A System of Systems view on Collaborative Industrial Automation

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Abstract—**Industrial systems are increasingly integrating Internet and other emergent technologies, concepts, methods and tools, coming from the IT world, such as cloud- or service-based approaches. As a first main consequence, the industrial automation landscape is also increasing in complexity, presenting new challenges for engineers and practitioners. Examples include dealing with evolvable heterogeneous structures that do not appear fully formed and where functions and purposes are added, removed or modified along the life cycle; as well as managing emergent properties and behaviours of entire systems, e.g. resulting from integrating new systems being not localized to any single system component. Although the component systems keep their operational and managerial independence, when they are interconnected and integrated, collaboration, cooperation and competition relationships, appear all along three major collaboration axes (lifecycle, value chain and enterprise), which should be understood, controlled and managed. In this work an effort to examine those systems under the prism of System of Systems approach, and address first recommendations to determine architectures, evolutionary steps, benefits, roadblocks as well as migration approaches that need to be followed is presented.**

Keywords—industrial collaborative automation; cloud-based systems; service oriented architecture; web services

I. INTRODUCTION

In the last decade we have seen significant changes in the industrial automation domain and the initial assessment is that their impact will be a long-term one. Among other things, the rapidly increasing penetration of Internet technologies and concepts, have increased openness, interconnection, information-driven integration and cross-layer interaction [1]. As today agility is a key characteristic of modern enterprises, decisions need to be made based on real-time data and in parallel be enforced not only at local industrial processes but factory-wide as well as at several partners that interact with them. This is challenging, especially when we consider the whole business network ecosystem, which itself is a System of Systems (SoS). Bringing it together with collaborative automation concepts may increase the competitive advantage and provide significant benefits; however, doing so assumes the tackling of several technical and architectural challenges.

The term SoS has no clear and widely accepted definition [2][3]; several of them exist and are applicable in different domains depending on the knowledge about system´s structure and behaviour [4]. Nevertheless, for the objectives of this work, we will concentrate on an emergent class of industrial automation systems, which are built from components that are large-scale systems [5] themself. Multidisciplinary in nature, they link many (sub-)systems of a wide variety of scales, from individual groups of sensors to e.g. SCADA and DCS, process execution and planning systems, MES and ERP, etc. The resulting combined systems are able to address problems, which the individual components alone would be unable to do, and to yield control and automation functionality that is only present as a result of collaboration and the creation of new, “emergent” behaviour, that directly depends on the information sources, and results of composition or aggregation of existing and emergent distributed management functionalities [6].

However, existing methods, tools and system engineering practices do not scale well to this kind of complex eco-system that relies for its critical operations on the interactions of different systems. Industrial solutions built on top of the Systems of Systems engineering paradigm are implemented using specific technologies, depending on the application domain and the range of sometimes conflicting requirements and constraints that have to be respected.

Today, implemented "Collaborative" Industrial Systems of Systems should be distinguished from large but monolithic systems by the independence of their inter-related components. Following the Collaborative Manufacturing Model (CMM) paradigm [7][8] (as depicted in Figure 1, from [9]), those systems are on the one side generally distributed along the supply chain and the enterprises axes, but on the other side they are from evolutionary nature, showing emergent behaviours along the life-cycle axe. Moreover, they present a geographic extent that generates strong limitations to mainly interact by data and information exchange and only sometimes also physically exchange of material and energy.

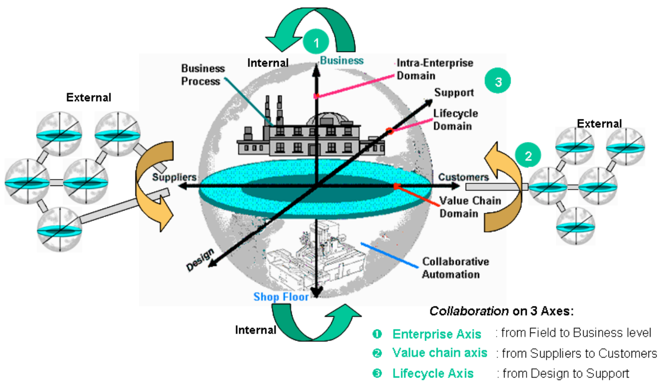

Figure 1. Collaborative Manufacturing Model Paradigm - a System of Collaborative Systems

