence, etc. Autonomous agents working together have the ability to create evolvable systems due to the characteristics previously referred [28]. An autonomous agent has these features and it can represent logical or physical entities.

A MAS is basically a system composed by many and different autonomous agents that together have the capacity of reaching the overall goals of the system where they are inserted (see Fig. 6). These agents can have two distinct approaches [4]:

- Functional decomposition: agents are used to encapsulate modules detailed to functions (order acquisition, process planning and scheduling, material handling).
- Physical decomposition: agents are used to represent the physical world (workers, machines, tools, operations).
The functional approach implicates the share among separate agents of many variables between many and different functions that can induce some inconsistency (see Fig. 7). On the other hand, in the physical approach, the agents have less variables to share and therefore more easiness in his individual managements. However, the large number of agents that it is necessary, can carry new problems like communication overhead and a complex agent management is need [4].

![Fig. 7. Conventional vs Multi-agent manufacturing control system [42]](image)

A MAS offer many advantages in a DMS implementation, however to be practicable the implementation, a good architecture for the MAS organization and agent encapsulation is needed, and it is necessary a correct choice of the protocols for communication, cooperation and negotiation [4].

The future DMS will need a great diversity of autonomous agents and mechatronic devices interacting intensively. All components need understand the exchanged information and know how to communicate among them. For these reasons, information syntaxes, interaction syntaxes and new semantics are still necessary to avoid chaotic situations [6].

Other problem is the proliferation of standards and specifications that can restrict the integration of functional and physical agents (e. g., mechatronic devices) [6]. For example identical devices from different vendors have different protocols and specifications. In an IMS we have many technologies from different vendors. How can an IMS deal with heterogeneity in an easy and fast way? To deal with the problem of the proliferation of standards, investigators and technology suppliers need work together to standardize protocols and specifications, and at the same time protect the intellectual property rights. For example, recently OOONEIDA [34] have been approved as a Community of Common Interest [33] by the internacional IMS Program [30]. In the future, initiatives like OOONEIDA (or programmes like ITEA [31]) will be capable of defining standards and create technological infrastructures for open knowledge for automation components and automated industrial products [12].

In a IMS different agents can be used. Each agent represents a function, a process to be done, a production cell or even an entire production system. Some agents usually referred in several papers are concisely described below [5], [21]:

- Order agent, represents an order to be accomplished by the production system.
- Process planning agent, plan of the several processing phases to produce a workpiece of an order.
- Process scheduling agent, minimize the production time and costs from process planning.
- Coordinator and Supervisor agent, coordinate and supervise the actions between different agents imposing the correct execution of the rules established in the system.
- Resource agents, have the responsibility of manage different resources. For example workpiece agent manages the processing state of the workpiece, the transport agent decides autonomously in which direction a workpiece is forwarded inside the production system, and the machine agent, controls the machine.

### IV. Networking needs

The current manufacturing systems are compose by specialized devices coupled using closed nets (proprietary networks). Central systems coordinate communications and actions between the individual devices in a hierarchical mode.

In a simple representation of an current industrial application the activation of several actuators in function of the signals send by sensors needs intermediate devices like a programable logic controller (PLC) to scan the state of all sensors and activate the actuators. In the future, intermediate devices like PLC's won't be necessary (can be used for monitoring) because the intelligent sensors and actuators can be linked in direct, asynchronous or real-time communication mode over the network where are inserted [8], [36].

Internet technology is a promising way to interconnect intelligent electronic devices. It is cheap and is gradually increasing. At lower ISO communication layers, the ethernet is actually replacing traditional fieldbus networks, and everyday the wired and wireless local area networks have more followers [13], [17]. For instance, the emergency of wireless had a strong impact of industrial communication architectures. It is really convenient to connect devices to the network, without the use of wires. Using wireless, tasks like re-cabling or installing a new device on an automation system can be made much more efficiently. For instance, when there are mobility requirements of a given device, wireless provide a good alternative to the use of sliding contacts [7].

The SIRENA [35] project is a European research and advanced development project with the objective to develop distributed applications in diverse realtime embedded computing environments (e.g. industrial or home automation) [13].

The SIRENA vision, represented in the Fig. 8, intends to change the traditional master-slave architectures and substitute for new forms of device networking (intelligent devices). The SIRENA framework is based in the services-oriented architecture (SOA) and the web services (WS) technology. The WS technology a central point of the implementation of SOA for building autonomous and interoperable systems, and at the same time, the Extensible Markup Language (XML) can be used by the WS as a form of standardize data formats [9], [13].
V. CONCLUSIONS

In this paper we surveyed the fractal, bionic and holonic manufacturing concepts and we presented the main characteristics to implement intelligent manufacturing systems based on autonomous agents. Multi-agent systems can offer distributed intelligent control actions to create evolvable systems required on the flexible and distributed manufacturing systems already needed in ours days and essential for the future. We also dealt with the networking needs of IMS as the platform that will support the communication need of a DMS and the SOA architectures as the Internet technology that shows potential to interconnect the future intelligent devices.

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