Abstract—The new enterprise organizations, such as virtual enterprise and smart enterprise, require the usage of collaborative automation approaches, addressing the flexibility and dynamic re-configurability. Collaborative automation is a result of the integration of emerging technologies and paradigms like smart agent-based control technology, mechatronics, communication and information. This paper reviews the paradigms evolution from CIM to the collaborative manufacturing management and discusses how and why the holonic control architecture ADACOR is a typical architecture that exhibits the real meaning of the collaborative manufacturing management concept.

Index Terms - Collaborative Production Automation, Flexible Manufacturing Systems, Intelligent Control.

I. INTRODUCTION

The recent production technologies reflect a worldwide trend towards both, batches of small and medium size, and part/product families of increasing variety. The importance of products’ intangible elements has increased considerably, e.g. software, built-in service capabilities, on-line maintainability etc. Customers have more individualistic desires and participate in the design and production processes [1].

The tendency shown in Fig. 1 often comes in conflict with the demand on high productivity, i.e. on production-time/time-to-market minimization, on simultaneous improvement of machine utilization, and on flexibility of the whole production environment when it is integrated in a global network of related enterprises [3].

The process of globalization forced traditional manufacturing systems development and operation to evolve to inherently multidisciplinary tasks. Manufacturing paradigms such as mass customization generated rapid changes in the economic, technical and organizational manufacturing environments. Under this new vision, a complicated mix of people, software systems, processes, and equipment (hardware) constitutes the manufacturing system of the 21st Century [4-5]. The research and development (R&D) activities linked to the management and control of such complex systems are, as a consequence, a multidisciplinary task grounded in knowledge of manufacturing strategies, planning, and operations, and in the integration of mechatronics, communication, information, and control functions across the entire supply-chain (intra- and inter-enterprise levels) [2, 6, 20].

Trends:

- Mass Production
- Mass Customization
- Lot Size ≥ 1

Target:

Fig. 1. Trends in Manufacturing

In this paper the collaborative manufacturing management (CMM) paradigm is briefly reviewed and presented as a main result of the evolution of the original CIM/PWS concept. From CMM is derived the collaborative industrial automation system paradigm, which is the final result of the integration of emerging technologies like smart agent-based control technology, Holonic control systems, and mechatronics. It is also described the collaborative/holonic control architecture ADACOR [16], and analysed its positioning and contribution to the several domains of the collaborative manufacturing paradigm.

This paper is organised as follows: First, Section 2 reviews the paradigms evolution from CIM to the collaborative manufacturing management. Section 3 introduces the concept of Collaborative Industrial Automation. Section 4 makes reference to the ADACOR collaborative control architecture and discusses how and why ADACOR is a typical architecture that exhibits the real meaning of the CMM concept. Finally, Section 5 rounds up the paper with conclusions.
II. FROM CIM / PWS THROUGHOUT HETER-ARCHICAL AUTOMATION TO THE COLLABORATIVE MANUFACTURING MANAGEMENT

A. The CIM/PWS Paradigm

New revolutionary manufacturing concepts and emerging technologies, which take advantage of the newest mechatronics, information and communication technologies and paradigms, and address many of the fundamental problems described above, are being researched and developed since the last decade of the 20th Century [1, 2, 4].

The Computer Integrated Manufacturing (CIM) and the Plant Wide Systems (PWS) concepts has been promoted as solutions that can somehow deal with all above addressed challenges, e.g. more flexibility in product spectrum and processes, agility of the production system, more responsiveness and integration of hardware and software components [7].

Nevertheless, this centralized and sequential manufacturing planning, scheduling and control mechanism is increasingly being found insufficiently flexible and agile to respond to changing production styles and highly dynamic variations in the product requirements. Moreover, its construction always risks the requirements of huge investment, long lead times, and generation of rigid systems due to large size and centralization. Such a centralized hierarchical organization leads normally to situations where the whole system is shutting down by single failures at one point in the CIM-hierarchy.

B. The Heter-archical Automation Approach

Due to the reasons addressed above, before the CIM idea made its way into practice, its original approach changed from the mainly centralized model to a decentralized one [2].

