COLLABORATIVE AUTOMATION
FROM RIGID COUPLING TOWARDS DYNAMIC RECONFIGURABLE PRODUCTION SYSTEMS

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Abstract: This paper makes a case for the widespread adoption of a "collaborative automation" paradigm, which promises to provide more flexible and reconfigurable production systems overcoming many of the inherent limitations in traditional, rigid approaches to production automation. The collaborative automation approach implements production automation systems as a conglomerate of distributed, autonomous, and reusable units, which operate as a set of cooperating entities. A brief overview of existing developments and implementations of collaborative automation systems is presented together with discussion of some of the critical issues related to the realisation and industrial adoption of the approach. The current state of relevant research is briefly assessed, gaps in knowledge identified and areas for future research suggested.

Keywords: Agile automation, reconfigurable production, flexible manufacturing, agent technology.

1. INTRODUCTION

The efficient design, development, implementation and setup of automated production systems are key requirements for maintaining the viability of manufacturing in Europe. There is a growing need for more flexible and agile manufacturing through greater reconfigurability within the manufacturing environment in order to realise lower production costs and reduced time-to-market for highly customised products, e.g., in the context of new manufacturing paradigms like mass customisation (see the upper part of figure 1).

However, using current practices, the complete engineering process for production systems is inefficient and requires extensive human effort in terms of time, costs and expertise. The lifecycle engineering of automation systems is today not adequately supported by the available data and knowledge modelling paradigms and is typically reliant on either ad-hoc or brute-force development and implementation techniques. The effect of this is seen in the growing lead times necessary to realise new production plants. Using current industrial practice it typically takes three to five years from initial product planning to production set-up and operation, as illustrated in the lower left-hand side of figure 1. Based on the use of a rigid, hierarchical approach, system development typically occurs as a series of vertically isolated activities.

The need for more agile and reconfigurable production systems has led to growing interest in new automation paradigms that model and implement production systems as sets of production units/agents/actors interacting/collaborating in a complex manner in order to achieve a common goal (Anon, 1998). Traditional sequential engineering methods, whilst appropriate for largely monolithic production systems are inappropriate in the context

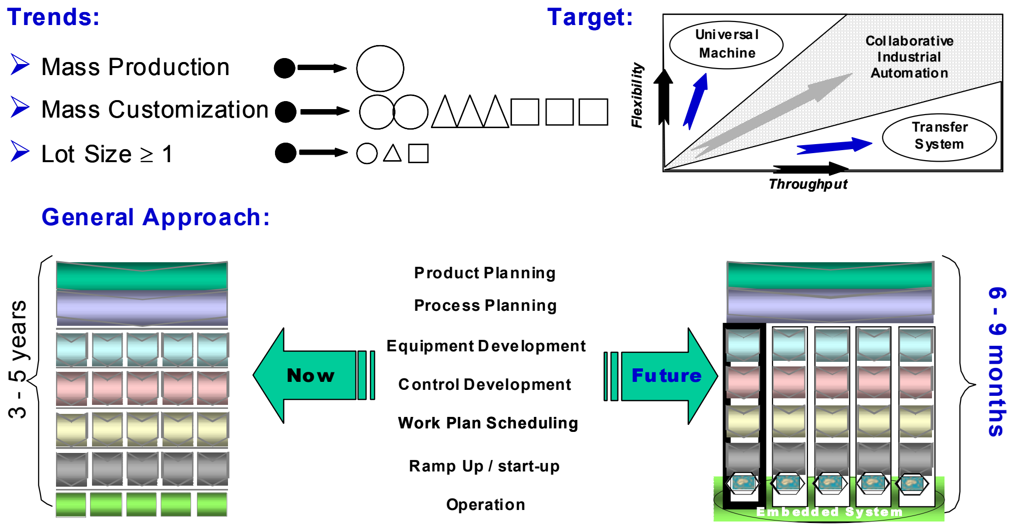

Fig 1. Production system engineering process – today and tomorrow

of these new distributed unit/agent/actor based approaches to system implementation. New engineering environments are needed that are capable of supporting inherently multidisciplinary, parallel system engineering tasks. The realisation of appropriate engineering tools requires not only a broad appreciation of mechatronics, manufacturing strategies, planning, and operation, but also a deep understanding of the required integration of communications, information and advanced control functionality.

