ADACOR: A Collaborative Production Automation and Control Architecture

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An analysis of the ADACOR collaborative manufacturing control architecture from the point of view of the Collaborative Manufacturing Management paradigm shows how ADACOR supports integration and extension across the manufacturing value chain.

Manufacturers are under enormous pressure to comply with market changes and the continual shortening of product life cycles. Changes on the factory floor are the order of the day. Traditional production-planning methods no longer sustain business profits, whether you're designing a new plant or retrofitting an existing one. Moreover, the geographic expansion of enterprises through geographically distributed factory plants, administrative facilities, and sales offices has created the concept of distributed production systems. This trend affects all levels of the enterprise, from the inter-enterprise level to the shop-floor level (see Figure 1).

To answer these problems, factory-floor technology must evolve into a highly flexible and reconfigurable work environment.[1] The tendency shown in Figure 2 for extreme customization often conflicts with the demand for high productivity—that is, for minimizing production time and time to market, improving machine utilization, and maintaining system flexibility.[2] One result of this tendency, which is a major challenge, is the migration from conventional factory-floor control strategies to collaborative production automation and control systems. The new trend toward extreme customization is being applied, for example, in the mobile-communications area, where highly reconfigurable, electronic assembly systems can produce one product (such as a mobile phone) for one customer. Only systems that are built using the collaborative paradigm can reach this high degree of reconfigurability.

Traditional manufacturing control systems can't adapt their production control processes. In fact, centralized and hierarchical control approaches are good at optimizing production but weak at responding to change, mainly because their control structures are rigid and centralized. On the other hand, heterarchical manufacturing control approaches respond well to change and unpredictable disturbances but, because decision makers have only partial knowledge of the system, aren't as good at global production optimization. In these circumstances, the challenge is to develop manufacturing control systems that have autonomy and intelligence capabilities, can quickly and easily adapt to environment changes, are robust when disturbances occur, and can easily integrate manufacturing resources and legacy systems.

Researchers have proposed several manufacturing control architectures that use emergent paradigms and technologies, such as multiagent and holonic manufacturing systems, to address this challenge. (Arthur Koestler proposed the term *holon* to indicate a basic unit of organization in biological and social systems; see http://hms.ifw.uni-hannover.de and elsewhere.[3,4]) Nevertheless, some important issues are still open, such as how to achieve global optimization in decentralized systems, evolve production control structures to adapt to change, how to formally specify

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holonic systems' dynamic behavior, how to introduce learning and self-organization capabilities, and how to integrate automation resources. PROSA (Product-Resource-Order-Staff Architecture)[4] and MetaMorph (http://isg.enme.ucalgary.ca/research.htm), two established approaches reported in the literature, answer some of these open questions. Nevertheless, some aspects of existing solutions (for example, the formal specification of dynamic behavior) can be improved, and of course, all those solutions and the one presented here must reach a certain level of maturity before being able to be deployed in industry.

ADACOR (*ada*ptive holonic *co*ntrol a*r*chitecture for distributed manufacturing systems),[5] which we review from the viewpoint of the Collaborative Manufacturing Management paradigm,[6] aims to answer some of these challenges by supporting integration and extension across the value chain.

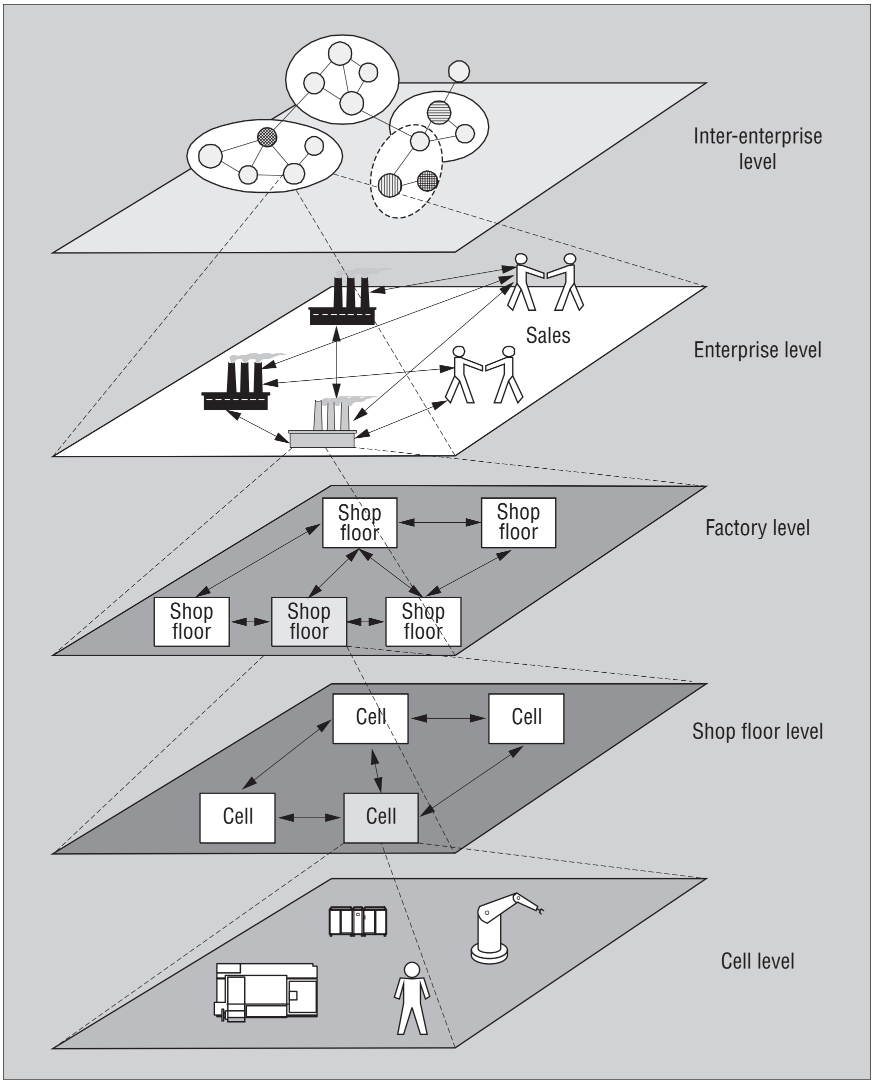

Figure 1. The layered approach to distributed manufacturing.

