A CPPS Architecture approach for Industry 4.0

Federico Pérez, Edurne Irisarri, Darío Orive, Marga Marcos
University of the Basque Country, UPV/EHU
Bilbao, Spain
{federico.perez, edurne.irisarri, dario.orive, marga.marcos}@ehu.eus

Elisabet Estevez
University of Jaen
Jaen, Spain
eestevez @ujaen.es

***Abstract*— New demands, coming from the industry 4.0 concept of the near future production systems have to be fulfilled in the coming years. Seamless integration of current technologies with new ones is mandatory. The concept of Cyber-Physical Production Systems (CPPS) is the core of the new control and automation distributed systems. However, it is necessary to provide the global production system with integrated architectures that make it possible. This work analyses the requirements and proposes a model-based architecture and technologies to make the concept a reality.**

Keywords—Cyber-Physical Production Systems (CPPS), Industrie 4.0, Model Driven Paradigm

I. Introduction

In recent years we are witnessing an investment effort on the part of public institutions to reinforce or recover the industrial manufacturing as a key driver for innovation, economic growth and job creation. Initiatives such as Factory of the Future (FoF) in the European Union Industrie 4.0 driven by the German Federal Government or Advanced Manufacturing launched by the US Government are clear examples of that.

The three of them have common general goals including underpinning manufacturing industry competitiveness; addressing global demand for affordable, customized and eco-efficient products and adapting manufacturing to a smart, green and inclusive economy [1]. These initiatives pursue more specific R&D objectives such as high-tech manufacturing processes based on the use of adaptive and smart manufacturing equipment and systems as well as resource-efficient factory design and data management aiming at increasing production performance. Achieving collaborative and mobile enterprises, human-centred and customer-focused manufacturing are also important.

To achieve these objectives is crucial to make use of the latest advances in Information and Communications Technologies (ICT). The concept of smart manufacturing [2], indeed, is based on the integration of both Internet of Things (IoT) and Cyber-Physical Systems (CPS) concepts.

The vision of IoT [3] is the interconnection of millions of devices with each other and with enterprise systems. Self-organized intelligent entities and virtual objects will be interoperable and will act in an independent way towards their own or shared objectives interconnected via the IoT.

The application of the generic concept of CPS [4] to industrial production systems is known as Cyber-Physical Production Systems (CPPS). Transforming the traditional production mechatronic systems into CPPSs, the Data Collection will be customized and sent to the Big Data, becoming accessible via Computing Cloud. It can be said that the CPPS is the enabler for the IoT in manufacturing. Thus, the CPPS concept increases the autonomy and flexibility in the industrial environment, allowing a higher level of integration and interoperability of manufacturing applications and systems.

As [2] states, in smart factory both IoT and CPS concepts are converging to the Internet of Services, which uses the cloud-based manufacturing for creating, publishing, and sharing the services that represent manufacturing processes, and could be offered by virtual enterprises.

In such a wide environment, connectivity among systems and equipment is mandatory. However, this is not a simple task due to heterogeneous models, systems and concepts from an extremely wide range of domains have to be integrated [6]. Interoperability of devices, equipment and systems demands an integration architecture that makes possible information exchange.

To face the integration challenge that the factory of the future demands [7], three main axes could be defined: horizontal, vertical and throughout the life cycle of engineering phases integration. The horizontal axis focuses on ad-hoc added value networks optimized in real time whereas the vertical one tries to connect business processes with technical processes. The third axis addresses the continuity of engineering throughout the different phases of the lifecycle.

This work specifically focuses on vertical integration, proposing a CPPS architecture that uses specific domain models based on standards to cover the different layers. In particular, this architecture aims to collect data from the production process and to exchange this information in customizable formats with remote clients. The approach is in line with the objectives planned by the Industry 4.0 framework. In this sense, the integration between production process and business areas is a first step towards an adaptive and smart manufacturing and data management for increased production performance, collaborative and mobile enterprises.

