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IFAC PapersOnLine 51-11 (2018) 803–808

# Distributed control via modularized CPS architecture Lessons learnt from an industrial case study

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Abstract: This paper provides a discussion about modularization of production systems equipment (i.e. logistic or manufacturing equipment) with embedded controllers that are at the basis of the paradigm of CPS (Cyber Physical Systems). The paper strongly grounds both on a solid scientific background and on an industrial case study implementation, thus, providing empirical evidences that the authors of this paper tested within an industrial pilot.

***Keywords***: Distributed control, for MES, Cyber Physical Systems, Modularization, Logistic modules, SOA

## 1. INTRODUCTION

The manufacturing industry is facing the tendency of shorter and shorter products' and production systems' lifecycles. This calls for responsive production systems designed to be ready to be re-configured quickly and at an affordable cost (Yoram Koren 2013). Many research works have been proposed on the fascinating topic of re-configurability in production systems. Prevalent literature on this topic suggested that re-configurability is based on six enabling characteristics, among which modularity of the production system equipment plays a fundamental role (Y. Koren et al. 1999; Mehrabi, Ulsoy, and Koren 2000). It is possible to speak of modularity when the production system and its components are modular at both software and hardware level, or, in other words, they should be made of modules combinable with each other. Modularity is at the basis of the re-configurability because managing, updating and changing single modules is easier than the production system as a whole, giving the system the possibility to continuously evolve and to be re-configured in a shorter time (Napoleone, Macchi, and Pozzetti 2016, 2017). Research on modularity has received a great boost, thanks to the recently proposed technologies at the basis of the Industry 4.0 and Smart Manufacturing, such as the Cyber Physical Systems (CPS), an evolution of embedded systems featuring a tight combination of collaborating computational elements that control physical entities (DG CONNECT 2013). CPS enable a great potential of innovation in many areas including manufacturing and production (Raj et al. 2010). In fact, CPS promise a breakthrough in achieving interoperability, flexibility, and re-configurability of devices and systems (Leitao, Ribeiro, and Lee 2017). Indeed, with the emergence of CPS, the agent domain may experience a renaissance (Karnouskos and Leitão 2017), allowing to deploy solutions that have been postulated in research since many years in real industrial contexts. CPS powered by Web Services (WS) are able to connect computers and devices with each other using the Internet to exchange and combine data in new ways, while enhancing interoperability (Iarovyi et al. 2016). WS are commonly deployed in Service-Oriented Architectures (SOA), although the SOA principles are generally applicable to services and are not specific to WS. SOA includes one or more service requesters coupled to one or more service providers via a bus. In a context with CPS, SOA and WS can provide high benefits in terms of high flexibility, offered by the joint characteristics of a loosely coupled WS-based SOA and the modular nature of CPS. SOA guarantees interoperability among system components and easy re-configurability in a Plug & Produce fashion. SOA and WS are already used in many research activities and projects, also including manufacturing automation (François Jammes et al. 2005; F Jammes and Smit 2005; Severa and Pišl 2015), where SOA has been tested as a valuable solution for supporting the communication of the CPS infrastructure, proving to be powerful, flexible, modular and capable of communication, data gathering and command to / from the shop floor (Lobov et al. 2008). Moreover, flexibility has been also proved by the introduction of autonomic service management in such SOA architecture to foster the capabilities of CPS (Dai et al. 2017).

However, when implementing the CPS approach to manufacturing, the way to supply the needed domain knowledge to real manufacturing applications arises as a problem to solve. In fact, a SOA based CPS architecture is made of smart but generic components without any knowledge of the role they have to play in the target application domain (Marco Garetti, Fumagalli, and Negri 2015). This knowledge can be supplied by ontologies, that are defined as explicit, formal and shared representations of entities, to represent a certain system (Gruber 1995)

Being born in the IT field, ontologies have then been exploited also in the manufacturing sector, as previous research activities have shown (Chungoora et al. 2013; Imran and Young 2013; Lin et al. 2011; Colledani et al. 2008; Negri et al. 2017; Yang, Dubinin, and Vyatkin 2017), among which it is interesting to mention the proposal of the Politecnico di Milano Production System Ontology (P-PSO),,