II. From Today's Automation to System of Systems

Today's factories are structured, from the administrative as well as from technical or IT infrastructure point of view, in a hierarchical manner. Complexity becomes increasingly visible as systems are often composed as sets of numerous other systems, usually including separate systems for plant operation, maintenance, engineering and business. These systems are usually multi-disciplinary and heterogeneous with limited interoperability. Also, each such system can include a number of other sub-systems themselves e.g. isolated control and/or monitoring systems within the overall process automation system. Individual sub-systems are able to work autonomous, although they are intended to support the overall operation of the production that, depending on the production schedule, will be reached while using all or several of the sub-systems.

Significant effort has been invested towards laying down the fundamentals of structuring complex production systems, defining models and exchange formats of information representing different aspects of equipment used or to define suitable protocols for horizontal or vertical communication. There are numerous standards addressing that area on global or specific level. The most popular and applied in practice are the definitions set up within the ISA 95 / IEC 62264 standard [10]. Typically, today's production systems (factory and process) are structured in a 5-level hierarchical model. IEC 62264 additionally defines a manufacturing operations management model, implicitly represented by real installations. The standard defines functions mainly associated to level 3 and level 4, objects exchanged and their characteristics and attributes, activities and functions related to the management of a plant, but does not explicitly define the implementations (tools) hosting a specific operation nor the precise assignment to one of the levels 2, 3 or 4. Realizations depend on individual customer needs and the tool manufacturer strategies. For instance Maintenance Management operation may typically be assigned to a Computerized Maintenance Management System (CMMS) or a Manufacturing Execution System – both being typical Level 3 tools – but also to an Enterprise Resource Planning or a Distributed Control System.

The ways of communicating among the levels are very different. Level 1 and level 2 are commonly connected through either point-to-point cabled solutions (4-20 mA current loop) or through field buses (Profibus, Foundation Fieldbus, etc.). Ethernet based communication protocols (like Profinet) are getting more popular, however even HART communication are also present.

A high degree of interoperability in decentralised or distributed automation systems is achieved by smart field device profiles. Profiles are very common for nearly all field bus systems since many years. The basic models of these profiles are usually parameter lists with the related behaviour descriptions for example state machines, function block profiles or object based profiles. Common for all of them is the existence of a tightly-coupled connection between the field devices and host devices such as PLCs. Usually there is no direct connection among the field devices.

Field buses, Ethernet based protocols or application profiles use, can give an impression of a standard solution but there are numerous of such real or company standards. Figure 2 highlights the diversity of interfaces between the different levels and tools, as well as data models and standards used, which may even be distributed across the life cycle of a production system.

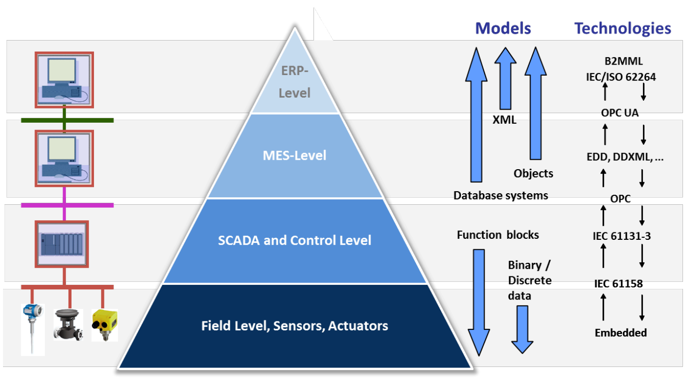

Figure 2. Media breaks throughout production hierarchies

Service oriented architectures are seen as a promising concept for overcoming this situation [1]. Cutting edge research projects such as SOCRADES (www.socrades.eu) and IMC-AESOP (www.imc-aesop.eu) have shed new light to the way service oriented architectures can be used within automation and integration into production management applications. SOCRADES was dedicated to investigate the SoA use in manufacturing applications with focus to integration and communication characteristics to be supported by production management and control components distributed across several layers, as depicted in Figure 2.

