IT Support of Mechatronic Networks: A Brief Survey

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***Abstract*—The contribution of IT in reshaping the industrial automation contexts is undeniable. If years of investment in research have not been in vain, the next generation of automation devices shall be IT enabled. This research has been carried out in multidisciplinary teams fusing the Academia and Industry and has developed along two main lines: theoretical production paradigms and IT middleware support. This paper mainly concerns the second as it provides the instantiation mechanisms for the former. There is an ongoing dispute between Multiagent and Service Oriented concepts and platforms as implementation constructs. The literature is vast in detailing their application potential and inherent benefits. There is however a set of technical challenges that must be addressed if the next generation of IT-ready devices is to be properly exploited and the true value of emerging production paradigms extracted. In this context, the present paper reviews the main technical challenges matching them against a brief survey on recent research initiatives and supporting platforms.**

I. Introduction

The socio-economic challenges triggered by a fast paced changing world dictated the end of the mass production concept as preconceived by the Fordism and Taylorism. People became generally aware of the social and environmental impact of prevalent production policies while costumer continuously increased the demand for customized products. The advent of the microcomputer introduced new possibilities for reshaping existing automation technologies. Specially European and American companies triggered significant research activities for the automation of the production processes. Machine flexibility was wrongly perceived as a panacea for the new production requirements. In an attempt to develop machines that could produce a great deal of products the research lost a holistic perspective that condemned their utilization [1]. Local flexibility, as implemented in these initial efforts, was progressively abandoned towards the development of Agile Manufacturing Systems.

Mass Customization has been traditionally perceived as the excellence paradigm in industry and services it is the new frontier in business competition for both manufacturing and service industries. At its core is a tremendous increase in variety and customization without a corresponding increase in costs. It promises the mass production of individual customized goods and services to provide strategic advantage and economic value [2]. Sustainable development requires a responsible implementation of such paradigm. To face competition, modern enterprises are increasingly adopting more efficient organizational dynamics that enable an agile response to socio-economic pressures while tackling profitable but volatile business opportunities. This led to the emergence of several types of networked interactions [3], [4], [5]: Supply chains, Extended Enterprises, Virtual Enterprises, Collaborative Networks, etc.

Overall agility is fundamental as the establishment of such networked organizations is not trivial. Partners will share profits, risks and responsibilities and ultimately the performance and success of the entire structure will always be dragged down by the less agile participant. The concept of agility has been widely debated in the literature [5], [6]. Traditionally, agility has been understood as the capability of an enterprise to operate in a "competitive environment of continually, and unpredictably, changing costumer opportunities" [7]. At enterprise level agility has to be understood in a holistic perspective. Being agile is different from being flexible. Agility implies understanding change as a normal process and incorporating the ability to adapt and profit from it. Agility covers different areas, from management to shop floor. It is a top-down enterprise-wide effort. The agile company needs to integrate design, engineering, and manufacturing with marketing and sales, which can only be achieved with the proper IT infrastructure.

Under this umbrella of Agility, several production paradigms have emerged: Bionic Manufacturing Systems (BMS) [8], Holonic Manufacturing Systems (HMS) [9], [10], [11], Reconfigurable Manufacturing Systems (RMS) [12], [13], [14] Evolvable Assembly Systems (EAS) and Evolvable Production Systems have emerged [15], [16], [17]. These paradigms denote the common concept of encapsulation of functionality in self-contained modules. These modules are then used as building blocks for the production system. Interaction between modules plays a fundamental role in the convergence of the distributed components towards a joint action supporting several production processes. Although these paradigms set the theoretical background and the main architectural guidelines, implementation remains a very significant challenge. Within the past 20 years there have been several prototype implementations with elusive results. Agent-oriented

978-1-4244-9312-8/11/$26.00 ©2011 IEEE

middleware was the preferred implementation support in the 1990's as a result of the significant achievements in the field of Distributed Artificial Intelligence (DAI). More recently Service oriented applications gained a considerable attention with the progressive adoption of web-services in well known ERP tools and the development, stabilization and adoption of several XML-based Web standards. Currently, Multiagent Systems (MAS) and Service Oriented Architectures (SOA) are perceived as competing concepts and technologies. The continuous development of both is a clear indication that neither are stable or provide the final support for automation components. This is in itself an holistic problem. This paper mainly addresses the IT support aspects that haunt most implementations and that to a great extent render them elusive from an industrial point of view. In particular, the existing research is still insufficient in covering the following aspects: cross layer interoperability, platform deployment and management and performance among other challenges later detailed. The remainder of this paper is organized as follows: section II details emerging the emerging technological challenges addressed by this paper; section III briefly surveys recent research initiatives that tackle the issues presented in section II; section IV assess existing middleware support for Agent/Service-based automation; finally, section V presents the conclusions pointing critical research/development topics.

