Management and Production Engineering Review
Volume 6 • Number 4 • December 2015 • pp. 26–32
DOI: 10.1515/mper-2015-0033

ROLE OF ONTOLOGIES FOR CPS IMPLEMENTATION IN MANUFACTURING

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Received: 23 November 2014
Accepted: 9 January 2015

Abstract

Cyber Physical Systems are an evolution of embedded systems featuring a tight combination of collaborating computational elements that control physical entities. CPSs promise a great potential of innovation in many areas including manufacturing and production. This is because we obtain a very powerful, flexible, modular infrastructure allowing easy (re) configurability and fast ramp-up of manufacturing applications by building a manufacturing system with modular mechatronic components (for machining, transportation and storage) and embedded intelligence, by integrating them into a system, through a network connection. However, when building such kind of architectures, the way to supply the needed domain knowledge to real manufacturing applications arises as a problem to solve. In fact, a CPS based architecture for manufacturing is made of smart but independent manufacturing components without any knowledge of the role they have to play together in the real world of manufacturing applications. Ontologies can supply such kind of knowledge, playing a very important role in CPS for manufacturing. The paper deals with this intriguing theme, also presenting an implementation of this approach in a research project for the open automation of manufacturing systems, in which the power of CPS is complemented by the support of an ontology of the manufacturing domain.

Keywords
Cyber Physical System (CPS), ontology, advanced manufacturing.

Introduction

Cyber Physical Systems are an evolution of embedded systems and are based on a tight combination of collaborating computational elements (i.e. micro computing units or embedded systems interconnected by a communication system) that control physical entities. Therefore, in CPS all types of smart equipment (i.e. sensors, actuators, devices, machines, robots) are interconnected creating a smart community with data capture and action capability from/to the physical world with a great potential of innovation in areas as diverse as aerospace, automotive, civil infrastructure, energy, healthcare, transportation, entertainment and consumer appliances, but also in manufacturing and production. In particular, this paper addresses the application field of manufacturing and production. Here the CPS approach allows looking to the various hardware components that compose a manufacturing system in an abstract way. This solution is of fundamental importance because it offers the possibility to set up a model based engineering approach to the configuration of a complete manufacturing system, thus reducing building, ramp up and reconfiguration time of manufacturing automation systems significantly. We can call such kind of module based automation architecture as "open automation manufacturing". For realizing it, standard solutions must be adopted for the communication infrastructure linking together the embedded systems that control the various manufacturing modules. Possible solutions are the use of the field-bus level approach (e.g. PROFINET) or using standard web technologies [1] (e.g. following the SOA – Services Oriented Architecture approach).

However, when developing this very interesting concept, problems are found in structuring and managing the domain knowledge that is required to give a definite shape to the congeries of undifferentiated elements that compose a pure CPS architecture. To this concern, ontologies seem able to provide a noticeable breakthrough for providing the required need of knowledge content. The paper is organized in the following way: after the introduction in Sec. 1; Sec. 2 is dedicated to a short presentation of CPS; Sec. 3 illustrates the way the communication architecture can be realized for supporting CPS implementation; Sec. 4 introduces the use of CPS as an architecture for the support of the control of manufacturing systems; Sec. 5 deals with the role of ontologies for Cyber Physical Systems in manufacturing; while Sec. 6 is dedicated to the presentation of MSO (the Manufacturing Systems Ontology developed in Politecnico di Milano); finally, in Sec. 7 an application example developed within an Artemis European research project is illustrated. Section 8 contains the concluding remarks.

Cyber Physical Systems

The rising complexity in computer-controlled systems, due to their increasing size and to the heterogeneous nature of the components they are made of, has led to a radical transformation of their architecture by introducing the networking capabilities and thus generating the Cyber-Physical Systems (CPS) solution. The main benefit deriving from Cyber-Physical Systems is the higher level of efficiency achievable, thanks to control-computing codesign [2]. Moreover, the economic and societal potential benefits of CPS are high; therefore, worldwide investments spent for the development of this technology are quickly increasing [3]. Exploitations of the Cyber-Physical Systems are numberless because they can offer automation in a huge number of domains, ranging from the possibility to create a highly efficient national electric grid; to networked building control systems with higher energy efficiency and demand variability; to benefited tele-presence and acquisition systems for senior care [3, 4]. Other fields of application may be: traffic control and safety, advanced automotive systems, process control, energy conservation, environmental control, avionics, instrumentation, critical infrastructure control (electric power, water resources, and communications systems for example), defense systems, etc. [2, 3, 5]. For what specifically concerns the manufacturing sector, "converged modular automation" is a current manufacturing trend, where systems are built of a network of modular cyber-physical components, which have their own embedded controller. This ensures more reconfigurability than in custom-designed systems [6]. Also CPS, as large scale interconnected systems of heterogeneous components, may give relevant contributions to the efficiency of industrial processes control systems by creating a large control loop instead of many small ones [5].