Due to the tremendous amount of interaction between the different components and the variety of performed functions, the control of such production systems is currently based on a hierarchical and distributed structure, i.e., heter-archical structure, as shown in Fig. 2.

C. The Collaborative Manufacturing Management (CMM) Paradigm

Due to the recognition of their position within a Value Network or Value Chain, manufacturers have begun to optimize processes for overall enterprise-wide effectiveness rather than individual plant efficiency. They are transforming their companies in a collaborative enterprise that focuses on business processes to operate and optimize the business from a global perspective [9].

In [10] Collaborative Manufacturing Management (CMM) is defined as the practice of managing key business and manufacturing processes in the context of a global value network. CMM knits together internal manufacturing and business processes, and connects them seamlessly and in synchrony with external business processes of strategic partners with the focus on building an effective and agile value chain. CMM builds upon a collaborative infrastructure and real-time strategic business management tools. It connects critical applications, production systems, and enterprise information, to maximize the responsiveness, flexibility, and profitability of the manufacturing enterprise, in conjunction with its value network partners.

The central concept of CMM is built around three intersecting domains: Enterprise, Value Chain, and Lifecycle. This concept is depicted more clearly in Fig. 3.

One promising architecture, in this respect, is to have a conglomerate of distributed, autonomous, intelligent, fault-tolerant, reusable production units, which operate as a set of co-operating entities. Each entity is capable of dynamically interacting with the others to achieve both local and global manufacturing objectives, from the physical/machine control level on the shop floor to the higher levels of factory management systems and global networked enterprises [8].

Recognizing that today’s manufacturer needs to operate on information in real-time, CMM provides a holistic approach to manufacturing that is equally well-suited to global multinational companies and small, local operations, as well as process, discrete, or hybrid production models. This approach allows that manufacturers visualize the relationships among plant and enterprise applications, markets, value chains, and manufacturing nodes in order to understand and implement collaborative manufacturing systems
Up to this concept, a collaborative manufacturing environment consists of manufacturing units connected by material, information and process flows.

In the context of today's markets, many industrial companies are looking for a flexible, network-shaped, but sometimes temporally restricted, virtual co-operation of decentralized and distributed production competencies [7, 20].

This decentralization originates within a single company (spread over several different production sites) or through the association of several different companies within a single supply chain (virtual enterprise). Collaborative automation approaches are required for such scenarios, i.e. a shared but remote supervision is necessary. Autonomous automation units with local supervision functionality installed in each production site interact or co-operate, providing a global (network-wide) supervision (control, monitoring, diagnosis, HMI, maintenance).

### III. INTELLIGENT COLLABORATIVE PRODUCTION AUTOMATION

In the context of today's markets, many industrial companies are looking for a flexible, network-shaped, but sometimes temporally restricted, virtual co-operation of decentralized and distributed production competencies [7, 20].

A software agent approach seems well suited in relation to the control and supervision of each mechatronics component in an intelligent manufacturing system. Agent-based software systems are becoming a key control software technology for smart manufacturing control systems. A multi-agent based software platform can offer distributed intelligent control functions with communication, co-operation and synchronization capabilities, and also provide for the behaviour specifications of the mechatronics components and the production specifications to be fulfilled by the manufacturing system [12-15].

### IV. ADACOR: A HETERARCHICAL COLLABORATIVE PRODUCTION AUTOMATION AND CONTROL ARCHITECTURE

It is worth notice that a collaborative production system would be of little use without suitable embedded control software and reliable control and automation architecture. Moreover, the production system's reliability, agility, and degree of flexibility will not only be conditioned by the reliability, agility and flexibility of its mechatronics components (workstations, storage, handling and transport systems, etc.) but will also depend fundamentally on the reliability and flexibility of the embedded control and automation architecture [6, 16].

It is this collaborative control and automation system which has to organise the production and to schedule and synchronise the resource utilisation.

**Remark**: A production system managed and controlled by a collaborative automation system possesses the ability to attain efficiency and versatility by producing a wide range of different product families and/or different types of a product with a minimal effort in changing the involved manufacturing environment, it is dynamic re-configurable.