10.1016/j.ifacol.2018.08.417

which is based on a structured representation of the domain of manufacturing systems, supported by the object-oriented methodology, enabling the description of all relevant aspects of a generic manufacturing system (Marco Garetti and Fumagalli 2012b; Marco Garetti and Fumagalli 2012a) and the investigation of the role that ontologies can play in CPS-based manufacturing systems (Fumagalli et al. 2014; Negri et al. 2015). Moreover, discussion on the best ontological languages to address manufacturing domain requirements has already been released in (Negri et al. 2014; Negri et al. 2016). An interesting development has been proposed by the Artemis project, eScop, that contributed with an ontology-driven architecture for manufacturing automation services orchestration, thus supporting this research activity (Iarovyi et al. 2016; Ramis et al. 2014). Indeed, regarding automation in the production environment, the PLC (Programmable Logic Controller) world has been consolidated over time as a sector closely tied to proprietary standards that work together with great difficulty. The reasons for this segmentation are primarily commercial and only partially respond to an end user request of reliability and integrated turnkey solutions. Since this technology is extremely mature, costs may be reduced if technological barriers to interoperability of devices from different manufacturers are overcome. The regulatory (IEC 61131) and technological (OPC servers) efforts in this direction have so far provided very limited responses to industry needs to combine different manufacturer devices to maximize performance and increase competition. Indeed, a pluggable/modular architecture will allow to work with different control processes and different manufacturing systems, and will enhance the reusability of the systems' modules. Such architecture should be agnostic/unaware of concrete monitored information and technology platforms (platform independent model). This architecture would also facilitate the implementation of features such as "Plug & Produce", adaptability of the systems to changes, to new equipment and to new production plans.

Nevertheless, an appropriate ontological description of the system can be fruitless if the manufacturing system is not physically modularized in accordance with the ontological definition of classes (Colombo et al. 2005). And the CPS-based modularization could be the right answer for such a need. Thus, the CPS concept promises a great potential of innovation in many areas, including manufacturing and production, in particular when following the SOA-based and ontology-based approach to production control, because physical objects are controlled by smart embedded systems and are coordinated by the communication infrastructure to which they are connected, acting as coordinated and smart physical modules. These smart physical objects are also fully compliant with the "ambient intelligence" philosophy because they contribute to an intelligent service system in which technologies are implemented for powering context aware, personalized, adaptive and anticipatory services. This powerful architecture can be used for composing different manufacturing assets in a very open way. The main benefits described in literature are:

i) more re-configurability than in custom-designed systems (Energetics Incorporated - NIST 2012),

ii) higher level of achievable efficiency, thanks to control-computing co-design (Wolf 2009),

iii) more efficient control systems of industrial processes by creating a large control loop of heterogeneous components instead of many small ones (Wang et al. 2008). Furthermore, practical benefits of CPS application in factory automation are: reduced time to market; agile response to consumer demand; integrated energy management; optimized plant operations and safety; asset management through predictive maintenance and improved reliability; detection of anomalies to prevent catastrophic events; improved productivity and flexibility, reduced production costs (Energetics Incorporated - NIST 2012).

## 2. OBJECTIVES

The paper presents a practical case in which the theoretical concepts of CPS, SOA, WS and ontology, found in literature, have been exploited to better investigate the modularity issue for a quicker and less expensive re-configuration of production systems. In particular, an industrial application is proposed in order to discuss implementation details on how to build industrial relevant results from the theoretical concepts in literature and to share important lessons learnt.

## 3. THE REFERENCE ARCHITECTURE

The present research is thus based upon the well-known concepts of CPS, WS, SOA and ontology as a way to provide system knowledge through semantic representation.

Knowledge-based semantic web services in factory automation have been already postulated by (Lastra and Delamer 2006; Loskyll et al. 2011) and the shift towards a knowledge-based control system for production systems is accompanied by the transition from traditional control architectures to ontology-based approaches (Lobov et al. 2008). In such a new context, the components can be modular and independent and the coordination can be supported by ontology based systems. MES (Manufacturing Execution Systems) can be improved by a generic ontology level, as suggested by (Long 2010) and then further analysed by (M. Garetti et al. 2013).

The research foundations of the work reported in this contributions are rooted on the eScop project, which proposed an architectural platform for the MES based on the WS, SOA and ontology principles, in order to fully exploit the CPS paradigm expressed in Section I, as presented in (Fumagalli et al. 2014).

Figure 1 represents the kernel module of the eScop platform architecture that is apt to control the physical system and to put it into connection with the upper applications. The Physical Layer corresponds to the hardware components of the production system. Each hardware component is supplemented by a SOA-based Remote Terminal Unit (RTU). Web services then guarantee the control capability of these RTUs.