II. Emerging Technical Challenges in Supporting Mechatronic Networks

In the implementation of networks of mechatronic components, either using MAS or SOA, there is a set of persisting technical challenges that render their use in production contexts premature. These challenges shall first be detailed so that current working solutions and research initiatives tackling them can be properly presented in section III.

A. Cross Layer Interoperability

Inside a manufacturing company or organization there are many stakeholders whose views and system requirements must be harmonized. This implies that relevant runtime information must be seamlessly accessible [18]. This requirement is specially challenging at shop floor level. One of the most pressing challenges is how to get devices information and status to the proper recipients and tools. With the advent of SOA and its quick adoption in ERP tools Web-service technology became an interesting mechanism to easily identify a specific device and extract relevant data [19]. There is however no standard way of describing the services hosted by a specific device. Most description languages, like WSDL [20], are generic and imply the use of an ontology where the system specific vocabulary is stored. Therefore, the information is accessible but there is not a standard way of making any semantic sense out of it. In this context the introduction of new tool may imply the re-design of the services hosted by all relevant shop-floor entities.

The lack of standards not only affects information exchange. As importantly, the interaction patterns between shop floor components become very hard to control without a standardized reference model. The agent community has attempted to tackle this problem introducing carefully designed interaction protocols. The FIPA Communication protocols are widely known and applied [21]. However, while they ensure robust communication, the handling of automation specific constraints is not covered.

B. Deployment

Deployment is a fundamental step in the creation of industrial systems. There is no interest in developing pluggable architectures if the main entities (Agents or Services) cannot be seamlessly deployed in different classes of controllers. Deployment encompasses in a first step the instantiation of executable code in a specific controller and in a second phase changing the hosted functionalities without the need for reprogramming or machine stop.

C. Re-Usability

The issue of adding and removing functionality from a specific target is closely related with re-usability aspects. It is, in this context, fundamental to ensure that successful coding and interaction patterns can be re-used independently of the technical specificities of a particular controller. Reusability implies that architecturally the systems should be modelled in a layered fashion with a clear distinction between device specific logic and the generic abstract functionalities that promote plugability and seamless reconfiguration. This requires a careful interface design so that all the relevant data is properly wired and handled.

D. Performance

The modelling metaphor considered in the emerging production approach cannot be easily implemented at the cost of any language. In particular, conventional logic-based descriptions (as available in most controllers) do not provide the adequate level of abstraction. It is with no surprise that most MAS and SOA implementation are JAVA/C-Sharp based and only a few are coded in C programming language (to the authors knowledge there is none written in lower level languages). There is an obvious trade-off between the abstraction of the language and the execution time. In particular managed languages (supported by virtual machines) generally introduce a significant computational overhead that undermines raw performance and excludes their use in hard real-time control. Even in Mass Customization-oriented plants motion control support is a priori excluded. In a modular architecture, performance directly impacts the way modules can be composed to deliver new functionality. The higher the number of devices being composed the less performance can be attained by the group of devices.

E. Supporting Tools and User-friendliness

Even if the previous challenges were fully addressed it must be taken into account that the resultant system instantiating a modular architecture is inherently complex. As opposed to conventional systems, emerging approaches are designed for change. System evolution and adaptation introduced a certain degree of unpredictability that has to be addressed firstly by design and secondly by the development of a specific toolbox providing a comprehensive support to the system at hand. Device interaction, if not properly understood and managed, can introduce significant disturbances in the system [22]. The system has to be presented to the user so that the underlying intricacies are transparent. This issue is closely linked with educational aspects. In a transitional period shop floor workers, with a strong background in logic based control, will have to handle a system partly designed by computer engineers and whose functioning premises are far from conventional shop floor knowledge.

These technical issues are not yet stabilized and have motivated several research projects which shall be detailed in the incoming section. While some of these challenges require a more paradigmatic approach the great majority is attached to IT support constraints as detailed in section IV.

III. Research Initiatives

Several research initiatives have pushed the early adoption of both MAS and SOA-based technologies by industrial players, but history shows that only a reduced part of the results were really applied and used in a daily basis in real industrial production scenarios.

The literature on this field is vast as attested by several significant surveys

[23] [24] [25] and [26]. Given the novelty of the area and the set of emerging challenges the pursuit for better and improved solution has never ceased. It therefore also worth mentioning some pioneering projects that contributed to the dissemination of these technological solutions: SIRENA [27], PROSA [28], MASCADA [29] and INT-MANUS [30].