One promising approach, which has the potential to overcome the technical, organizational and financial limitations inherent in most current approaches, considers the set of production units/agents/actors as a conglomerate of distributed, autonomous, intelligent, fault-tolerant, and reusable units, which operate as a set of cooperating entities. Each entity is typically constituted from hardware, control software and embedded intelligence, as depicted in the right-hand side of figure 2. Due to this internal structure, these production entities (intelligent automation unit / physical-agent / holon / actor) are capable of dynamically interacting with each other to achieve both local and global production objectives, from the physical/machine control level on the shop floor to the higher levels of the factory management systems. The terms *physical-agent, holon, actor and intelligent automation unit*, and their associated concepts, are now quasi-synonymous, although they have originated from somewhat different ontologies.

According to the specifications of the Foundation for Intelligent Physical Agents, an *agent* is the fundamental actor on an agent platform which combines one or more service capabilities into a unified and integrated execution model that may include access to external software, human users and communication facilities (see www.fipa.org/).

A *holon* is defined as an autonomous and cooperative building block of a manufacturing system for transforming, transporting, storing and/or validating information and physical objects. A holon consists of an information processing part and often a physical processing part. The concept of holonic systems in the area of manufacturing emerged from the Holonic Manufacturing Systems (HMS) project (Leitao, *et al.*, 2005) within the Intelligent Manufacturing Systems (IMS) international research programme. See sections 4.1 and 4.8 for more details and also the HMS website at: http://hms.ifw.uni-hannover.de/.

An *actor* is a self-controlling participant in a system, and in the manufacturing context, this term has recently been adopted by researchers involved in the development of reconfigurable micro-assembly systems (Lastra, 2004). See section 4.4 for further details.

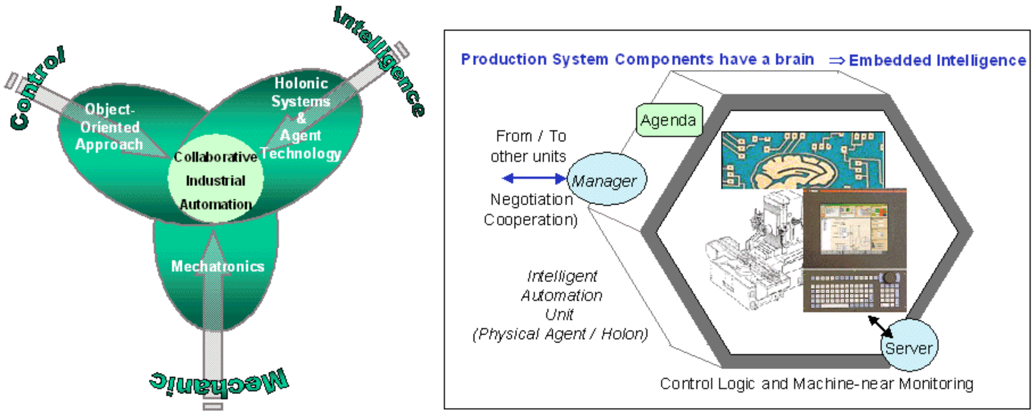

Fig. 2. Collaborative automation paradigm

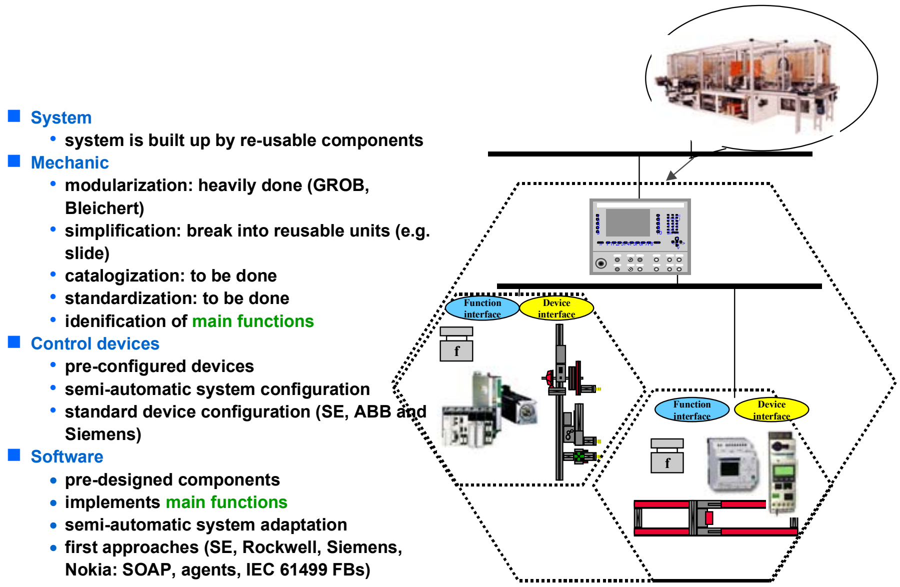

Fig. 3. Collaborative automation approach

Intelligent automation unit is a term originating from Schneider Automation to broadly describe holons/actors/agents in a manufacturing automation context. More general background information can be found in the paper Collaborative (Agent-Based) Factory Automation (Colombo, *et al*., 2004).