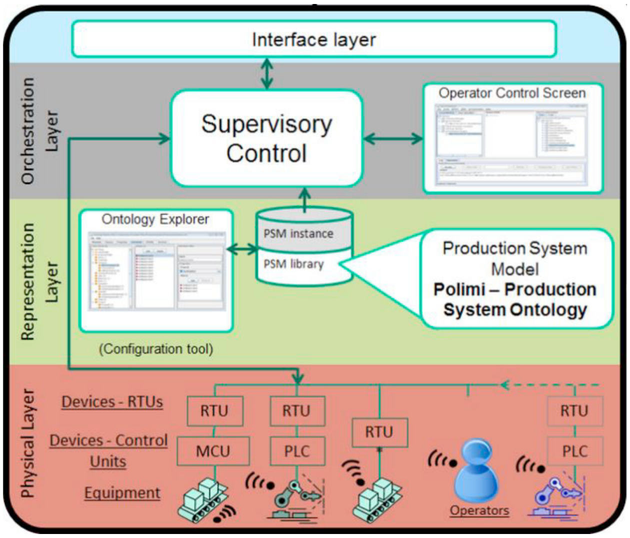

Fig. 1. Detail of the eScop Kernel (from eScop project)

The main element for the Representation Layer consists in the knowledge representation and instantiation of the specific production system, through a domain ontology of production systems (in the eScop project, this is the so called eScop Manufacturing System Ontology – MSO (Fumagalli et al. 2014)). The ontology describing the domain of production systems allows to formally instantiate a specific physical plant, in this way supporting its orchestration, i.e. the SOA-based Supervisory Control System. eScop MSO entails a meta-model of the production systems domain and is an evolution of the P-PSO mentioned above (Marco Garetti and Fumagalli 2012a). It is composed as an object-oriented model, where the objects are the entities (building blocks corresponding conceptually to the CPS modules) composing the production system and their properties, in terms of attributes (i.e. parameters) and relations (connections between objects). The language in which eScop MSO is written is OWL, as explained by (Pan 2007; Negri, Fumagalli, and Garetti 2015; Marco Garetti et al. 2015). The Supervisory Control System of the manufacturing equipment is hosted in the Orchestration Layer. The ontology is exposed as a service itself through the Ontology Service on the Orchestration platform (Iarovyi et al. 2016). The resulting architecture was designed for industrial environments.

## 4. THE INDUSTRIAL CASE

Within the eScop project, a picking system (see Fig.2) has been used as a test case. The use of this picking system is to offer a small ring carousel where the pallets of the most required products continuously turn and can be quickly called into the picking station, where the operator or an automated system can withdraw them in a short time, without waiting for their arrival from the further main warehouse. The system is composed of four main subsystems, as it is shown in Figure 3, namely: a carousel ring (indicated by "A" letter), an input/output warehouse station (B), a picking buffer station (C) and a gravity conveyor (D). This system is herein named Incas pilot line. Due to the nature of the system, a high-level control system is needed that manages the in- and out-coming pallets in a coordinated way.

Fig. 2. Incas pilot line

The traditional control system implemented in this type of picking systems is based on a rigid and hierarchical structure on a three level control schema (according to the IEC 62264 [18]).

- The lower level can interact only with the level immediately above and includes electro-mechanical devices and controllers that can autonomously take decisions. An example of such decisions is to check if the next modules is full and consequently to stop the pallet in its own module.
- The second level is composed by the PLC that coordinates the actions with other modules for a correct sorting of pallets: in fact, it is a controller station that interacts with the lower level devices to collect information and coordinate the action of actuators. This level also communicates with the third level.
- The third level is the supervisory control, that has visibility and inputs in the control system the orders of the products to be picked at the picking station by the operators and coordinates the action with other parts of the system (such as with the warehouse control system).

This work proposes a new SOA-based architecture (Fig. 1) to replace the traditional, rigid and hierarchical one in order to support the CPS modular solution. The main requirement in the development of the new architecture and in the identification of the proper CPS modules within the system is that the behavior of the system in the two solutions should be the same.

## 5. CHALLENGE OF THE INDUSTRIAL CASE

A harmonious practical result cannot be easily achieved, especially when the physical system you are using for implementing the new methodology is designed to be managed by a traditional architecture (according to the IEC 62264 (ISO/IEC 19501:2005, n.d.)). Some steps have been thus followed to practically implement the new SOA-based architecture, considering the focus on the identification of modules and the related challenges.