978-1-4673-7929-8/15/$31.00

The layout of this paper is as follows: section II presents the identification of requirements and the available technologies for achieving the vertical integration. Section III describes the proposed CPPS architecture approach. In section IV a simple but illustrative example is presented, and finally some conclusions and current work are drawn in section V.

II. Vertical Integration

Industry 4.0 pursues and extensive automated exchange of information between production and business processes. To achieve this, interoperability is necessary assuring global usability and cross-systems consistency. This section focuses on the vertical integration axis and presents the requirements identified as well as a selection of currently available methods, techniques and technologies that are widely used at their respective domains.

Vertical integration aims at collecting data from the production process and transforming it into valuable information to remote clients.

In order to capture process data to obtain valuable information, two types of requirements need to be fulfilled: those that refer to the user, i.e. *what* data (magnitudes, engineering units, range, etc.), *where* these data are with respect to the physical plant (what process it refers to) and *how* these data have to be captured (one shot, synchronously, asynchronously, etc.). On the other hand, from the implementation point of view, means for describing the plant (where), describing the data to be acquired (what) and defining the acquisition mechanism (how) are also necessary.

To meet both, user and implementation requirements, methods, techniques and technologies exist that are well spread and consolidated in industry, and can be used to fulfil the challenges.

With respect to methods and techniques, the Model Driven Engineering paradigm fits very well as it offers:

- Separation of concerns through domain modelling, promoting system descriptions from different points of view.
- Domain model mappings through model-to-model transformations, supporting consistency analysis.
- Automatic generation of configuration files and code through model-to-text transformations.

With respect to the description of information for the different actors, consolidated standards exist for each layer in process automation.

Some representatives have been selected, and presented below although there are many others that can collaborate to achieve actual integration and exchange of information.

1) Description of Plant Topology: AML (IEC 62714) define models describing production plants and their components, including information of topology, geometrics, kinematics and logics. CAEX (IEC 62424) is used to define a neutral data format for plant information exchange between heterogeneous CAE tools. ISO 15926 gives a plant model based on an ontological frame, provided with semantics and time specification. Finally, ISO 15531 defines a model for the data acquired at control level in order to be stored in the production management tools. AutomationML (AML) seems to be very promising as it defines a data format specifically designed for the exchange of plant engineering information. The format allows seamless integration of engineering tools from different disciplines and lifecycle phases. In [8] the interoperability of both standards, OPC UA and AML, is analysed. The goals are to exchange the plant component descriptions by means of creating the OPC UA information models based on AML. But it is not enough for real time acquisition of process data when big data analysis of production is required.

2) Plant devices data: PLCopenXML interface defines a model to make PLCs interoperable through the use of IEC 61131-3 standard. It is also used by AML to define the application logic. FDI [9] is focused on device integration for process automation applications, based on EDDL and DTM technologies. Semantic Sensor Network (SSN) [10] defines models for sensors including a description, accuracy, capabilities, observations and methods used for the sensor.

3) Information exchange: The IEC 61850 standard [11] defines a set of models to give access to electric substations while an extension, the IEC 61400-25 standard [12] has been defined for wind power plants. Mature and well established information models representing concepts, relationships, constraints, rules and operations to specify data semantics. Although automation is much broader in terms of concepts, device and data types and equipment, the concept of defining adapted models could be useful in manufacturing.

4) Communication Technologies: OPC UA (IEC 62541) offers middleware mechanisms to integrate heterogeneous platforms. The information model uses high level concepts, as Mahnke et al. have shown [13] as well as entities like hierarchies, aggregation, variables and data types. Ethernet POWERLINK standard is a deterministic real-time protocol for standard Ethernet that enables the communication between the devices closest to the production process, as i/o devices, sensors, servodrivers, etc. MTConnect standard intends a greater interoperability between devices and software applications, establishing a channel of communication for plug-and-play interconnectivity between devices, equipment and systems, providing real-time data from throughout the factory.