The umbrella paradigm, encompassing this general form of automation system, is recognized in this paper as "collaborative automation." As depicted in the left-hand side of figure 2, it is a result of the integration of three main emerging technologies/paradigms: holonic control systems utilizing agent-based technology, object-oriented approaches to software, and mechatronics. The aim is to utilize these technologies and methods effectively to achieve flexible, network–enabled collaboration between decentralized and distributed intelligent production competencies. Autonomous automation units with embedded local supervisory functionality, installed in each production site, are able to collaborate to achieve production objectives at the shop floor level, and to interact / co-operate in order to meet global (network–wide) supervisory needs (e.g., related to control, monitoring, diagnosis, HMI, and maintenance).

An innovative aspect of this approach is that the control of production sequences is achieved by means of negotiation and autonomous decision making inherent in the co-ordinated operation of the functional production automation entities (intelligent, collaborative automation units), e.g., system devices, machines and manual workstations. This collective functionality, distributed across many mechatronics system devices and machine controls, replaces the logical programming of manufacturing sequences and supervisory functions in traditional production systems.

The first developments and pilot applications of this collaborative automation paradigm have indicated that the approach may have the potential to reduce the total amount of time for production system engineering (i.e., from design, via configuration, to operation) from years towards a scale of months, as depicted in the lower right-hand side of figure 1. The new approach focuses on the development and lifecycle support of vertically integrated collaborative automation units, in sharp contrast to the vertically isolated activities that typically characterize the current approach to production system engineering.

2. BASIC APPROACH

The basic approach underlying the collaborative automation paradigm is that, by defining a suitable set of basic production functions and then combining these in different combinations, it is possible to create more complex production activities, i.e., a complex linear function is the result of the combination of simpler functions. If a production system can be seen as a set of mechatronic devices and each device is responsible for a basic operation as its production function goal, then combining these simple (basic) mechatronic devices together in suitable combinations will enable the generation of systems capable of addressing the needs of many complex production scenarios. Changes in production activities can thus be easily accommodated, and the simple mechatronics devices can be reused to create different production systems, by re-configuring these simple devices. In this manner, it is potentially possible to attain structures and behaviours for production environments able to react effectively to meet extreme product customisation requirements, see figure 3.

3. STATE OF THE ART

In the context of the "collaborative automation" paradigm, the authors have carried out an in-depth study of the current industry practice, and the future needs for production automation. As summarised in figure 1, this work has highlighted that: 1) there is a lack of innovation in industrial equipment and that radical changes in control products and associated engineering processes are necessary and could provide the key to initiate a radical renovation of manufacturing industries within Europe, and 2) although a large body of research exists relevant to the collaborative automation paradigm, there is a lack of understanding from an industrial applications perspective. Industrial requirements are often poorly understood by the research community, whilst within industry there is little appreciation of the potential of the collaborative automation approach to address many the deficiencies in current manufacturing automation systems. The remainder of this section briefly summaries some of the major shortcomings in current automated production systems that are common to many application domains, e.g., automotive machining and assembly, consumer goods assembly, electronics manufacturing, warehousing.

Current industrial control at the physical machine level is typically implemented by using large, expensive hardware platforms that support monolithic computer control applications (typically the result of the application of CIM technology). As a consequence, when the control system is installed, commissioning typically takes months to complete, and once the system is operational, changes are often complex and difficult. These factors contribute significantly to the total costs of ownership of control systems.

Although the utilization of individual production machines can typically be as high as 98%, the overall factory utilization is normally about 50 to 70%. This is often due to the fact that there is typically only one linear line of production, so that if a bottleneck occurs, then the whole of the production is affected. For example, in the automobile industry, the breakdown of a single machine that forces a production-line system to stop will typically cost over €6,000 per minute.