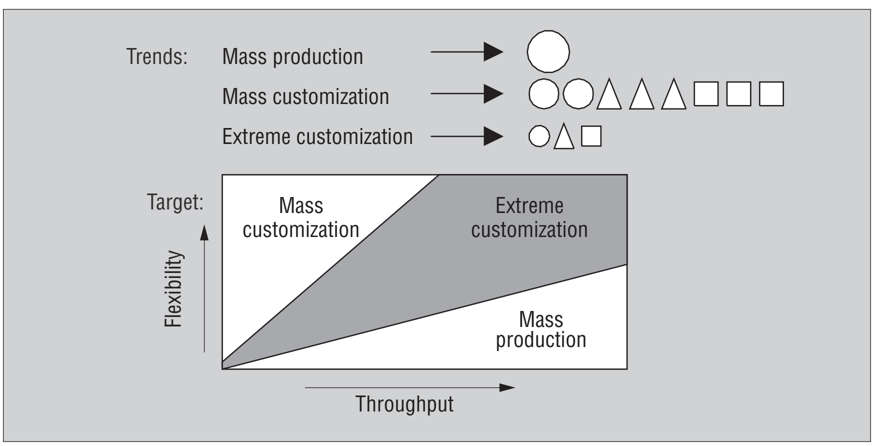

Figure 2. Today's manufacturing trends.

The CMM paradigm

The CMM model involves managing key business and manufacturing processes in the context of a global value network.[6] Its central concept is built around three intersecting domains (see Figure 3): the enterprise, the value chain, and the life cycle.[7]

Recognizing that today's manufacturers must operate on information in real time, CMM provides a holistic approach to manufacturing that's equally well suited to global multinational companies and small, local operations, as well as to process, discrete, and hybrid production models. This approach lets manufacturers visualize relationships among plant and enterprise applications, markets, value chains, and manufacturing nodes in order to understand the context for planning and implementing their collaborative manufacturing systems.[6]

According to this concept, a collaborative manufacturing environment consists of manufacturing units connected by material, information, and process flows. In Figure 3, each sphere represents a unit. Above the central plane or disc in the unit are the business functions, and below it are the production functions. Collaborative processes can be formalized in both the business and automated-production domains. The ADACOR approach relates to the latter (the lower side of the central plane in the figure)—that is, to collaborative factory automation.

Collaborative factory automation systems result from integrating emerging technologies and paradigms such as smart agent-based control technology, holonic control systems, and mechatronics.[2]

Technologically speaking, a software agent approach seems well suited for controlling

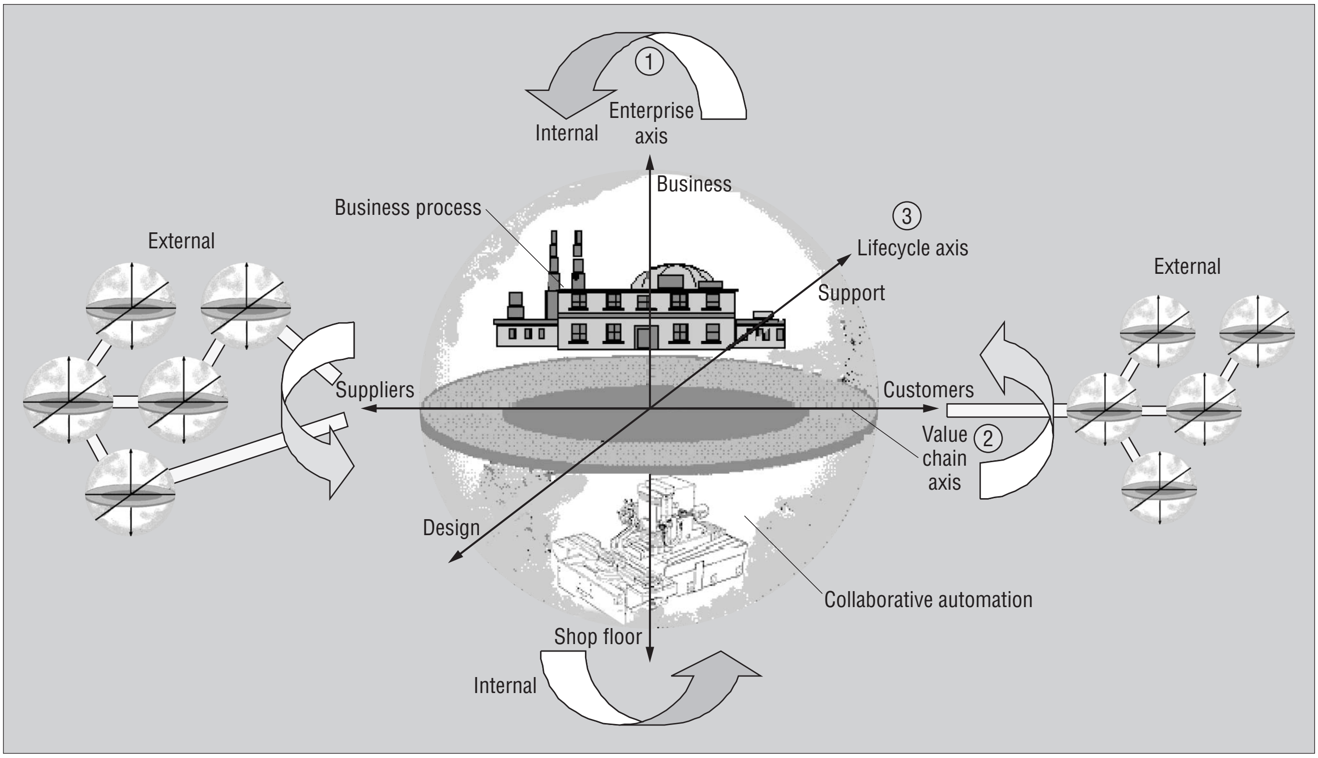

Figure 3. The ARC Advisory Group's Collaborative Manufacturing Management Model (adapted from R. Mick and C. Polsonetti[7]). Collaboration goes from shop floor to business level on the enterprise axis, from suppliers to customers on the value chain axis, and from design to support on the lifecycle axis.