III. CPPS Architecture

Taking into account model based techniques and standards in the field or belonging to other application fields, the general scenario Fig. 1 is proposed as the CPPS architecture. As commented above this architecture focuses on the vertical integration between productive processes and business areas. Thus, the goal is to give access to data from the production process and extract information through Big-Data analysis.

The architecture is composed of a set of components that manage a set of models representing the physical world, the information exchange as well as the information to be accessed.

The following sub-sections detail the concepts managed by each component of the architecture.

A. Production Process Model (PPM)

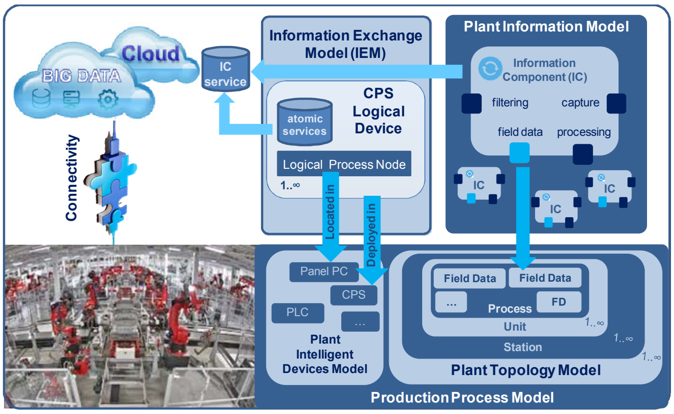

Fig. 1. CPPS – General Architecture

The following sub-sections detail the concepts managed by each component of the architecture.

B. Production Process Model (PPM)

This model is composed of the accessible data, generated in the production process (data *source*), as well as the intelligent devices belonging to the plant that are responsible for communicating the actual data values (data *suppliers*). Data can be grouped depending on the productive process they come from (for instance a press, a robot or a screwdriver). Intelligent devices, potentially suppliers of data, jointly with the accessible data related to processes characterize the so-called Production Process Model (PPM).

1) The *Plant Topology Model (PTM)* collects the physical components of the plant, i.e., the set of production processes that group the accessible data from each process. The PTM represents the layout of the plant. It should be generic enough in order to describe any productive process although it can be customized to fit the interest of the enterprise. For instance, the hierarchy: Station -> unit -> process -> field-data may be used to represent a plant composed of a number of stations. A set of units may compose a station and a unit may have a set of processes (data sources) associated. Independently from the number of layers of the hierarchy, at the bottom layer the set of processes characterized by its data properties (such as physical magnitude, engineering units, range of possible values or timestamp, among others) are defined.

2) Plant Intelligent Device Model (PIDM): describes those devices with processing capabilities that can play a role in the CPPS (data suppliers) e.g. PLCs, embedded systems, HMI, etc.

C. Information Exchange Model - IEM

This model, illustrated in Fig. 2, is the core model for the proposed architecture. As commented above, the solution adopted is an adaptation of the information exchange model of the IEC 61850-7-2 standard in order to fit the particularities of CPPS. The IEM is composed of three different entities:

1) Atomic Services (AS): A set of basic services which perform data acquisition and related issues. There are several types of atomic services ranging from security, filtering, pre-processing aspects to command and monitoring (get/set, publish/subscribe, report, logging, etc.).

2) Logical Process Nodes (LPN): LPNs represent a process of the PPM. There is an LPN for process and every LPN refers to the intelligent device where services (role in the CPS) to access process data are deployed. Therefore, each process defined in the PPM is related to an intelligent device which is responsible for providing the related dataset.

3) CPS Logical Devices (CPSLD): They are the intelligent devices of the PPM where the architecture is deployed. CPSs manage PTM and PIDM models and implement the complete IEM model. Furthermore, they content at least one LPN.