Today it is typical for about 80% of the software-engineering processes related to automation systems to be performed in the equipment-manufacturer's office, with the remaining 20% carried out onsite at the actual production plant. There is a pressing industrial need to reduce the later 20% by applying advanced configuration and reconfiguration capabilities, and to reduce the other 80% by utilising improved engineering tools. Onsite commissioning activities are highly costly and often directly result in delays in the ramp-up to full production. Achieving a 50% saving in the "ramp-up" time to full production capability (i.e., in two months compared with the current industry average of about four months) would typically save the automotive industry €20 million per production line.

In response to the ever-increasing business need for greater product variety and more frequent product changes, there is a worldwide trend toward both smaller batch sizes and part-families of increasing variety. Therefore, highly flexible production systems are required, capable of meeting the demand for high productivity whilst at the same time minimizing production times and achieving high levels of machine utilization. The traditional, hard-coded, deterministic approach to the logical control of most production automation systems today is too rigid and inflexible to enable efficient configuration and robust operation. It inhibits the adoption of intelligent, reconfigurable manufacturing systems which are necessary to meet the challenges of highly dynamic markets. Whether an existing plant is being upgraded or a new production system is being installed, traditional methods for the organization of production processes and the programming of production sequences are no longer applicable. The migration from today's control and management strategies to more flexible, intelligent manufacturing systems is one of the most difficult tasks facing industry today. However, the need for improvement is obvious.

Being aware of the deficiencies and problems with current production systems mentioned above, some automation hardware manufacturers have started to design intelligent modular production equipment. This approach potentially provides: 1) a huge set of opportunities, especially for small and medium sized equipment manufacturers and 2) many potential production-related benefits for end-users. However, it is not easy to introduce intelligent control systems in a conservative market. It is necessary from the marketing perspective to have identifiable intelligent control products offering added value and to provide cost-effective solutions avoiding additional hardware costs. Fortunately in the control technology domain there is now a trend towards the customised integration of appropriate control and network-enabled communication technologies on standard hardware platforms. A prospective marketing strategy can make use of this trend to conceive new control products capable of effectively supporting the "collaborative automation" paradigm.

4. DEVELOPED PROTOTYPES

Recently a number of strands of both industrial and academic research have been undertaken that have contributed in different ways to the state of the art in the field of "collaborative automation." These projects have typically resulted in the creation of prototype machines or pilot industrial installations, although none of them has, as yet, resulted in a broad migration of the approach into industry.

4.1 HMS

In 1997 the former vice president of Allen-Bradley, Dr. Odo Struger, initiated the "Holonic Manufacturing Systems (HMS)" project within the international Intelligent Manufacturing Systems (IMS) programme. The inspiration for the holonic