and supervising flexible manufacturing systems' mechatronics components. Agent-based software systems are becoming a key technology for smart manufacturing control systems. A multiagent-based software platform can offer distributed intelligent-control functions with communication, cooperation, and synchronization capabilities; it also provides for the mechatronics components' behavior specifications and the manufacturing system's production specifications.[4,5]

A brief review of the recent literature helps us identify some solutions in the area of collaborative automation systems. FactoryBroker is a collaborative, agent-based industrial-automation solution for manufacturing applications.[2] Its components meet all the specifications that are needed for the shop floor's collaborative unit. Moreover, although the community of physical agents that it represents can be perfectly positioned on the lower CMM sphere, it supports all three of the CMM model's collaborative axes. ADACOR is a second solution. Its major contribution lies in its adaptation and agility features, where high-level Petri nets can be used to model and formally validate agent-based and holonic control systems.

ADACOR: A collaborative control architecture

A collaborative production system would be of little use without suitable embedded-control software and a 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, and so on) but will also depend fundamentally on the embedded-control and automation architecture's reliability and flexibility.[2,5]

The collaborative control and automation system organizes production and schedules and synchronizes resource utilization. A production system managed and controlled by a collaborative automation system is dynamically reconfigurable—it can easily change the manufacturing environment to produce a wide range of product families and different types of product.[2]

ADACOR's holonic, collaborative manufacturing control architecture,[5] which was developed and implemented at the Polytechnic Institute of Bragança, Portugal, addresses many of the issues that the ARC Advisory Group's CMM model encompasses.[6] It addresses the agile reaction to disturbances at the shop-floor level, increasing the enterprise's agility and flexibility in environments in which unexpected disturbances frequently occur. Its original contribution was at the shop-floor level. However, it also provides functionalities that support vertical and horizontal integration—that is, interaction among several levels within the enterprise and between different enterprises, namely in distributed environments.

ADACOR specifications

ADACOR is built on a set of autonomous and cooperative holons, each representing a manufacturing component—either a physical resource (such as a numerical control machine, robot, or pallet) or a logic entity (such as a product or order). A generic ADACOR holon comprises a logical control device responsible for regulating all activities related to the holon and, if it exists, a physical resource capable of performing the manufacturing task.

The architecture defines four manufacturing holon (object or collaborative-unit) classes: product (PH), task (TH), operational (OH), and supervisor (SH). The PHs, THs,

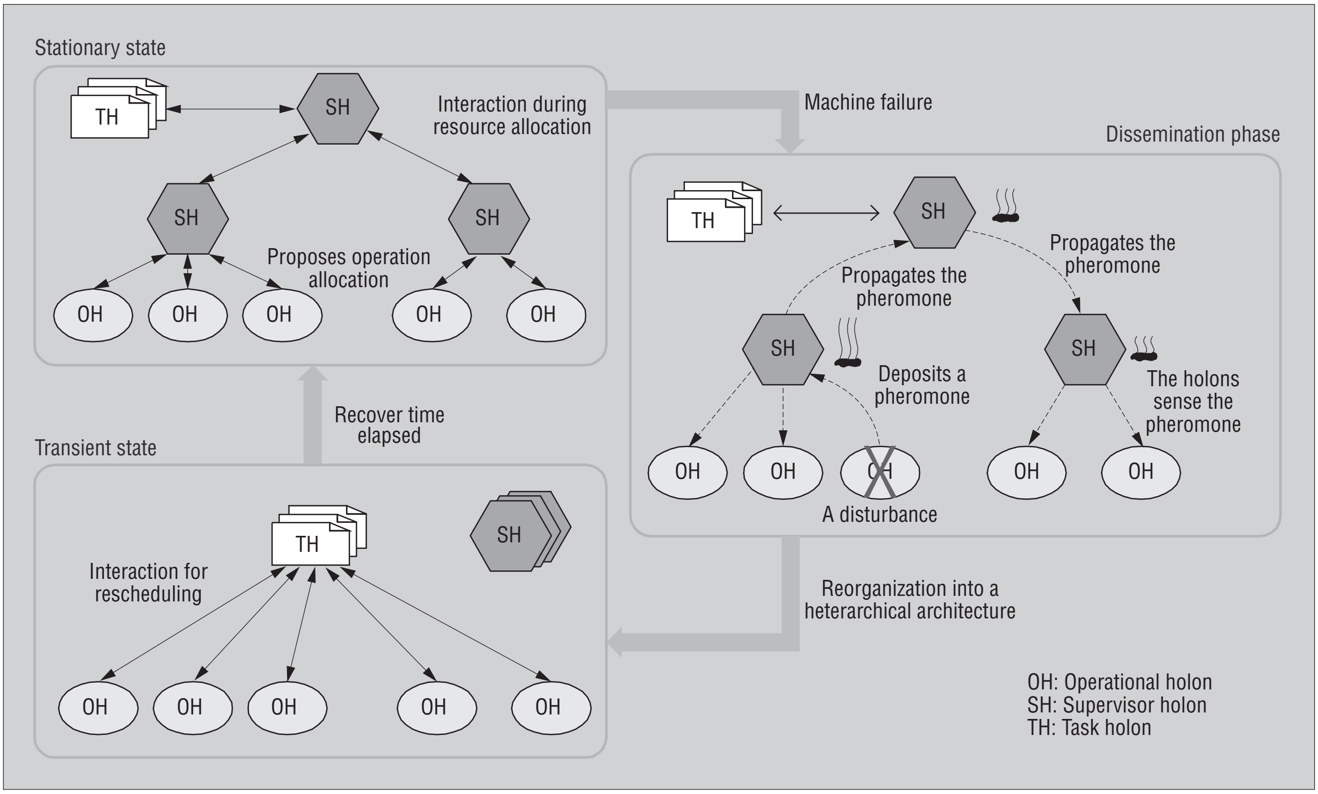

Figure 4. ADACOR's adaptive production control.