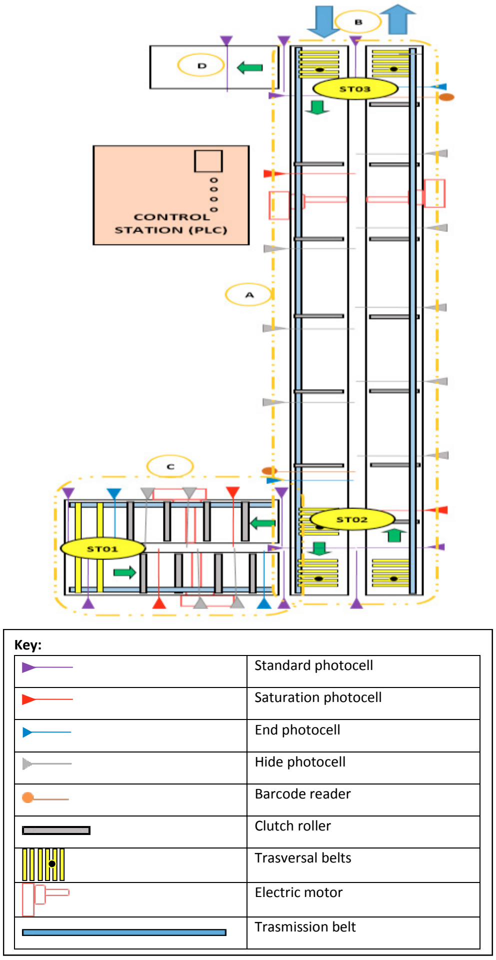

Fig. 3. Layout of the logistic system

**Definition of Module**: from the industrial user perspective (i.e. a system integrator) the first step for designing a modular solution consists of defining what is a module and how a module can be identified. By following a pragmatic philosophy, a module can be postulated as an entity of the system (e.g. subsystem) that must be self-sufficient both from the physical and control point of view. Although today the system is physically designed and realized to be driven by the current architecture, the implementation of the new ontology- and SOA-based solution requires that all elements are treated taking into account the new control architecture.

**Positioning of RTUs**: a specific importance is covered by deciding which are the components that are part of each module and controlled by its own embedded device (i.e. RTU). This is a key aspect for the definition of the eScop Physical Layer (P. Balda and Štětina 2015; Pavel Balda and Štětina 2015). To this regard, the logistic system used as test bed within the eScop project has been split into several modules. Each module has few sensors (i.e. photocells) allowing the control system to supervise and regulate the flow of pallets. In the traditional architecture there is just one single entity, i.e. the PLC, controlling the sensors, thus easily elaborating signals and keeping the related decisions. Instead with a distributed architecture the sensors signals should be captured, sent to orchestrator (i.e. the supervisor), elaborated and communicated to the embedded device of the following module for synchronization purposes. However, when implementing the new control architecture, it was discovered that the communication phase is affected by a relevant latency of signal. This issue represented a serious challenge to overcome while implementing the solution. Facing this problem in a proper way forced the team on re-designing the assignment of components to each module (and to its own embedded device). For some photocells the signals were even split to be used from both adjacent modules. A second issue the team has been working on is defining a loop between two neighboring modules, without involving the orchestration, thus speeding the communication for those signals, that need to be used outright for managing the system. This is a simple example of what a real implementation implies, compared to a theoretical design.

## 6. POSSIBLE SOLUTIONS FOR PRACTICAL IMPLEMENTATION

Physical realization of control hardware consisting of 10 RTUs is depicted in Fig. 4. For simplicity of installation, the RTUs are located in one unique place, instead of physically distributed on the plant. This schema followed for this demonstrative pilot does not anyway prevent the concept of distributed control. Each RTU is based on the microcomputer Raspberry Pi equipped with the UniPi input/output board.

The combination of physical equipment (e.g. conveyor) and RTU creates a CPS module. At this point the issue is: how to properly transform the centralized control system of the logistic system into a distributed one consisting of several interconnected CPS? The natural way of dividing a centralized solution to a distributed one is to use a standalone CPS for each equipment module and to control the module using adjacent physical inputs (from photocells and barcode readers) and outputs (to motors and clutch rolls) corresponding to the module instrumentation. But how should signals be handled from photocells located between two modules (see Fig. 5)?