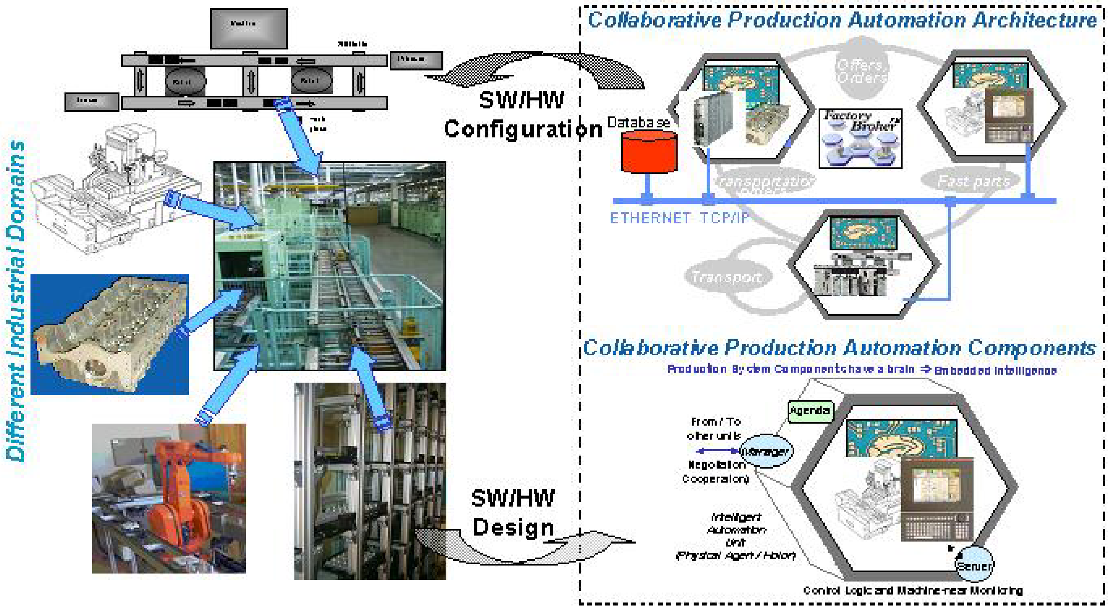

Fig. 4. FactoryBroker™ solution

approach to manufacturing systems adopted, came from Arthur Koestler´s book "The Ghost in the Machine". Koestler describes a very particular perspective on the principle, design and function of biological and social systems. These design patterns enabled the creation of systems with behavioural characteristics well matched to meeting the requirements of advanced manufacturing. The technical basis for the Holonic Manufacturing Systems was subsequently identified as agent technology emerging from the IT sector (see http://hms.ifw.uni-hannover.de/ and the references therein). In the activities of the holonic research community, two well-established approaches are reported in the literature, PROSA (Van Brussel, *et al.,* 1998) and MetaMorph (see http:// isg.enme.ucalgary.ca/research.htm).

4.2 FactoryBroker™

In parallel with the HMS initiative, and mutually inspired by the work of Stefan Bussmann (http://www.esinsa.unice.fr/etfa2001/Etfa-MFA/index.html), the first industrial agent controlled manufacturing line was developed by Schneider Electric Automation and successfully set in operation in a car production facility. This line is still in operation and proves the concept of reconfigurable systems in the control of manufacturing systems (Colombo, *et al*., 2004) see figure 4.

4.3 Loughborough University

MBODY (Modular Build for Distributed Systems) is the current phase of a research initiative in the Department of Mechanical and Manufacturing Engineering at Loughborough University, which began in 1999. This research has focused on the replacement of centralised PLC-based control systems with a component-based control approach, where the control functionality becomes embedded into the modules of the production machinery. The work has been carried out in close collaboration with the Ford Motor Company and a number of their machine builders including Krause, Cross Hueller and Lamb Technicon. The resultant system architecture has been derived from an in-depth study of application lifecycle requirements from both an end-user and system builder's perspectives. A major goal of this work has been to achieve more efficient machine reconfigurability via a functionally modular, component-based approach to automation. The system is primarily targeted at sequence- and interlock-based applications that typically form the bulk of control applications for conventional PLCs (Harrison, *et al*., 2003).

At the core of the system is an engineering environment that supports the lifecycle of the machine and enables all machine-related information to be maintained as a single Common Engineering Model in a database. This includes 3D representations of all machine modules, the complete machine structure, application logic and potentially all mechanical, electric and controls related information; see figure 5 (b). A new application is created by selecting machine modules from a library and then configuring them graphically. All application logic is defined at a high level without the need for writing low-level code (e.g., ladder logic or sequence charts). The engineering environment supports the complete machine lifecycle (e.g., pre-sales, design, build, commissioning, monitoring, diagnostics and reuse) and provides internet-based support for distributed engineering teams via an integrated set of tools; see figure 5 (a).

To date, two industrial demonstrator machines have been implemented in the automotive sector, one for engine assembly and the second for a machine tool application. The approach is, however, widely applicable and applications in both supermarket warehousing and electronics manufacturing have also been evaluated (Harrison, *et al*., 2004).