The IMC-AESOP project has proposed a new information-driven interaction [11] among the different layers and systems, which is cloud-based [12] and can be used for realising the vision of collaborative System of System approaches. Although today factories are composed and structured by several systems views, and interacting in a hierarchical fashion, following mainly the specifications of standard enterprise architectures, there is an increasing trend to move towards information-driven interaction that goes beyond traditional hierarchical deployments and can coexist with them. With the empowerment offered by modern service-oriented architectures, in theory the functionalities of each system or even device [13] can be offered as one or more services of varying complexity, which may be hosted in the cloud and composed by other (potentially cross-layer) services, as depicted in Figure 3. In practice we expect that mostly monitoring aggregated functions that convey information needed by other services (e.g. visual servo control [14]) or cross-enterprise systems are good candidates for such a step, at least in the mid-term. In any case, this is an issue for future discussion and evaluation as to what degree actually it makes business sense, the technology challenges and the impact on the operational phase.

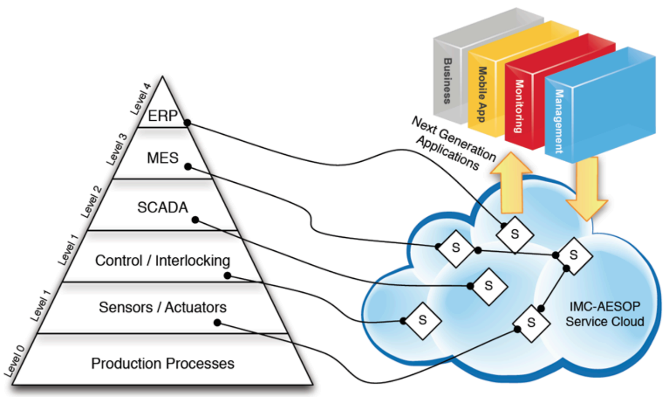

Figure 3. Future industrial system view of cloud-based composition of cyber-physical services

This marks a paradigm change in interactions among the different systems, applications and users. Although the traditional hierarchical view coexists, there is now an alternative/complementary flat information-based architecture available that depends on a big variety of services, exposed by the cyber-physical systems and their composition. Thus, next generation industrial applications can now be rapidly composed, by selecting and combining the new services and capabilities offered (as services in the cloud) to realise their goals. The envisioned transition and migration to the future cloud-based industrial systems is depicted in Figure 5 [15].

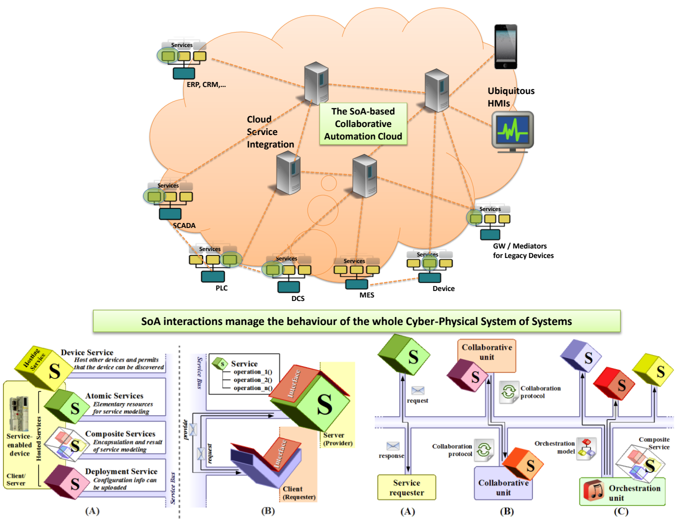

Figure 4. SoA-based Cyber-Physical SoS

Within IMC-AESOP, the results stemmed from SOCRADES are applied to the process automation domain, starting with applying SoA concepts to SCADA systems. While identifying and defining affected SCADA services, fundamentals for encapsulating typical characteristic of SCADA systems are laid down. Combining this approach with concepts coming from cloud computing [12] potentials are seen using these services at the application layer executed on real or virtualized resources of a next generation SCADA [11]. Such SCADA/DCS systems are dynamically accessible by other sub-systems, like systems for plant operation, maintenance, engineering and business, are building one of the elements of a System of System styled production management system.