A statement of the role of CPS in manufacturing is found in the report prepared by the Energetics Incorporated in 2012 for the NIST (National Institute of Standard and Technology). CPS are seen as enablers for efficient smart manufacturing, thanks to the large scale of the control system, providing efficient, reliable and interactive control. Some of the possible practical benefits of CPS 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 (leading to reduced production costs) [6].

Communication within CPS

CPS are made of embedded systems integrated in a communication network. Therefore,communication technologies play a fundamental role in CPS architectures. Considering the solutions that have been used in recent research papers, we see that two main options are considered: the first is to use well-established standards such as Profibus, the second is to use Service Oriented Architecture, in which functional modules are abstracted as services. Many researchers consider SOA as a very promising solution because it is based on Web Services [7], thus offering an interface that encapsulates the required process, which in turn is self-described. The scientific community has already started to prove the validity of the use of web services and SOA for manufacturing automation, through industrial test-beds (see for instance SOCRADES and eSONIA European project web-sites: http://www.socrades.eu and http://www.esonia.eu).

Use of CPS in manufacturing systems

Difficulties appear when going to practical implementations of flexible CPS solutions for manufacturing; the reason is that they are aggregations of smart objects, which do not have any knowledge of themselves from a systemic point of view. Consider, for instance, the following example: we want to transform a traditional mechanical assembly line into a flexible assembly system, based on the CPS approach. The traditional line is composed of a paced mechanical conveyor and a series of automatic assembly stations. The paced conveyor transfers assemblies (i.e. assembly pieces) step by step from one station to the following one (see Fig. 1). In this case, the assembly stations do not need to have any control information to work on the assembly piece, because all the logics of the system (i.e. the type of components to be added in each station, the sequence of assemblies and so on) has been integrated in the line configuration at its design stage. In other words, the designer has "frozen" his/her knowledge on all the functional options that might be adopted for building the line by selecting the design choices defined as specifications of the line itself. The flexible assembly system based on CPS approach presents a completely different situation. In fact, in this case, the physical configuration of the line will be very flexible: all the cyber physical components of the line (such as the modular components of the transportation system, the assembly equipment, actuators, sensors, etc.) will be elementary modules that can be put together and operated in different ways thanks to their integration through the communication network and the control action of the software.

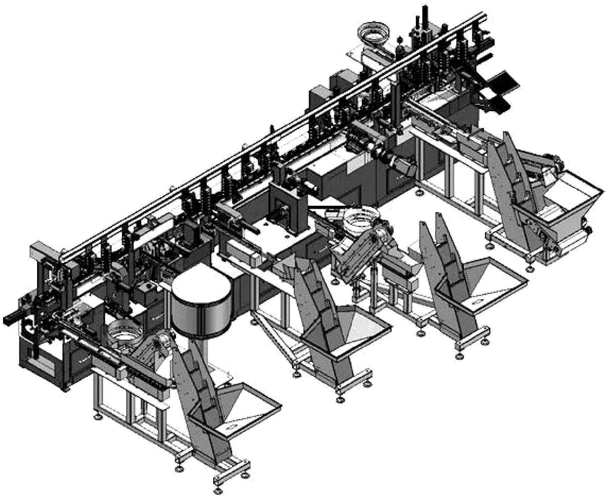

Fig. 1. Example of a paced mechanical assembly line.

Thus, the result that we obtain can be condensed in the following sentence: "*all components are intelligent and connected, but none of them knows its role and the coordination required to act as an assembly system.*"

A way for better understanding the problem we are facing is to try to deploy the control situation by dividing it, *from a logical point of view*, in various levels, as it is exemplified in Fig. 2. In order to describe it, we may start from the elementary physical components that are smart and connected in a communication network. Then we shift our attention to the *control layer* which is based, first on the capability of *acquisition and command* and then on the capability of *synchronization* of the various elements/events.

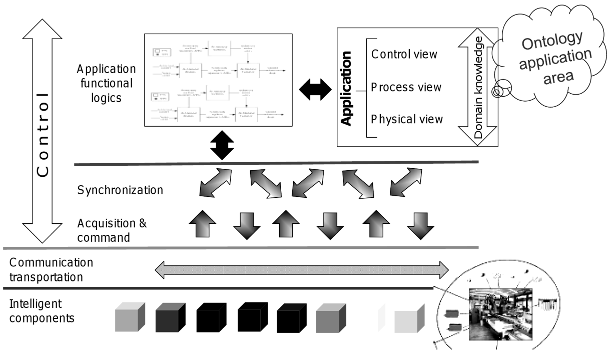

Fig. 2. Logical control components in a CPS based solution for manufacturing.

The role of ontologies

Ontology derives from ancient Greek *ontos*, which means "being" and *logos*, which means, "discourse". Then, ontology has assumed other meanings:

- *Ontology* is a formal, shared and explicit representation of a domain concept [8].
- *Ontology* (in computer science) is a method for formally representing knowledge as a set of concepts within a domain, using a shared vocabulary to denote the types, properties and interrelationships of those concepts.