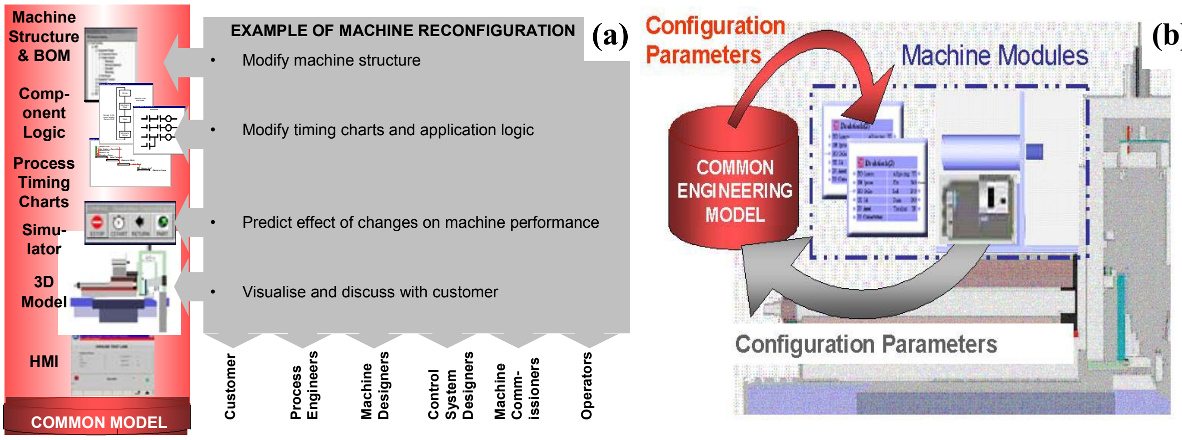

Fig. 5 (a) Common model based engineering environment, and (b) the concept of configuration parameters

4.4 ABAS®

The Actor-Based Assembly System (ABAS®) claims not only to attain but also to exceed the objectives of mass, lean, agile and flexible manufacturing. It offers a highly accurate collaborative automation platform, free from the traditional rigidly coupled assembly system structure. It provides a highly dynamic, reconfigurable assembly solution demonstrated in a pilot installation located in Tampere, Finland; see figure 6. In his work, the author (Lastra, 2004) presents a collaborative electronics assembly automation architecture that defines a set of mechatronic devices/modules that map their functionality to basic assembly activities, which are named "assembly operations." More complex activities are referred to as "assembly processes", which are formed by aggregating these basic operations. By rearranging these mechatronics modules or by populating the system with different modules, the system is able to accomplish different assembly processes.

4.5 ADACOR

The ADACOR (ADAptive holonic COntrol aRchitecture for distributed manufacturing systems) is a control architecture developed and implemented at the Polytechnic Institute of Bragança, Portugal. The system claims to provide agile reactions to disturbances at the shop floor level, increasing the agility and flexibility of the enterprise where it operates, in environments characterized by the frequent occurrence of unexpected disturbances (Leitão, *et al.*, 2005).

ADACOR is built 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, when required, also the physical resource to perform the manufacturing task. The LCD is responsible for regulating all activities related to the holon. The ADACOR architecture defines four manufacturing holon (object or collaborative unit) classes: product (PH), task (TH), operational (OH) and supervisor (SH). The product, task and operational holons are quite similar to the product, order and resource holons defined in the PROSA reference architecture, while the supervisor holon is a unique feature of ADACOR architecture, being different from the PROSA staff holon. The supervisor holon introduces co-ordination and global optimization in decentralized control and is responsible for the formation and co-ordination of groups of holons.

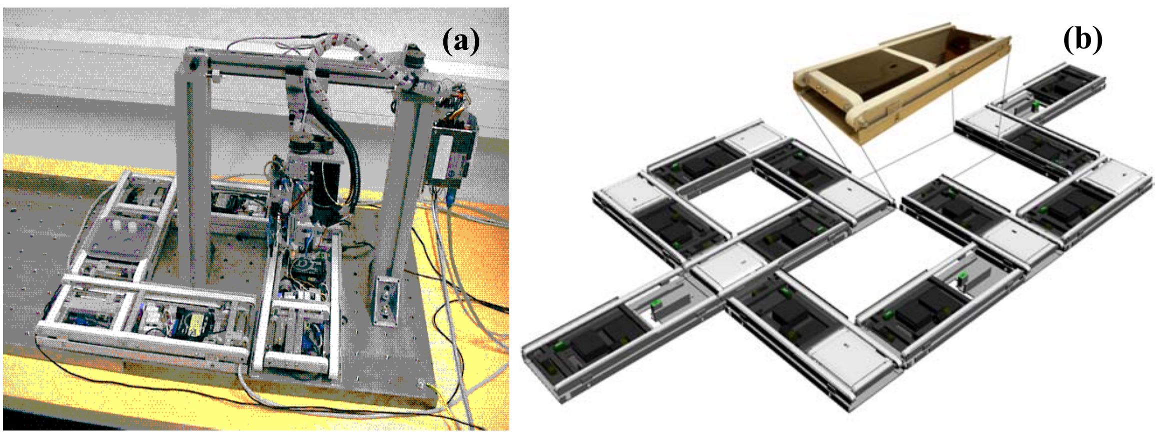

Fig. 6. (a) ABAS pilot installation in a micro-assembly cell (b) Actor-based transporter

The ADACOR adaptive production control approach is neither completely decentralized nor purely hierarchical, but seeks to implement a system between these architectural extremes. It supports other intermediate forms of control, due to the self-organization capability associated with each ADACOR holon, implemented through their autonomy factors and propagation mechanisms inspired by ant-based techniques.