III. Concept Cartography and Mapping

Maier in his report about "Architecting Principles for Systems of Systems" [4] addresses five principal characteristics that are useful in distinguishing very large and complex but monolithic systems from true Systems of Systems i.e. (i) Operational Independence of the Elements; (ii) Managerial Independence of the Elements; (iii) Evolutionary Development; (iv) Emergent Behaviour and (v) Geographic Distribution.

A set of key challenges appears across the enterprise architecture, especially during its specification, design, implementation and operation with consideration of the Service-oriented Architectures (SoA) and Systems of Systems (SoS) paradigms. These challenges become more evident when brought in conjunction with the characteristics depicted in Table 1, which are an extension of the characteristics of SoS as these are addressed in [16].

In order to make the implementation of a collaborative System of Systems, fulfilling all (or at least a big number) of these characteristics feasible, major features such as structural, operational and managerial independence of the shop floor, enterprise constituent systems and collaborative network of suppliers and customers have to be well understood, implemented and managed (supervised and controlled). This implies the ability to connect heterogeneous HW/SW components, interoperability of information systems, plug and play, self-adaptation, reliability, energy-awareness, high-level cross-layer integration and cooperation, event-propagation and management, among others.

A. *Concept Amalgamation*

The fusion of CMM, SoA and SoS implies an significant paradigm change, which basically is based on the fact that the data is computed within the network but not in a priori known places. As a matter of fact, a shop floor, an enterprise or a network of enterprises configured and managed (from architectural and behavioural viewpoints under this technology fusion paradigm) is virtualized by the services generated and exposed by its components (HW and SW). One of the main results of this virtualization is then that individual and composed functionalities emerge and are exposed for being accessed by all systems of the collaborative network.

Table 1. SoS characteristics and mapping to collaborative industrial automation domain

CMM SoS Characteristics	Definition for Industrial Collaborative SoS
Degree of Centralization	Extent to which a single authority can make all decisions
Stakeholder diversity	Commonality of needs, interests, and expectations
Operational Independence	Ability of constituent systems to operate without interaction with other systems
Diversity of constituent systems	Technical heterogeneity
Independent evolution of participant systems	Synchronization of changes to participant systems capabilities and technologies
Asynchronous demand	Expectations on the capabilities of the SoS change unpredictably
Volatility	Rate at which participating systems enter and leave the SoS
Predictability of quality attributes	Degree to which users can rely on stable qualities
Range of capability provided	Number of different types of functions
Problem class	Degree to which objectives are complete, consistent, well-defined
Control of Evolution	Degree to which changes can be managed or controlled
Degree of Emergence	Degree to which behaviour (or properties) of the whole not exhibited in any of the parts
Stability	Stable Behaviour of the whole is required
Traceability (convergence)	Reaching Solutions in traceable manner. Converging to a required solution or set of solutions
Controlability	Limitations to degree-of-freedom from component systems (what is allowed and what is not allowed), which system takes leadership to start collaboration and how the control will be transferred among system components
Observability	How the SoS behaves. Is it continuously observable?
Flexibility / Reconfigurability	Many different behaviours are known. New parameterization and/or combinations facilitate new behaviours.
Evolvability	Quantity of components is not closed. New components can at any time be added Plug-in and Plug-out.

We are moving towards an amalgamation of the existing physical infrastructure with a software (cyber) component, which allows the virtualization of structural specifications and of functional features of the first one. But contrary to the traditional way of developing and implementing this SW, this time it follows service-oriented approaches by enabling the abstraction of the infrastructure's capabilities as services that are exposed in a "Service Cloud" (as envisioned in Figure 1 and realized in Figure 3). These "Services" can then be composed, orchestrated and choreographed in order to allow system's structural evolvability, the creation of evolutionary behaviours like "collaborative automation functions, but maintaining operational and managerial independency of the component systems.