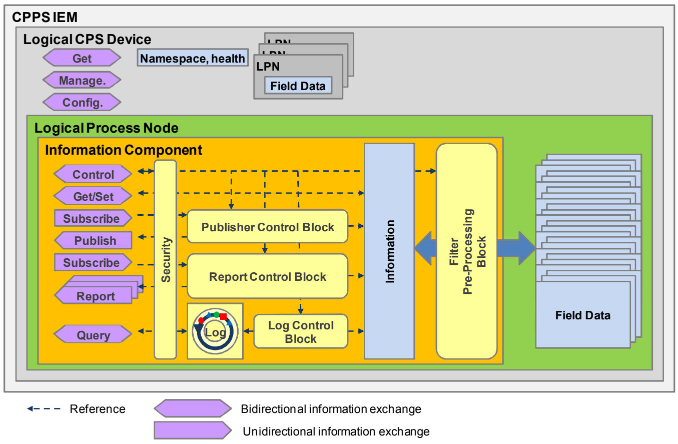

Fig. 2. IEM – Conceptual Structure

D. Plant Information Model (PIM)

The PIM defines the information the user wants to acquire from the process. This information is structured in the so-called Information Components (IC). ICs are the mechanisms to access the plant data. They are composed of a set of atomic services offered by Logical Nodes of the CPS (CPSLD) that handle process data (FD). The user defines ICs by means of configuration services. Once created and launched, an IC offers a unique service (ICS) that is responsible for performing the functionality of the IC. The simplest IC is the minimum access to the plant such as, for instance, the access to read field data of a process (which is associated to a LPND).

This is a user-oriented model, thus the remote client applications are responsible for defining it. As illustrated in Fig. 1, this characterization refers to Field Data belonging to Processes of the PTM, as well as acquisition, pre-processing and filtering configuration issues. From the PIM (set of ICs) the set of services for each IC can be automatically generated as a composition of atomic services of the Information Exchange Model. Consequently, ICs are temporal services and their life expectancy depends on the application that defines them.

IV. CASE STUDY

This section describes a laboratory application aiming at illustrating the application to factory automation. This case study is based on a factory automation cell (see Fig. 3) in which five stations assemble different elements in a piece over a pallet. Each station contains a set of processes offering the access to its data. A Process Controller governs the five stations and the conveyor belt. Additionally, an OPC-UA server gains admission to the variables of the Process Controller and makes them accessible from the CPS.

The CPS is a device based on an ARM architecture with Linux-Debian operating system. The connectivity capability of this CPS provides access to the dataset from the Cloud. The run-time of the CPS is an OPC-UA server, the Cloud and an OPC-UA client to access process data.

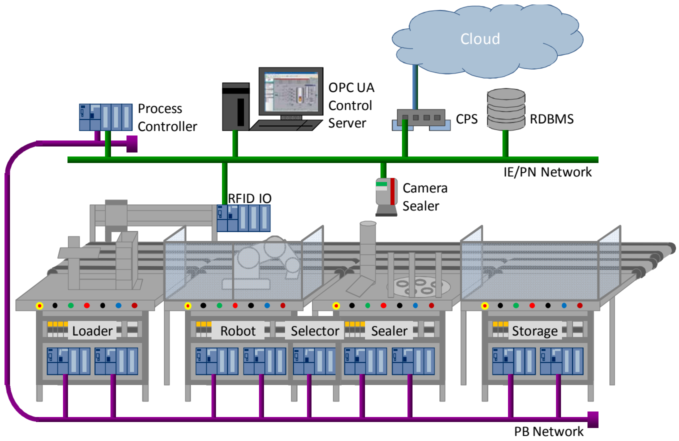

Fig. 3. Manufacturing case study

Let us assume that the station 2 contains only one process, the Robot, and that the intelligent device providing access to field data is the process controller. There is only one CPS device that provides access to field data from the Cloud. Fig.4 illustrates the PPM for this system detailing the station 2 that contains the process *Robot* and its field-data.

V. CONCLUSIONS AND FUTURE DEVELOPMENTS

This work is the first step of a model-based architecture that making use of well-established standards can be the basis for a seamless integration needed in the industry 4.0 concept. Second step is to fully implement the proposed architecture and to focus on other integration axis while including mechanisms to introduce enough flexibility to address new demands.