The results of the previous projects paved the way to the most recent ones present in Table I. This table summarizes the most recent projects that continue to address and lead the research community and convince the industry partners by providing robust solutions to the challenges enunciated before.

As table I details the research in automation IT platforms is reaching a mature state and most of the current project are mainly focusing in advanced aspects of distributed control namely: fostering autonomous response, dynamical reconfiguration, handling complexity and deployment in heterogeneous devices.

IV. On the existing Middleware

A. Hard Requirements

The concrete IT supporting platform plays a fundamental role in facilitating the instantiation of the different production paradigms. A Internet search quickly yields a overwhelming number of agent platforms. There are however no Mechatronic IT platforms readily available which conditions most development projects to build upon existing software. In this context there are some hard requirements that must be met namely:

- Effective Support: including an active community of developers and users which are most likely supported by a mailing list and updated stable releases of the platform.
- Documentation: consistent and complete technical documentation including updated samples that clarify the typical usage of the platform should be available as well as a detailed bug/limitations list.
- Suitable for Embedded Devices: the automation world is characterized by controllers that use the minimum amount of power which directly translates into low computational resources in comparison with standard PC-based solutions (where most academic prototypes are implemented). To balance costs and performance there must at least exist optimized versions (low memory footprint, reduced complexity algorithms, etc) for embedded devices.
- Open Source: this is probably one of the most controversial issues. Using open source is often a trade-off between ease of utilization and community support and the potential for later exploring any further implementation commercially.
- Natively Distributed Environment: one of the main points of the modern production approaches is the computational distribution and decoupling of the shop floor entities. If this functionality is not supported natively the programming overhead to make it distributed is considerable.
- Decentralized: if the platform has single points of failure (a centralized management node, or a yellow pages service) there must the a safe way of making those resources redundant so that their failure does not compromise the remaining system.
- FIPA Compliance: FIPA (Foudation for Intelligent Physical Agents) is an IEEE Computer Society standards Organization [21] which has developed several standards to ensure interoperation between heterogeneous agents. FIPA standards cover robust communication and interaction as well as management. Compliance with FIPA standards is an assurance of well structured and optimized interaction patterns even if sometimes in most implementations the performance of the system is sacrificed.

B. Platform Resume

Most platforms that meet the requirements earlier specified are Agent based. However, some service-oriented specifications must also be taken into account. It is also important to remark that these rely on existing WS-* standards to build standard stacks of protocols. Contrary to MAS platforms, the focus here will be mostly over the suitable standards to the domain and not on their existing implementations. Table II details how closely the candidates match the requirements.

Indeed the table is not extensive and concentrates on the main active platforms for supporting mechatronic networks. Other platforms that would potential fit in the table (Grasshopper, ZEUS, AMES, April, ADK, Aglets) have been excluded since the respective projects have been abandoned. An active community of users and developers is probably the most important safeguard against platform abandonment