and OHs resemble the product, order, and resource holons defined in PROSA,[4] while the SH is an ADACOR feature (different from the PROSA staff holon). The SH introduces coordination and global optimization in decentralized control and is responsible for forming and coordinating groups of holons.

ADACOR's approach to production control is neither completely decentralized nor purely hierarchical; it balances between a more centralized approach and a flatter one. It passes through other intermediate forms of control,[5] owing to the self-organization capability associated with each ADACOR holon. This capability translates into a degree of dynamic autonomy and propagation mechanisms inspired by ant-based techniques.

ADACOR alternates between two states: stationary ones, where system control relies on supervisors and coordination levels to achieve global optimization of the production process, and transient ones, triggered by the occurrence of disturbances and behaving quite like heterarchical architectures in terms of agility and adaptability.

In the stationary state, the holons are organized hierarchically, with SHs coordinating several OHs and interacting directly with the THs during the operation allocation process. Each SH, as a coordinator, proposes optimized schedule plans to the THs and to the OHs within its coordination domain. In this state, each OH has a low degree of autonomy, following the proposals sent by the SH.

When a disturbance occurs, the control system enters the transient state, characterized by holons reorganizing in a heterarchical-like control architecture. This lets the control structure react nimbly to disturbances, as Figure 4 illustrates.

In the case of a machine failure disturbance, the OH that detects the disturbance increases its autonomy factor parameter and propagates the need for reorganization to the other holons in the system, using ant-like techniques—that is, depositing a "pheromone" containing the information to be propagated. The other holons that sense this pheromone also increase their autonomy factors, reorganizing themselves into a heterarchical structure. In this transitory state, the THs interact directly with the OHs to achieve an alternative schedule plan. The holons remain in the transient state during the reestablishment time. When this time elapses, they verify if the pheromone odor has dissipated. If it's still active, the OHs stay in the transient phase during an additional reestablishment time, until the pheromone is gone.

After the system has recovered from the disturbance, the OHs reduce their autonomy factors, and the system evolves to a stable control structure (often returning to the original one). The SHs return to their coordination functions, eventually optimizing the schedule achieved during the transient state.

Formal specification of the ADACOR control system

Distributed manufacturing control systems, like ADACOR, are difficult to comprehend and design because of the presence of concurrent and asynchronous activities. The ADACOR control system's structural and behavioral specifications must be formally modeled to make it easier to understand and to get a comprehensive view of system functionality, playing a key role in its design and later in its implementation.

ADACOR uses a method to model and formally validate agent-based control systems for flexible production systems using a category of Petri nets tailored for production control modeling,[8] ensuring rigorous specification and validation due to its powerful mathematical foundation. Using this category of temporized Petri nets, ADACOR formally models each holon class's specifica-