ACKNOWLEDGMENT

This work was supported in part by the Government of Spain and FEDER under projects DPI2012-37806-C02-01, the Government of the Basque Country (GV/EJ) under Project IT719-13 and by UPV/EHU under grant UFI11/28.

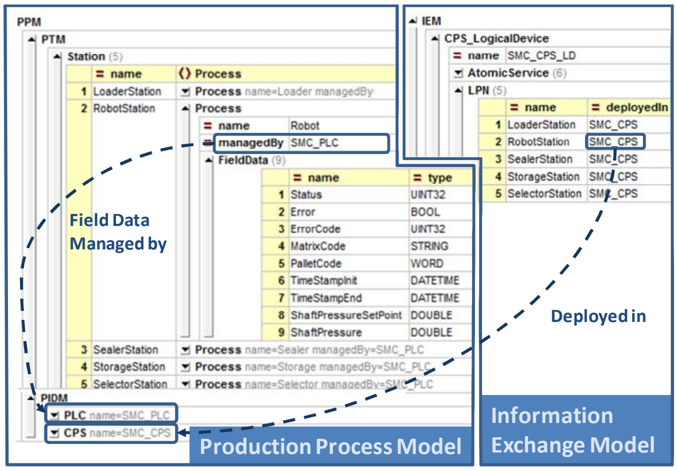

Fig. 4. PPM of the case study

REFERENCES

[1] European Commission: Research and Innovation, “Factories of the Future PPP: towards competitive EU manufacturing”. European Union, 2013.

[2] M.A. Pisching, F. Junqueira, D.J. Santos Filho, P.E. Miyagi, Chapter: “Service Composition in the Cloud-Based Manufacturing Focused on the Industry 4.0”, Book: Technological Innovation for Cloud-Based Engineering Systems. IFIP Advances in Information and Communication Technology. Vol.450, pp 65-72, 2015.

[3] J. Gubbi, et al., “Internet of Things (IoT): A Vision, Architectural Elements, and Future Directions”, Future Generation Computer Systems, vol. 29, issue 7, pp. 1645-1660, September 2013.

[4] S. Haller, S. Karnouskos, and C. Schroth, “The Internet of Things in an Enterprise Context”, Springer, 2009.

[5] J. Schlechtendahl, M. Keinert, F. Kretschmer, A. Lechler, A. Verl, “Making existing production systems Industry 4.0-ready”. Production Engineering Journal, Vol.9, Issue 1, pp 143-148, Springer Berlin Heidelberg, 2015.

[6] R. Rajkumar, I. Lee, L. Sha, J. Stankovic, “Cyber-physical systems: the next computing revolution”, in Proc. 47th Design Automation Conf., NY, 2010.

[7] CPS Reference ARTIST2, “Roadmap on Real-Time Techniques in Control System Implementation – Control for Embedded Systems Cluster”, EU/IST FP6 Artist2 NoE, www.artistembedded.org, 2006.

[8] R. Henßen, M. Schleipen, “Interoperability between OPC UA and AutomationML”, 8th International Conference on Digital Enterprise Technology – "Disruptive Innovation in Manufacturing Engineering towards the 4th Industrial Revolution", 2014.

[9] IEC 62769-1 CDV: Field Device Integration (FDI), Technical Specification - Part 1: Overview. IEC, 2013.

[10] M. Compton, et al, “The SSN Ontology of the W3C Semantic Sensor Network Incubator Group”, Journal of Web Semantics, 2012.

[11] International Electrotechnical Commission Std, “IEC 61850, Communication networks and systems in substations” TC 57 - Power systems management and associated information exchange, 2003.

[12] F. Perez, E. Estévez, I. Calvo, D. Orive, and M. Marcos, “Fundamentals of the IEC 61400-25 Standard: Communications for Monitoring and Control of Wind Power Plants”, The Industrial Communication Technology Handbook, Second Edition. CRC Press, 2014.

[13] W. Mahnke, S.H. Leitner, M. Damm, “OPC Unified Architecture”, Springer-Verlag, October 2009.