The heart of these infrastructures relies on SCADA and DCS systems to realise real-time monitoring and control, and to support collaborative automation. Monitoring, control and collaborative automation are key issues in this new era, where the trends point towards real-time (i) data acquisition for large-scale systems, (ii) analytics and decision support processes and (iii) management (both closed-loop control and soft-control) [11].

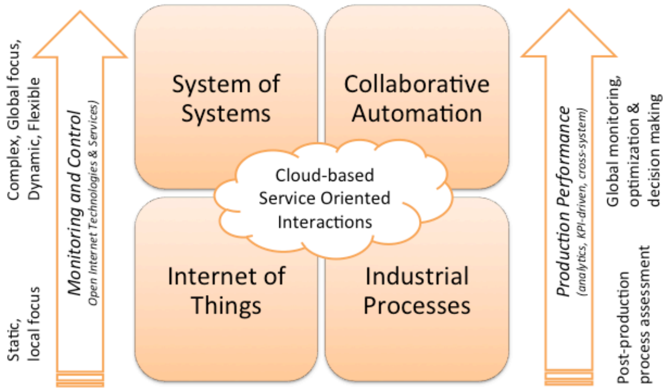

Figure 5. The paradigm shift linking SoS with Collaborative Automation via cloud based SOA interactions

The IMC-AESOP project envisions the next generation of such SCADA/DCS systems that depend on SoA and cloud technologies [11]; it also partially demonstrates their capabilities in constraint scenarios. The addressed approach already penetrates several key infrastructures such as e.g. smart grid, manufacturing, process industry, etc. Additionally, the approach IMC-AESOP fosters, could provide a hint on challenges and capabilities that the next generation monitoring, control and collaborative automation infrastructure may have to deal with.

This paradigm shift that links collaborative automation and System of Systems is depicted in Figure 5. The focus is on open technologies that link together simple devices and systems as well as larger groups of them. The interaction is cross-layer and information-driven; hence a collaborative infrastructure is created where several stakeholders can interact independent of their complexity and goals. As we move towards the system view and taking into account the collaboration nature sought, the more we rely on real-time analytics, monitoring and control not only for (sub-)systems but for processes and their groupings. The complexity increases and the interaction among them becomes highly dynamic and temporal, which presents new challenges on our understanding how such systems may function, operate, be maintained and supported for their lifecycle. Support will be needed also from the infrastructure in order to enable the collaboration and open interactions. As an example an initial architecture and a set of services is proposed [6] that could help towards this direction.

B. *Example: Next Generation SCADA/DCS*

Let us consider as an example the next generation of SoA-based SCADA/DCS systems that are empowered by the advanced envisioned infrastructure, and assess the System of System characteristics that they depict [17].

Operational Independence: The future SCADA/DCS systems may be composed of functionalities that reside on operationally autonomous subsystems (upon which only supervision or optionally management can be imposed). A DCS system composed by aggregation of cloud-based services monitoring specific devices within factories for preventive maintenance is such a potential example.

Managerial Independence: All of the components operate independently. However as ad-hoc and cross-location goals come into play (e.g. the monitoring of specific devices), one can set up easily a virtual monitoring system for the specific functionality that coexists but does not enforce any management dependencies. Hence all systems operate autonomously and can collaborate at various levels if needed (e.g. in case of a failure prediction)

Geographical Distributions: Components can be located anywhere and the interactions of these cyber-physical systems happen on the cyber-world i.e. as interaction among higher level services or applications (e.g. at enterprise level).

Emergent Behaviour properties/capabilities: A basic set of functionalities, corresponding to the physical properties, as well as their time envisioned interactions might be available. However as these systems interact with each other, an emergent behaviour is realized. For instance early identification of problems and re-adjustment of the processes may lead to strengthening of self-* features such as self-healing and self-management.

Moreover, the composition, orchestration and choreography of the services exposed into the "Service Cloud" guarantees the generation of sometimes new emergent behaviour that were not existing or shown by the initial systems and allow performing, among others, collaborative automation functions.