TABLE I

BRIEF SURVEY OF RECENT RESEARCH INITIATIVES

Project Name	**Summary**	**Key Topics**
FP7 IST AESOP – ArchitecturE for Service-Oriented Process - Monitoring and Control (www.aesop-mc.eu)	Investigate a Service-oriented Architecture approach for monitoring and control of Process Control applications (batch and continuous process); Enable monitoring and control information flow in a cross-layer way. All systems will collaborate in an enterprise-wide system of systems, dynamically evolving based on business needs. engineering tools, application modelling and methodologies will be investigated and highlights on the future of the domain will be provided by research and academic partners.	Real-time web services, interoperability, plug-n-play, self-adaptation, reliability, cost-effectiveness, energy-awareness, high-level cross-layer integration and cooperation, event propagation, aggregation and management.
FP7 PEOPLE COLLIS.EUS – Soft Collaborative Intelligent Systems (http://cordis.europa.eu/ – ref. 255425)	Incorporation of a large number of interacting agents into distributed information environment composed by robotic and sensor systems employing sophisticated coordination and interaction tools. The project plans to cover a wide range of applications such as manufacturing, scheduling, control, diagnosis, logistics, environmental emergency management, energy managing, and road traffic management.	Soft-computing techniques will be applied the design, analysis, and implementation of MAS including hybrid systems where several human and autonomous agents collect, exchange, and process information to regulate system behaviour.
FP7 NMP COSMOS – COSt-driven adaptive factory based on MOdular Self-contained factory units (http://cordis.europa.eu/ – ref. 246371)	Design, development and implementation of a control system for factory management with a flexible, modular and evolvable automation approach which will permit to increase the assembly factory productivity without losing flexibility. Focus on wind turbine assembly process.	Autonomous behaviour of the factory units, Multi-layer decentralised control, local intelligence (self-adaptation to different parts conditions without human intervention), and collaboration among equipment/devices to complete specific tasks.
FP6 IST EUPASS – Evolvable Ultra-Precision Assembly Systems (www.eupass-fp6.org/)	Research of affordable, cost effective and sustainable ultra-precision manufacturing solutions by offering rapidly deployable ultra-precision assembly services on demand.	MAS architecture for reconfiguration of equipment modules driven by a set of production requirements defined in a Assembly system design ontology; specification of a new agent model to address the specific needs of precision modular assembly systems catering both for physical and logical constraints of the modules.
FP7 NMP GRACE – InteGration of pRocess and quAlity Control using multi-agEnt technology (http://cordis.europa.eu/ – ref. 246203)	Application of a cooperative MAS operating at all stages of a manufacturing system, integrating process control with quality control. The project seeks to close the gap between theory on MAS and adaptive/intelligent agents and the control systems actually implemented in manufacturing lines.	Development of an architecture integrating process and quality control, development of self-adaptation and self-optimization mechanisms, development of modular and adaptive testing systems, prototype validation.
FP7 NMP IDEAS – Instantly Deployable Evolvable Assembly Systems (http://www.ideas-project.eu/)	Address the instantiation of mechatronic agents in state of the art industrial controllers focusing in agent-based fault-tolerant control and reconfiguration aspects.	Embedding of a MAS environment into industrial controllers to explore the real application and validation of the domain at device level.
FP6 NMP I*PROMS - Innovative Production Machines and Systems (www.iproms.org/)	Assemble of a critical mass of world-class researchers focused upon jointly generating the innovative design and manufacturing concepts, tools and techniques; establish a common research infrastructure; provide EU industry, through research training/ education, with a constant flow of qualified specialists adept at designing, managing and maintaining knowledge-based manufacturing.	Integration of Human and technical resources to enhance workforce performance and satisfaction; conversion of Information to Knowledge; reduce production waste and product environmental impact; develop innovative manufacturing processes and products with a focus on decreasing dimensional scale.
FP6 NMP PABADIS PROMISE (http://www.pabadis-promise.org/)	Research the next generation of control system architecture enabling manufacturing systems to dynamically reconfigure assembly, production, and transport in a plug-and-participate way, enabling a fast, flexible, and efficient manufacturing processes.	Dynamic reconfiguration of assembly, production, and transport systems in a plug-and-participate way; dynamic design of control applications on demand related to the intended products; high degree of control code flexibility which enables an all-round plant, only limited by its physical parameters; integration of customer demands until their ultimate point of no return by physical/machine reasons; and cross company wide cooperation over the whole supply chain.
FP6 IST SOCRADES – Service-Oriented Cross-layer infRAstructure for Distributed smart Embedded deviceS (http://www.socrades.eu/)	Creation of new methodologies, technologies and tools for the modelling, design, implementation and operation of networked hardware/software systems embedded in smart physical objects. Application to perception and control systems in intelligent environments, in which enhanced system intelligence is achieved by cooperation of smart embedded devices pursuing common goals.	Development of a comprehensive device-level SOA infrastructure for encapsulating intelligence and sensing or actuating skills as services, as well as to specify associated frameworks for management and orchestration of device-level services; definition of a methodology for describing services with semantic mark-up that can be interpreted and processed by agents for the discovery, selection and composition of resources.
ITEA SODA – Service Oriented Device & Delivery Architecture (www.soda-itea.org/)	Create a service-oriented ecosystem built on top of the foundations laid by the groundbreaking SIRENA framework for high-level communications between devices based on the service-oriented architecture SOA paradigm.	Focus on the tools and methodologies to ease de design and deployment of intelligent devices and services into small intelligent automation devices to create a MAS-based service-oriented environment.

as well as a the existence of recent releases. None of the platforms analysed directly fulfils the automation requirements of Section II and the first relevant decision that has to be considered from a developing point of view is to whether consider MAS or SOA platforms. There is an open debate on which best suits automation requirements. The authors have discussed elsewhere that most of the controversy arises from a confusion between the conceptual framework of MAS and SOA and the corresponding implementations and that there are inherent benefits in considering the best of both world regardless of the platform [31], [32]. One of the fundamental differences that must be acknowledged is the notion of state management. Web-services are, by design, stateless among other defining characteristics which include a standardized service description/interface and the lack of support for the internal functions used by the service. MAS platforms, on the other and, have focused in the design and maintenance of the internal state of the agent.