4.6 Fraunhofer-IPA

Research into the realisation of a multi-agent system (MAS) for the commissioning of goods has been carried out at Fraunhoffer-IPA (Staab, *et al*., 2004). This work illustrates how a MAS may be used in industrial scenarios other than those related to manufacturing processes. As depicted in figure 7, the agent-based approach adopted by the researchers from Fraunhofer IPA in Stuttgart shows a fully-distributed automation architecture without any hierarchy, since the agents are free to interact proactively with each other, to be integrated in and also to leave the community of agents by self-decision via their communication facilities.

4.7 Interoperability among Agent-based Platforms (Schneider Electric and Fraunhofer-IPA)

In this research, two production sections of a Holonic Enterprise, each controlled by its own multi-agent-based control system (Neubert, *et al*., 2001), are presented as collaborative components within an intra-enterprise architecture.

A set of driving forces govern the collaborative activities of such a collection of production resources. These activities are chiefly related to the optimization of resources and the rapid (re)-configuration of schedules to accommodate new orders in a timely manner. Typical driving forces originate from:

1. Production specifications
    - Online ordering and negotiation;
    - Online and flexible production (re)-configuration, fault-detection and fault-recovery;
    - Online and dynamic (re)-scheduling of orders, and
2. Infrastructural perspectives
    - Registration of agents in the system;
    - Resources for finding information (including other agents from the other multi-agent-platforms);
    - Message routing, security management, error handling.

As expressed by the authors, all of these capabilities can only be successfully implemented if a reliable and safe inter-agent and where necessary inter-agent-platform communication can be guaranteed, from both functional and technical perspectives.

This work, which culminated in one of the first implementations of the integration of the two multi-agent-platforms, was presented to the scientific and industrial community at the Hannover Fair in 2002. The interoperability demonstrated was achieved based on the use of;
1) the Agent Communication Language (ACL) released by the Foundation for Intelligent Physical Agents (FIPA) as the communication tool and 2) socket technology for the technical implementation.

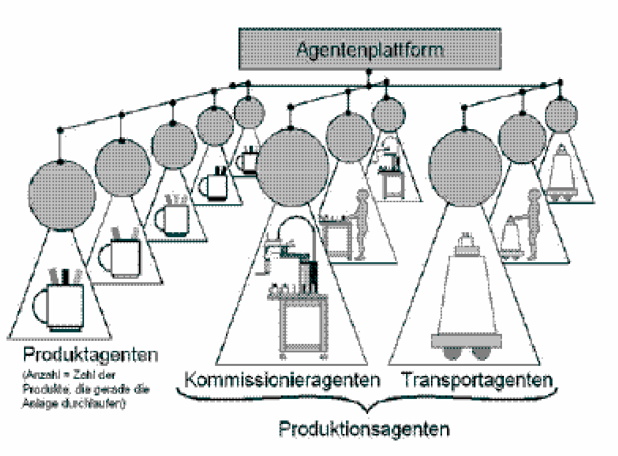

Fig. 7. Fully distributed agent-based architecture

4.8 Other International Projects

In addition to the collaborative automation solutions in the European production engineering field that have been reported here, there are some well-known international research and development initiatives that are providing prototype solutions in America and Asia, including on-going projects from Rockwell Automation (Voth, 2004) and the Holonic Manufacturing Systems Consortium (see http://hms.ifw.uni-hannover.de/).

4.9 Summary

These projects have studied the application requirements for various prototype forms of collaborative automation systems in a number of domains and have resulted in the development of a series of architectures for intelligent control systems and successful prototype implementations. However, as yet, none of these generic approaches has resulted in large-scale industrial application trials. This reticence is probably due principally to the commercial risks involved.

One of the major industrial requirements emerging from these projects is the need for powerful and well integrated engineering tools to support efficiently the design, implementation and lifecycle support of automation applications. The effort required to develop a commercially viable engineering platform of this type is obviously considerable. However, an even more important task is to raise the level of user awareness and to educate the industrial community, including both end-users and machine builders, about the characteristics and potential benefits of adopting the collaborative automation paradigm.