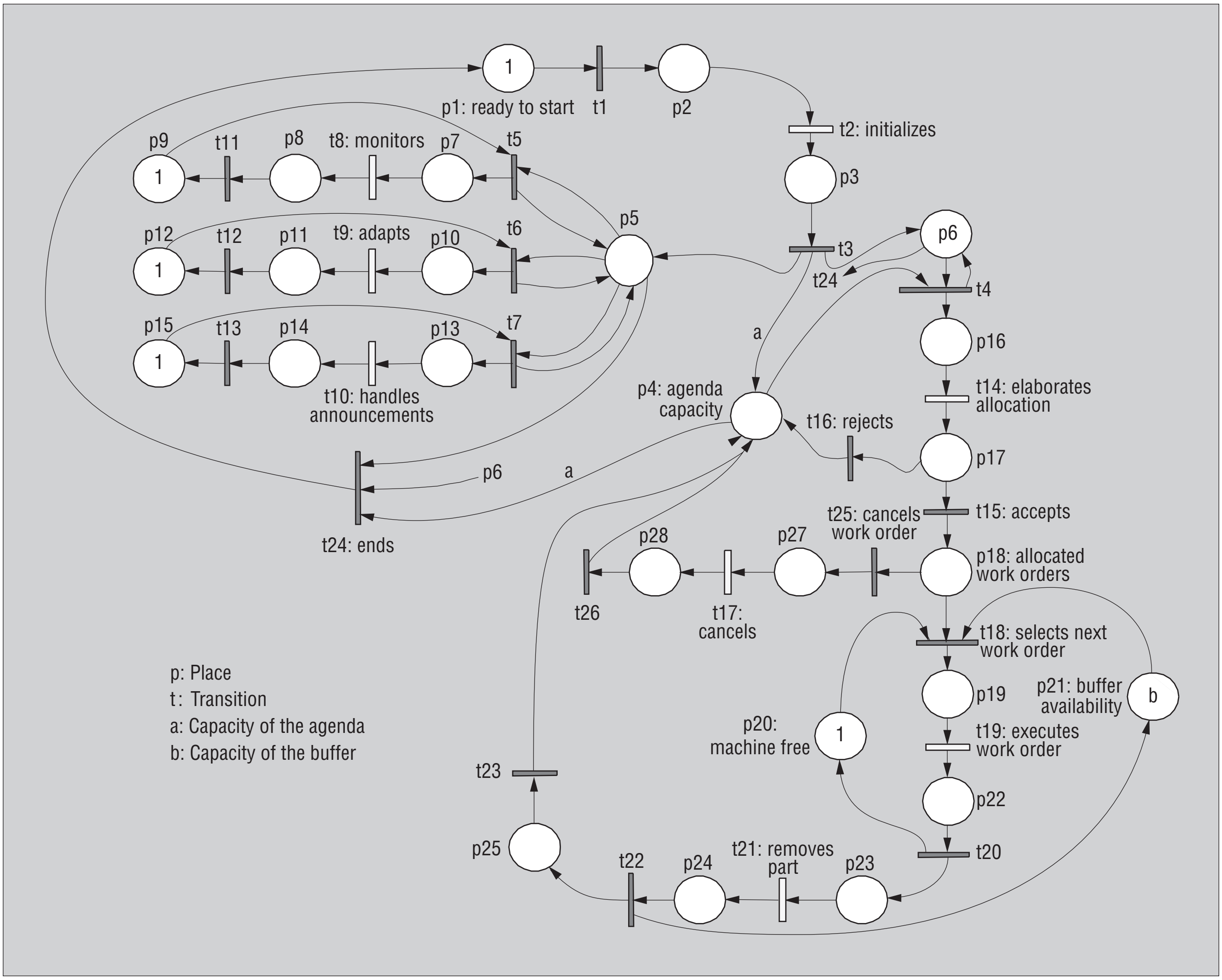

Figure 5. Operational holon behavior model.

tions and functionalities, with special attention to each component's behavior.[9]

As an example, Figure 5 illustrates the Petri net elaborated to model the OH's behavior, which contains several subbehaviors that must be handled asynchronously in parallel, so that the execution of one process doesn't block another's.

To understand some technical details of the Petri net model, let's look at the execution of a work order. In Figure 5, the place p18 represents the work orders stored in the local agenda, waiting for the appropriate moment to start executing. The transition t18 fires when the places p19, p20, and p21 are marked, which means that the machine is free, the buffer is available to receive a part, and at least one work order is allocated to the resource. In this case, the OH selects the next work order that the manufacturing resource is to execute according to the local scheduling. Then, p19 is marked with a token, and a token is removed from p20 and p21, which means that the machine becomes occupied and the buffer has one less place in its availability.

The physical execution of the work order is represented by the timed transition t19, which has associated a delay time that specifies how much time must elapse before the transition fires, modeling the required time to execute the work order. When the work order finishes executing—that is, when transition t19 fires—the net evolves to a state where p20 and p23 are marked. This means that the resource returns to the idle state, able to initiate another work order's execution, and the part can be removed from the machine buffer.

Thus, the global control system is achieved by coordinating the Petri net models of the individual ADACOR holon classes, using mailboxes to communicate between those models.

Formal validation of the behavioral models, elaborated for the ADACOR holon classes, lets us verify the models' and system specifications' correctness. It's based on the mathematical theory of Petri nets, which supports both qualitative and quantitative analysis. Petri net properties such as liveness (necessary condition), boundedness, and reversibility can be formally proven and used to validate the modeled system's structural properties. Moreover, quantitative analysis of the nets offers a broad spectrum of results that can easily be mapped to a rigorous set of ADACOR performance indexes.

Implementing ADACOR concepts

Validating ADACOR concepts (to analyze their correctness and applicability) requires