Adaptive or evolutionary development: The system may adapt to external or internal events coming explicitly as part of the interactions with the stakeholders or as a result of the emergent behaviour. Additionally, as its parts evolve independently (e.g. with better sensors, more sophisticated services, better algorithms for pattern recognition and management to name a few), the system is collectively evolving itself.

As we can see, the next generation of SCADA/DCS systems depicts several System of System characteristics, and in conjunction with the usage of an advanced service-based infrastructure as an enabler for collaborative automation, the different concepts complement each other well.

SCADA and DCS systems are in the heart of the modern industrial infrastructure. The rapid changes in the networked embedded systems and the way industrial applications are designed and implemented, call for a shift in the architectural paradigm. The next generation SCADA and DCS systems will be able to foster cross-layer collaboration with the shop-floor devices as well as in-network and enterprise applications. Ecosystems driven by (web) service based interactions will enable stronger coupling of real-world and the business side, leading to a new generation of monitoring and control applications and services witnessed as the integration of large-scale Systems of Systems that are constantly evolving to address new user needs.

C. *Potential Roadblocks*

The vision of collaborative automation based on SoS is challenging and several roadblocks will need to be tackled. The approach may fail not because of technology immatureness but because of unwillingness to share or collaborate (or failure to recognise when and how to do so). The appropriate business models and incentives need to still be investigated, demonstrated, and assessed. It is however clear that without open data exchange as well as open services that enable collaborative behaviour and interactions at several layers, any successful effort will have to overcome several grand challenges.

So far we see that SoS do have the properties to meet most of the requirements. Critical issues that may interfere include: event based control, security, real time guarantees, SoA interoperability, inter- and cross-domain integration, legacy to SoS migration, legacy SoS integration.

Some example difficulties / challenges experienced in the design of this SoS include:

- Modelling of SoS (hierarchical vs. distributed vs. federated) and capturing the multi-domain requirements and dependencies (domain specific, cognitive/social etc.).
- Capturing and managing complexity and its requirements at system level
- Capturing and managing collaborations at SoS levels / maintain adaptability (not context-specific behaviour)

Some example difficulties / challenges experienced in the operation of this SoS include:

- Dealing with emergent behaviours and shared (common) awareness
- Holonic simulation & testing of SoS infrastructures, particularly when "evolvability" is addressed.
- Maintenance and evolution of SoS with agility in mind (including risk assessment)

Especially in our case, some of the identified hands-on challenges include:

- Migration of competence from legacy to SoS collaborative automation
- Issues due to complicated technology and legal interaction between various stake holders
- Enabling collaborative interaction while maintaining the requirements at different levels in the operating organization e.g. robustness of event based closed loop control and real time performance.

What is of key importance in order to decide on the next steps, is the realization of concrete examples that demonstrate the viability of the approach on specific domains as well as in a cross-disciplinary manner. Typical example would be the full integration of information from all levels in a factory, with enterprise and information systems not only of that organization but at a wider level e.g. within a smart city. Especially cross-layer interactions among distributed systems operated by different entities and their collaboration are key examples. For instance in future smart cities, holistic monitoring in real-time of CO_2 emissions and energy usage is expected; and to achieve this information from SCADA/DCS systems managing in-city factories, the smart grid, smart buildings, PV and wind parks etc. will need to be integrated A better understanding of such highly dynamic and collaborative infrastructures needs to be obtained, and the potential roadblocks penetrating design, deployment and operation must be assessed and efficiently tackled.

IV. CONCLUSION

We are witnessing significant advances in the industrial automation domain, where information and communication technologies and concepts empower new approaches that may lead to the realization of a new breed of innovative industrial applications and services with widespread impact. In this direction, bringing together collaborative automation vision with the System of Systems may yield significant benefits for more agile enterprises that will handle the complexity and still optimize their performance. SoA as well as emerging technologies such as cloud-based approaches [18] may act as glue for a paradigm shift. Although some initial steps are done within the IMC-AESOP, significant efforts are still to be devoted towards better understanding, demonstrating and assessing real world approaches that utilize the proposed concepts.

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