1) JADE: Among the MAS platforms considered JADE [33] is the one with the most active community of users. By default it provides a behaviour based logic approach to agent programming implemented in JAVA. The platform is full-featured and open. Recent extensions, not provided in the default installation, include: JADEX that implements a Belief-Desire-Intention reasoning mechanism and WADE that supports the execution of workflows. JADE Agents are hosted by containers. The Main Container centralizes global information and services. JADE supports a replication mechanism to ensure the robustness of the platform. JADE is natively FIPA compliant which ensures robust and structured interaction between the agents. The communication between agents in different hosts is supported by JRMI.

2) JACK: JACK [34] is a proprietary agent platform implemented in JAVA, by Agent Oriented Software Pty. Ltd. (AOS), that can be programmed using BDI logic. The product provides a visual and integrated development environment. The source is not open and the community support is limited to the users of a commercial product. AOS provides different levels of customer's support. Communication between agents hosted in distinct machines is supported by a proprietary protocol implemented over UDP. JACK is not natively FIPA compliant yet a third party plugin is available.

3) MADKIT: MADKIT [35] is an open source platform, written in JAVA, that provides a customizable execution kernel which can be as little as 40 kb rendering it interesting for devices with constrained computational power. The latest stable release dates from 2008. The development release is from 2010 and it is not meant to be used by people without previous MADKIT experience. FIPA compliance is a work in progress. Communication can be specialized at will but shall typically be handle by CORBA. The community support appears to be rather limited at the moment although the development of a new release indicates the continuation of the project.

4) Cougaar: Cougaar [36] is the result of a military focused research, funded by US Defense Advanced Research Projects Agency (DARPA), for the development of high reliable distributed applications for large scale and complex systems. The main focus of Cougaar is tolerance to the lost of functionality in the agents constituting the system. Cougaar is written in JAVA and communication is handled by JRMI. The latest release dates from 2009 and the forum shows little activity.

TABLE II
MIDDLEWARE CONSIDERED

		Community	Documentation	Embedded Ready	Open Source	Distributed	Decentralized	License	FIPA
MAS	JADE	✔	✔	✔	✔	✔	!	**LGPL**	✔
	JACK	✔	✔	✔	!	✔	✔	**Prop.**	!
	MADKIT	✔	✔	✔	✔	✔	✔	**LGPL, GPL**	!
	Cougaar	✔	✔	!	✔	✔	✔	**Cougaar OSL**	x
SOA	DPWS	✔	!	✔	✔	✔	✔	**Prop., BSD, EPL**	x
	OPC-UA	✔	✔	✔	✔	✔	!	**MIT, RCL, RCBL, CSCL**	x

5) DPWS: A proposal for using WS protocols for device networking, entitled "Devices Profile for Web Services" (DPWS), firstly submitted in May 2004, is currently a standard by the OASIS Web Services Discovery and Web Services Devices Profile Technical Committee, since June 2009 [37]. DPWS is a common WS middleware and profile for devices, which defines two fundamental elements: the device and its hosted services. Besides Microsoft original stack, there are other open source implementations, such as the ones from WS4D and SOA4D, which already supported several prototypes in the domain of industrial automation.

6) OPC-UA: The OPC UA [38] is the new version of the well-known OPC architecture originally designed by the OPC Foundation to connect industrial devices to control and supervision applications. Although the adoption of web services technology is the most visible transformation, it is important to refer the support for secure communications, unification of several OPC data models, such as Data Access, Alarms & Events or Historical Data Access, as a single set of services, and extension to other domains such as manufacturing, production, maintenance and business applications. A tentative merge between these last two specification was already described in [39].

V. CONCLUSION

Emerging challenges in IT support for Mechatronic Networks have been tackled from a paradigmatic and a technological points of view. Despite the advances in both development vectors, IT platforms suitable for automation are only now reaching maturity. From a technical point of view, performance is still the main limitation, regardless of the technology considered, that requires a significant effort if these platforms are to be used in time constrained applications. Conceptually, the main challenges are in how to control the complexity of these modular systems. Despite powerful and sufficiently tested at prototype level there are no concrete evidences on the scalability of these distributed approaches when the system is composed of thousands of nodes. However, in the current socio-economic scenario, increasingly directed to good customization, the agile approach envisioned and implemented in the several initiatives cited is an unquestionable strategic advantage over the traditional approaches which are becoming obsolete in a sustainable development production framework.

ACKNOWLEDGMENT

This work was supported by FCT (CTS multiannual funding) through the PIDDAC Program funds.

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