A brief analysis of the latest R&D-results allows highlighting the fact that only a reduced number of real applications on the manufacturing area have been reported during the last couple of years. The Factory Broker™ solution is one of them [6]. Another one is the ADACOR (ADAptive holonic COntrol aRchitecture for distributed manufacturing systems) architecture [16].

It follows the description of the main specifications of the ADACOR architecture and its positioning in relation to the CMM paradigm.

ADACOR has been developed and implemented at the Polytechnic Institute of Bragança. It is a typical holonic/collaborative manufacturing control architecture, which addresses many of the issues that compresses the CMM paradigm.

**A. ADACOR Basics**

ADACOR architecture is build upon a set of autonomous and co-operative holons, each one being a representation of a manufacturing component that can be either a physical resource (numerical control machines, robots, pallets, etc.) or a logic entity (products, orders, etc.). A generic ADACOR holon comprises the Logical Control Device (LCD) and, if exists, the physical resource, capable to per-
form the manufacturing task. The LCD is responsible for regulating all activities related to the holon and comprises three main components: decision, communication and physical interface [17].

ADACOR architecture defines four manufacturing objects (holons or collaborative units) classes: product, task, operational and supervisor. The product, task and operational holons are quite similar to the product, order and resource holons defined in PROSA reference architecture [18], while the supervisor holon presents different characteristics from the PROSA staff holon. The supervisor holon introduces co-ordination and global optimisation in decentralised control and is responsible for the formation and co-ordination of groups of holons.

The ADACOR adaptive production control approach is neither completely decentralised nor hierarchical, but balances between a more centralised approach to a more flat approach, as explained in Figure 2. It passes through other intermediate forms of control [16], due to the self-organisation capability associated to each ADACOR holon, translated in the autonomy factor and in the propagation mechanisms [17].

ADACOR evolves in time between two alternative states: the stationary state, where the system control relies on supervisors and co-ordination levels to achieve global optimisation of the production process, and the transient state, triggered with the occurrence of disturbances and presenting a behaviour quite similar to the heterarchical architectures in terms of agility and adaptability (Fig. 5).

ADACOR proposes a method to model and formally validate agent-based control systems for flexible production systems using High-Level Petri nets. The approach proposes a High-Level Petri net model for each type of ADACOR holon class, representing the dynamic behaviour of a manufacturing component. The global control is achieved by the coordination and synchronisation among these High-Level Petri net models.

B. Implementation of ADACOR Concepts

The validation of the ADACOR concepts, to verify if the system works as specified, either in normal operation or in presence of disturbances, requires their implementation and testing in a prototype, to analyse their correctness and applicability [19]. For this purpose, the ADACOR prototype uses agent technology to implement each holon, taking advantage of its modularity, decentralisation and components re-use.

Multi-agent systems can be adequately developed using object-oriented languages, such as Java. However, the development of multi-agent systems requires the implementation of features usually not supported by programming languages, such as message transport, encoding and parsing, yellow and white pages services, ontology for common understanding and agent life-cycle management services, which increases the programming effort. The usage of agent development platforms, which implement the previously referred features, makes the development of agent-based applications easier and reduces the programming effort.

The choice of an agent development platform to implement the ADACOR prototype obeyed to a set of criteria: to be a free platform with good documentation and available support, ease to use, low programming effort, use of standards, features to support the management of agent communities like white pages and/or yellow pages and facilities to implement rule oriented programming.

The chosen platform was JADE (Java Agent Development Framework) because it responds better to the mentioned requirements. In fact, JADE simplifies the development of multi-agent systems by providing a set of system services and agents in compliance with the FIPA (Foundation for Intelligent Physical Agents) specifications: naming, yellow-page, message transport and parsing services, and a library of FIPA interaction protocols.

Each ADACOR holon is a simple Java class that extends the Agent class provided by the JADE framework, inheriting basic functionality, such as registration services, remote management and sending/receiving ACL messages [3, 6]. This basic functionality was extended with features that represent the specific behaviour of the ADACOR holon. The start-up of the holon comprises its initialisation (read the configuration files and load the behaviours) and its registration into a federation according to the organisational structure, followed by the actual start-up of the holon's components, i.e. the communication, decision and physical interface components.
The behaviour of each ADACOR holon uses multithreading programming, over the concept of JADE's behaviour, allowing to execute several actions in parallel. The behaviours launched at the start-up and those that can be invoked afterwards are provided in the form of Java classes.