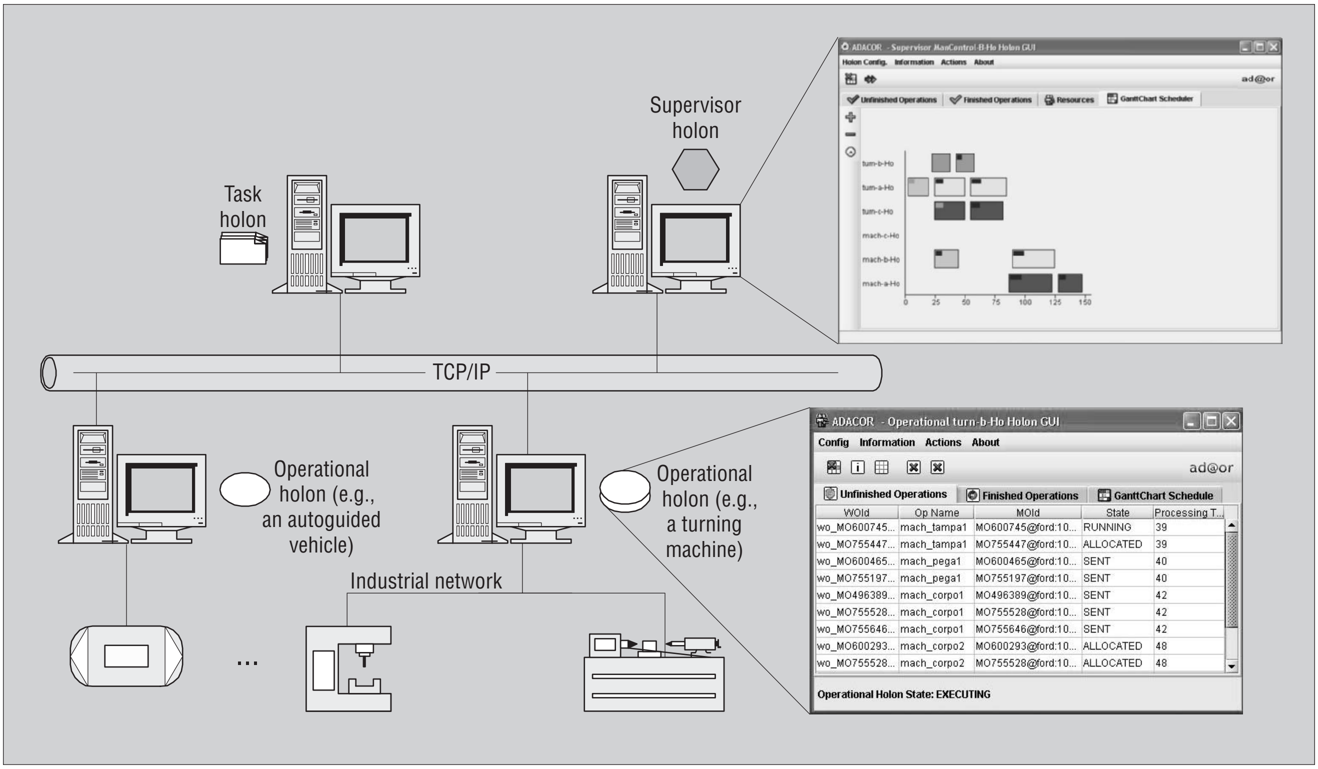

Figure 6. Architecture of our prototype implementation.

implementing and testing them in a prototype. The ADACOR prototype uses agent technology to implement each holon, taking advantage of its modularity, decentralization, and component reuse.

The development of multiagent systems requires implementing features usually not supported by programming languages, such as message transport, encoding and parsing, yellow-page and white-page services, an ontology for common understanding, and agent lifecycle management services. Using agent development platforms that implement such features simplifies the development of agent-based applications and reduces programming effort.

We chose the Java Agent Development Framework (JADE) to implement the ADACOR prototype because it simplifies the development of multiagent systems. It does so by providing a set of system services and agents in compliance with the Foundation for Intelligent Physical Agents specifications, including naming, yellow pages, 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 functionalities such as registration services, remote management, and the sending and receiving of messages. We extended the basic functionalities with features representing ADACOR holons' specific behavior. Starting a holon involves initialization (reading the configuration files and loading the behaviors) and registration into a federation according to the organizational structure, followed by the actual start-up of the holon's components—that is, the communication, decision, and physical-interface components.

The holons' use of multithreaded programming enables them to execute several actions in parallel. The behaviors launched at start-up and those that can be invoked afterwards are also provided in the form of Java classes.

Distributed holons communicate over the Ethernet network using the TCP/IP protocol and are asynchronous—that is, a holon that sends a message continues executing its tasks without waiting for a response. The holons encode messages in FIPA-ACL (Agent Communication Language) and format their contents in FIPA-SL0 (Semantic Language). The meaning of the message content is standardized according to the ontology defined by the ADACOR architecture.

The pilot installation was a semivirtual laboratory platform that included a flexible manufacturing system from the CIM (Computer Integrated Manufacturing) Centre of Porto.[5] The platform was extended with two virtual manufacturing cells that provided hardware-software redundancy and flexibility in achieving alternative production-planning solutions. The flexible-manufacturing-system platform, which consists of six processing machines, one calibration machine, two anthropomorphic handling robots, one SCARA (Selective Compliance Assembly Robot Arm) robot, one automated storage and retrieval system, and one auto-guided vehicle, is organized as a set of four physical cells: material storage and transportation, inspection, assembly, and flexible manufacturing. Our pilot plant must produce four products—Base, Body, Cover, and Handle—which, when assembled, can create two different final products: Box or Ashtray.

Figure 6 shows an ADACOR-based control system for the flexible manufacturing system we've described. Several personal computers with different operating systems (Windows XP, Windows 2000, and Linux) distribute the system's THs, OHs, and SHs. The figure also illustrates an OH's GUI and an SH's GUI during operation.

The OHs' GUI lets us

- Visualize the local schedule, using a Gantt

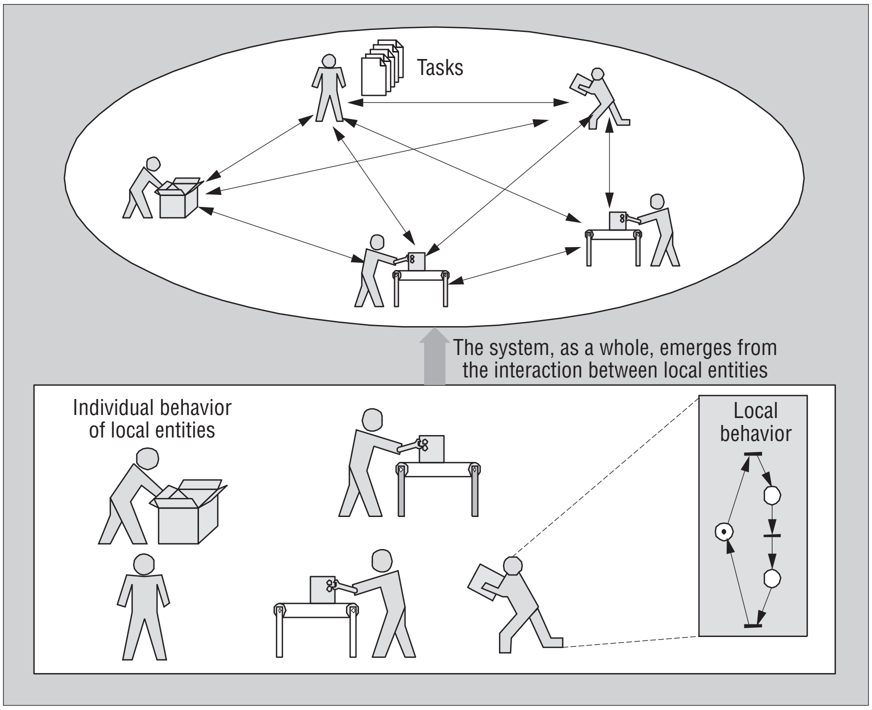

Figure 7. Global system emerging from local entities' behavior.

chart to show the work orders that the resource executes
- Configure some operational-holon parameters, such as the scheduler type
- Display statistical information related to resource performance, such as the degree of utilization, the number of executed work orders, and the number of delayed work orders

The SH's GUI lets us

- Visualize the global schedule, using a Gantt chart to show the work orders that each lower-level resource executes
- Display the resources under its coordination domain and their characteristics
- Configure some holon parameters, such as the schedule algorithm

The experience we gained while implementing, debugging, and testing the prototype enabled us to extract some important conclusions about ADACOR's applicability and the merits of the collaborative, holonic approach.