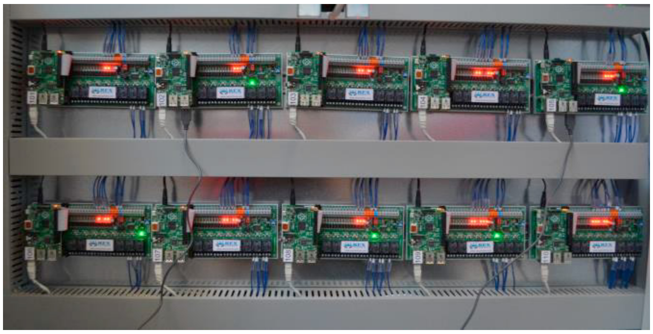

Fig. 4. RTUs installed on INCAS pilot line

This was one key challenge, representing something that can be conceptually seen as a simple issue, but that can become an important aspect to be solved in order to make an efficient implementation. With reference to Fig. 5, there are the following possibilities to handle the photocell F7 signal:

1. Read the photocell signal in D1 CPS
2. Read the photocell signal in T1 CPS
3. Split the signal and read it in both CPS
4. Read the signal in one CPS and communicate it to the other CPS.

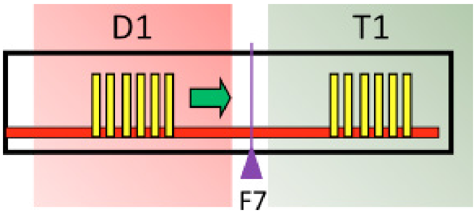

Fig. 5. Photocells between two modules

The first option cannot be used because T1 CPS needs the photocell signal for timing of stopping cases inside T1 module. This correspond to all the cases when sensors and information must be provided without time delay and impact on control of the equipment.

The second option is feasible because the F7 photocell signal is read locally in the CPS which controls input cases movement and this connection does not suffer from any additional delay. In this case the module D1 does not need the F7 signal. This practically correspond to all the cases in a manufacturing or logistic system when a sensor is located between two modules, but, indeed, it supports control functionality of just one of them.

The third option can be used when both adjacent CPS need the photocell signal. This is the case between buffers and neighbor decision making modules, where a unique photocell (at the end of the buffer) is installed. This solution is much better than communicating the signal through representation or orchestration layer, which causes significant signal delay. More than a simple logical deduction, this fact was experimentally verified and it can be thus stated that a SOA architecture cannot efficiently handle this kind of control if information and signal are not managed locally directly.

The fourth option removes the disadvantage of the third option. Nevertheless, this requires additional wiring, which degrades the concept of pure independent modules. This removes the long delay if there is a much faster (peer-to-peer) communication between CPS than communication using higher layers.

This simple example showed that the centralized solution cannot be divided to distributed solution without taking into account the overall system topology.

## 7. CONCLUSION

The present paper has introduced the general concept of the eScop research project, focusing on the issue of modularization for a CPS architecture. The theoretical use of modeling of a system for control logic has been addressed by a specific industrial case. The case refers to an industrial domain, where automation is particularly important. In fact, automated logistic systems are systems that allow efficiency in many different companies. Moreover, they represent a typical case where the problem of flexibility for new configurations is crucial. In order to cope with the problem, it has been demonstrated how different issues for modularization may arise and provide interesting lessons learnt for future works. In particular, it has been identified how system topology is a key issue to be managed by the control system (i.e. by representation layer) in order to properly achieve the right modularization of the system and thus proper working of CPS within the overall architecture. From the industrial point of view, the proposed SOA-based architecture has demonstrated to be ready to allow a new paradigm for the design of logistic conveyors line, with the objective to obtain high levels of modularity and flexibility. The technology gap has been also commercially fulfilled by the availability on the market of conveyors that embed assail 24V electric motors. By using such components, modules can be practically organized according to different classes of transporters (for linear movement, lateral, curves, etc.). Each conveyor is linked to a RTU, so all the functionalities of the module can be controlled by services and configured according to the different needs of the line. Such architecture can be then realized with high speed LAN (Local Area Network) in order to manage the RTU remotely without the need of any intermediate layer, such as PLC. Flexibility in the configuration of the line is then a real achievement. The capability to reconfigure and reuse the components of the line allows large savings for the companies. Authors strongly believe that the state of the art of the technological background for this architecture, which is belonging to the Industry 4.0 paradigm, allows to think that the proposed solution and/or similar emerging ones will strongly penetrate the market and will become soon common commercial solutions.

## ACKNOWLEDGMENT

The research leading to these results has received funding from the ARTEMIS Joint Undertaking under grant agreement n° 332946 and from the Italian Ministry of Education, Universities and Research (MIUR), correspondent to the project shortly entitled eScop, Embedded systems for Service-based control of Open Manufacturing and Process Automation. This publication was also supported by the project LO1506 of the Czech Ministry of Education, Youth and Sports under the program NPU I. The authors would like to personally thank all the European partners of the project and, in particular, INCAS S.p.a that provided the material and support for the development of the presented case.

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