Fig. 6 shows the graphical user interface of an operational and a supervisor holons during their operation.

The communication between distributed holons is done over the Ethernet network, using TCP/IP protocol and is asynchronous, i.e. the holon that sends a message continues the execution of its tasks without the need to wait for the response.

The messages specified in ADACOR are encoded using the FIPA-ACL communication language, being the content of the messages formatted according to the FIPA-SL0 language. The meaning of the message content is standardised according to the ontology defined by the ADACOR architecture.

The experience gained during the implementation of ADACOR concepts into a prototype using the JADE agent development framework and the posterior debugging and testing phases, allows extracting some conclusions, essentially the applicability of the ADACOR concepts and the merits of the collaborative/holonic approach.

C. The position of ADACOR within the CMM-Sphere

The ADACOR architecture is positioned on the semisphere down the central plane or disc shown in Fig. 3, addressing the production functions (i.e. the management and control functions over the manufacturing components, either the resources or the orders).

In spite of being focused at the shop floor control level, ADACOR can be extended according to the three axes (domains) of the CMM concept.

Related to the enterprise axis, all levels should be linked and integrated being possible to exchange data along the vertical structure of the enterprise, from the shop floor to the factory and inter-factory levels.

ADACOR holonic concepts can be extended to the business levels, by using the fractal feature associated to each ADACOR holon: an operational holon can be made of a set of several operational and/or supervisor holons, with the supervisor holon acting as the logic component, and the several operational holons acting as the physical part of the holon [19]. This feature allows a modular development of manufacturing control applications through the encapsulation of their functions or manufacturing components.

As an example, illustrated in Fig. 7, a manufacturing cell can be represented by an operational holon that constitutes of several other operational holons, each one representing a manufacturing resource, and one supervisor holon representing the manufacturing cell controller. Additionally, each one of these operational holons, that represent a manufacturing resource, could be constituted of several other operational holons, such as the numerical control machine itself and the several tools stored in its tool magazine.

Another different example is related to the integration of the design activities within the manufacturing activities: the product holons are used to represent each available product designed at the engineering phase, comprising the elaborated process plan, material and cutting parameters definition, etc.

Related to value chain axis, which deals with the horizontal integration, i.e. the interconnection with suppliers and customers, the extension of ADACOR concepts to cover these horizontal levels is not yet validated. In this axis, the main problems are associated to the definition of common manufacturing ontology that allow an easy communication and understanding between the entities belonging to the value chain.

Related to the life cycle axis, ADACOR concepts can be extended to support the levels ranging from the design to the operation. The High-Level Petri net-based approach, proposed in ADACOR, facilitates the conception, definition and formal specification of an “encapsulation process” in industrial production systems.

The catalogue includes elements for the identification of manufacturing components, the development of smart (agent-based) control units, the formal validation of the models and the formal specification of complete collaborative automation scenarios.

V. CONCLUSIONS

In the context of today’s markets, many industrial companies are looking for a flexible, network–shaped, but sometimes temporally restricted, virtual co-operation of decentral and distributed production competencies. The new
generation of production systems that fulfils the referred requirements have to be capable of addressing flexibility, agility and dynamic re-configurability.

The collaborative industrial automation systems is one paradigm of the new generation of production systems, resulting of the integration of emerging technologies and paradigms like smart agent-based control technology, holonic control systems, and mechatronics.

ADACOR architecture is a typical holonic/collaborative manufacturing control architecture, which addresses many of the issues defined by the CMM ARC model. Its real implementation, using the JADE framework, allowed to verify that in spite of being positioned on the semi-sphere addressing the production functions (shop floor control level), spans the three axes (domains) of the CMM concept. This is done mainly through using the concept of product holons, and the fractal feature associated to each ADACOR holon (allowing encapsulation).

Future work should be addressed to validate the extension of the ADACOR concepts in order to support completely the three axis of the CMM paradigm. An especially effort will be at the value chain axis, by developing mechanisms that support the inter-operability of production control systems within a supply network.

VI. REFERENCES