ADACOR's position in the CMM sphere

As we described earlier, the ADACOR control architecture is positioned on the CMM sphere's central plane or disc (see Figure 3). It addresses production functions—that is, the management and control functions of the manufacturing components, both the resources and orders.

In spite of the ADACOR concepts' focusing on the shop-floor control level, we can extrapolate them to other levels, where they support integration in a collaborative value network or value chain. To prove this expandability, we must verify how ADACOR fulfills the CMM specifications along each of its three axes.

The enterprise axis

All levels of the enterprise should be linked and integrated, as shown in Figure 1, and should be able to exchange data, from the shop-floor to the interfactory levels.

In distributed manufacturing environments, each distributed entity is autonomous and has partial knowledge of the problem. The manufacturing control emerges, as a whole, from the interaction among the distributed collaborative manufacturing and production units (holons), each contributing through its local behavior to the global control objectives, as Figure 7 shows.

ADACOR's holons support various business processes such as order entry, scheduling, and plan execution. ADACOR classifies the holons' interactions as

- Introducing new orders, including product and process information and global coordination
- Executing plans, including work order execution, monitoring, and physical synchronization
- Handling disturbances, including reorganization propagation and dynamic rescheduling

As an example, Figure 8 illustrates the interaction diagram for the scheduling process using global coordination. The presence of the coordination levels—that is, the existence of SHs—guarantees stable scenarios when the system runs without unexpected disturbances.

In this process, the THs interact with SHs to announce new work orders. Periodically, the SHs elaborate optimized schedules for the coordinated resources, decomposing them into individual work orders and proposing them to the OHs. The OHs take this proposed schedule as advice, having enough autonomy to accept or reject it based on its local knowledge and actual behavior. If an OH rejects one or more proposed work orders, the SH reschedules the production plan, trying to find alternatives. When the OHs accept the proposed work orders, the SH returns a calendar to the TH.

Another example relates to integrating design activities within manufacturing activities, in which OHs are used to represent engineering teams or resources and SHs to represent the teams' coordination entities (for example, departments). ADACOR uses the PHs to represent each available product designed at the engineering phase, comprising the elaborated process plan, definition of the material and cutting parameters, and so on. Thus, the PHs link engineering and manufacturing-control activities.

However, ADACOR hasn't yet achieved complete vertical integration, especially the integration of higher-level systems such as enterprise resource planning systems. In this case, integration can be performed using an additional holon, especially developed for each system, that imports and converts the information according to the ADACOR ontology and then supplies the information to the appropriate holons in the collaborative agent-based control system. Researchers have given various names to this additional holon according to the quantity and quality of the information that it has to process. Examples include Mediator, Facilitator, and Broker.[10]

On the other hand, we can extend ADACOR holonic concepts to business levels by using the so-called "fractal" feature of each holon, inherited from the foundations of holonic systems.[3] An OH can be made of a set of several SHs and/or OHs, with the former acting as the logic component and the latter acting as the physical part. This feature enables modular development of intelligent-manufacturing-control applications by encapsulating their functions or manufacturing components.

As an example, illustrated in Figure 9, we can represent a manufacturing cell using an OH that consists of several other OHs, each representing a manufacturing resource, and one SH representing the manufacturing-cell controller. Each OH, representing a manufacturing resource, can also comprise several other OHs, such as the numerical-control machine itself and the several tools stored in its tool magazine.

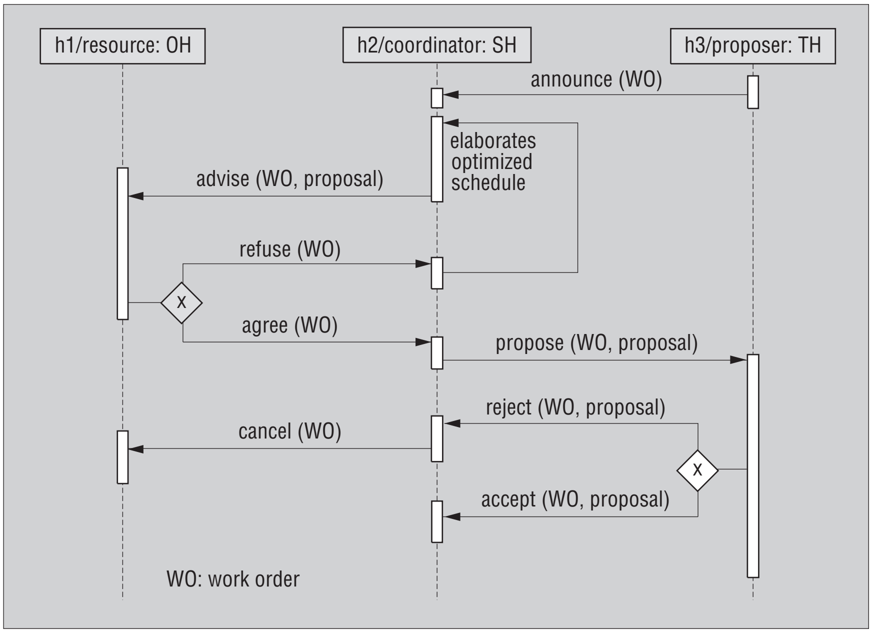

Figure 8. Interaction diagram for global coordination.