The role of humans in the collaborative physical networks has not yet been adequately researched. New ways of working will need to be adopted, but due principally to a lack of industrial applications, little practical experience of this has been gathered to date. If collaborative automation, based on reconfigurable, functionally modular production equipment, is adopted industrially, then it is likely to have major implications for the role of humans not only on the end-user's shop floor but also at the machine builders' and control system vendors' sites. Supply-chain interactions are likely to be substantially changed. At the machine–builders', there are likely to be more multi-disciplinary engineering teams working in parallel on many machine modules, control vendors will be able to offer many new remote support services and at the end-user sites, many manufacturing services may migrate to shop-floor-based manual workstations.

5. FURTHER WORK

5.1 Overall Goals

The authors' vision is the creation of a new approach to automation, based on the "collaborative automation" paradigm, which in the next five to ten years will have as profound an impact as the appearance of the Programmable Logic Controller in the 1970s. This practical realization of collaborative automation will only be achieved through the development and industrial exploitation of new enabling technologies in the fields of intelligent control and real-time middleware.

In this context, some key objectives need to be realised in order to make the vision of collaborative automation a reality. These are:

- To expand awareness of the behaviour of intelligent, collaborative agent-based industrial automation and control systems,
- To develop an engineering system platform and real-time distributed simulation system for collaborative agent-based controls with embedded functionality in different industrial application domains, i.e., mass production, mass customisation and lot size≥1 production with extreme customisation,
- To provide knowledge and initial tools for the successful, safe and efficient migration of intelligent collaborative automation and control techniques with embedded intelligence in these industrial domains,
- To explore the potential benefits of collaborative automation in these industrial production domains, and
- To initiate innovation-related activities aiming to integrate the advanced automation and control research into production system design and networked embedded systems to meet the needs of the manufacturing industries and to make the intelligent factory of the future a reality for Europe.

5.2 Scientific and technological objectives

With regard to the vision and the related goals mentioned above, a number of essential scientific and technological objectives have been identified. These are:

- Understanding of the processes, data sources and information needed for collaborative (agent-based) intelligent automation and embedded control at shop floor level.
- Development and evaluation of models for industrial automation considering the shop floor level as an integral part of the whole enterprise.
- Research and industrial evaluation of technologies for collaborative automation for a range of key industrial manufacturing domains.
- Development of algorithms and methods for embedded autonomous decision-making processes in distributed intelligent control environments; evaluation of the complexity of decisions to be managed by the system and of throughput of the system achieved autonomously in case of failure.
- Identification of new forms of human integration by the development of tailored human interfaces, which integrate humans into the collaborative production environment, allowing them to contribute to decision making processes as well as to learn and share knowledge.
- Development of appropriate methods and interfaces for the integration of legacy systems, i.e., to improve interoperability and knowledge sharing with existing control and management systems at all factory levels.
- Creation of a real-time distributed simulation environment for design, configuration, operation, and evaluation of collaborative agent-based controls for intelligent production systems in particular of distributed non-deterministic real-time systems.
- Specification and development of an integration platform (featuring a common physical and business run-time architecture) for collaborative production automation with special attention given to the integration with international initiatives like HMS and standardisation bodies like FIPA.
- Practical evaluations of this new technology in different production application domains in order to access to what degree the potential design, behaviour, set-up, and operational benefits of collaborative industrial automation systems can be realised.
- Provision of detailed specification and guidelines related to the standardisation and dissemination of collaborative agent-based control and automation technology within FIPA, IEC, and the European network of excellence "Innovative Production Machines and Systems."

6. CONCLUSIONS

Current approaches to implementation of production automation tend to result in a rigid coupling of related production entities (e.g., machine controllers, shop floor and higher level production, maintenance and business systems). This inflexibility inhibits the efficient configuration, flexible and robust operation, and subsequent reconfiguration of manufacturing systems. Limitations exist not only in the manner in which real-time automation systems are implemented but also in the engineering tools used to support their lifecycle.

The authors have presented a case for the widespread adoption of a "collaborative automation" paradigm that promises to provide more flexible and reconfigurable production systems. A brief overview of existing developments and implementations of collaborative automation systems has been presented, highlighting how these solutions are contributing to the state of the art in this field.

A discussion of the critical issues related to the realisation and widespread industrial adoption of collaborative automation systems has been presented. The industrial need and the current state of relevant research initiatives has been briefly assessed and gaps in current knowledge identified. Finally a set of the scientific and technical aims and objectives for future research into collaborative automation has been suggested.

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