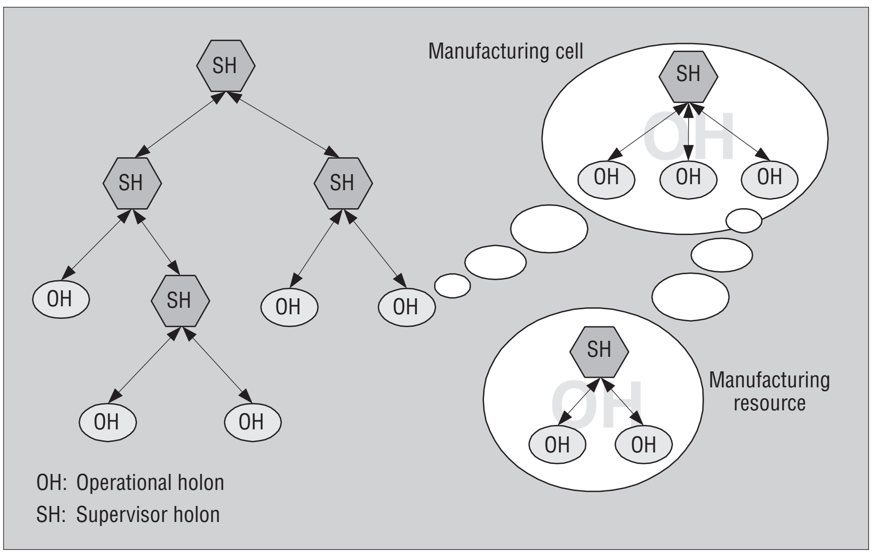

Figure 9. The ADACOR approach's "fractal" feature.

The lifecycle axis

ADACOR provides a catalog of elements that simplifies the development of agent-based control systems for flexible manufacturing, from design to operation. ADACOR's Petri net-based approach facilitates the conception, definition, and formal specification of an encapsulation process in industrial production systems. The catalog includes elements for identifying manufacturing components, developing smart (agent-based) control units, formally validating the models, and formally specifying complete collaborative-automation scenarios.

The identification element involves identifying and aggregating the production automation components (with different degrees of granularity—that is, machine, machine part, sensor-actuator, product, and so on) and grouping them according to ADACOR holon types. Each identified component has a corresponding smart (agent-based) control unit, which implements the main control functions such as scheduling, dispatching, monitoring, and reacting to disturbances. We represent each component's behavior using a Petri net model, built from ADACOR's catalog of such models. The quantity and quality of the information in the model of each smart (agent-based) unit strongly supports the production control function.

The catalog of models contains the results of the formal validation of specifications (structural and behavioral) when the hardware or software components (control and intelligence) are completely integrated in each model. The results of the formal analysis complete the set of information parameters used to supervise the collaborative automation unit.

The last set of elements relates to providing rules for modeling collaborative automation systems and providing evaluation parameters for each application. The relationships between collaborative units, and the constraints and rules for composing their Petri net-based model, constitute a *coordination model*. The rules in the catalog enable the production system designer/engineer to improve the structure and behavior of this model, which is used as the formal specification of a complete collaborative-automation scenario. This leads to automatic system adaptation and reconfiguration.

The coordination model can make decisions at the system level, supporting one of the main functionalities of a collaborative automation system—collaboration/cooperation (for example, introducing new hardware or new models in the catalog, breaking down and replacing components, and creating production specifications for new products).[9]

The value chain axis

The CMM model's value chain axis deals with horizontal integration—that is, the interconnection between suppliers and customers. We haven't yet validated extending ADACOR concepts to cover this. On this axis, the main problems are associated with defining a common manufacturing ontology that enables easy communication and understanding between the entities belonging to the value chain.

The ontologies currently used in the manufacturing domain are the result of noncoordinated efforts and don't offer interoperability with other agents' communities. The ADACOR architecture proposes a basic and proprietary manufacturing ontology to support interoperability between ADACOR holons. However, interoperability between different agent-based control systems requires a common manufacturing ontology capable of merging these systems. Applying foundational ontologies to support interoperability between agent-based manufacturing control applications can provide a feasible solution to this problem (see www.fipa.org).

Because a common manufacturing ontology is missing, the interoperability problem is currently handled by using XML parsers to convert information between different collaborative control and automation systems.

In the context of current global markets, companies are looking for flexible, networked, sometimes temporally restricted cooperation among their decentralized and distributed production competencies. The next generation of production systems that fulfill the requirements discussed here will be able to address flexibility, agility, and dynamic reconfigurability.

The collaborative industrial automation system is one paradigm of this new generation, resulting from integrating emerging technologies and paradigms such as smart agent-based control technology, holonic control systems, and mechatronics. However, researchers have reported fewer real manufacturing applications during the last few years.

ADACOR is a typical holonic/collaborative manufacturing control architecture, which addresses many of the issues defined by the ARC's CMM model. To support the CMM's three axes completely, future work should try to validate the extension of ADACOR concepts. The industrial dissemination and exploitation phases of ADACOR are being planned and first steps have been taken, mainly focusing on integrating ADACOR in the lower CMM hemisphere and then extending its functions across the vertical axis. On the other side, the University of Porto, the Polytechnic Institute of Bragança, and Schneider Electric are studying the possible application of ADACOR concepts and developments in various industrial scenarios (related to the other two axes).

As part of the work plan for the first 18 months of the EU-FP6-NoE-I*PROMS project (European Network of Excellence for Innovative Production Machines and Systems, www.iproms.org), we are evaluating the ADACOR approach. Primarily, we want to identify the model's relative merits and drawbacks compared with similar paradigms such as multiagent systems, holonic manufacturing systems, and reconfigurable manufacturing. We particularly want to integrate some of the results and proposals addressed here within a scientific and technological state-of-the-art roadmap, at least in the involved knowledge areas. ■

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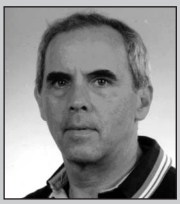

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