For the manufacturing system domain, one of the main issues related to knowledge management depends on the extreme variety of the configurations that manufacturing systems can assume. Consequently, the generalization of methods for the design and management of manufacturing systems has been often limited by the variety of the final application contexts. Many authors have addressed this issue in the past and even more in recent years. However, higher capability to handle these problems has become available thanks to the development of information technology tools and especially with Object Orientation (OO) concepts and related technologies (see [9–13]). To this concern, starting from the '90s, ontologies have been proposed for describing manufacturing systems (see [14–18]. Moreover ontologies, when properly implemented in appropriate languages, allow also including such knowledge into software and automatic systems. For what concerns the integration between ontologies and the communication infrastructure of CPS, [19] and [20] are some of the firsts who tried to establish this relationship. Indeed, [19] developed a prototype to demonstrate the feasibility of interoperability between manufacturing services. Cai's approach was demonstrated using the ontology of a limited manufacturing domain, but it was clear that a larger and more complete ontology could further improve this approach.

These preliminary works, focused on ontologies and frameworks for the manufacturing systems domain and others on web services and SOA, are suggesting that the combined use of these two technologies could be very profitable, as postulated in the field of factory automation by [21] and [22]. Different approaches were also taken by combining ontologies with the agent based communication architecture. An interesting example of the above-mentioned solution can be found in [15].

P-PSO and MSO ontologies for manufacturing systems

Research on the use of ontologies for the description of manufacturing systems was started at Politecnico di Milano with the development of P-PSO (Politecnico di Milano – Production Systems Ontology) in the '90s as a taxonomy of manufacturing systems (see [18]). P-PSO has been based on a structured representation of the domain of manufacturing systems, supported by the object-oriented methodology, enabling the description of the relevant domains of a generic manufacturing system. P-PSO specifies the entities (building blocks) composing a manufacturing system, together with their main attributes. Within the scope of the Artemis European project eScop, the new improved Manufacturing Systems Ontology (MSO) has been developed from P-PSO, which was only addressing the discrete manufacturing domain. In addition, MSO includes also process industries and logistics.

Following the approach of P-PSO, the modelling method of MSO defines a manufacturing system from the process and logistics point of view by separately addressing three main different domains:

- the physical domain contains the material definition of the system including workers, production facilities, material-handling and transportation equipment, storage and other supplementary devices (such as tools, jigs and fixtures);
- the technological domain defines the transformational (functional) view of the system, considering the conversion processes (i.e. manufacture and assembly) and the routing that products must undergo within the manufacturing system;
- the control domain in P-PSO defined the operating procedures of production at an abstract level, describing the so-called management cycle (i.e. planning, scheduling and control activities); in MSO, the control domain should provide the data fields that are necessary for the control activity which is performed by an orchestration engine.

MSO provides also classes for the visualization domain in a separate section of the ontology, providing modelling of elements that are needed for a proper management of visualization of the manufacturing system.

The main classes of the MSO are:

- Product class, modelling the product that has to be produced;
- Component class, modelling the physical domain of the manufacturing system;
- Routing operation class, modelling the technological domain of the manufacturing system;
- Operator class, modelling the activity of workers / human operators; and
- Subsystem class, a service class allowing the grouping of objects of the other classes in a nested way.

The product class models parts and products. A product is seen as composed of subassemblies and/or items. In turn, a sub-assembly is recursively composed of sub-assemblies and/or items; this structure models the product BOM of which the product is made. A product can be either a generic product (a family of products) or a specific product (a variant of a generic product).

The definition of the *physical domain* in MSO is based on the Component class, which specializes in main and secondary sub-classes. The Component class cannot be further divided, and it is used to model the physical elements of a manufacturing system. The main specializations of the Component class are the sub-classes: Operator, Processor, Transporter and Storage. Secondary sub-classes are Container, Sensor, Tool, Fixture.

The Operator class is a special sub-class of the component class that identifies workers that perform activities in the manufacturing system and interact with other components. This class needs a specific approach, since operators can carry out different types of operating activity (for instance processing, transport, inspection, maintenance) and carry out no-less-important control activities, like support and supervision over any type of component. The MSO ontology specializes the Operator class in Process Operator (further specialized in transportation, manufacture and assembly operator) and Control Operator (a supervisor, manager, quality control operator).

The *technological domain* is based on the transformational (functional) vision of the conversion processes that items to be manufactured undergo from a manufacturing and logistic point of view, following a process plan within the manufacturing system itself.

Before illustrating the technological domain in detail, some definitions are necessary:

- Workstation is defined as the environment in which product transformations are made possible (e.g. assembly, cutting, drilling, picking, etc.); a workstation is typically made of a floor space and some components, like a machine and an operator. In the MSO modelling approach a workstation is a sub-system composed of one or more components such a processor and an operator.
- Operation is defined as the technological process activity that is performed in a workstation, thus changing the product status (e.g. assembly operation, picking operation, chemical reaction, etc.).
- Process routing (or plan) is defined as an ordered sequence of individual operations, which has been decided by the process engineer, for producing a product by means of the visits to a certain number of workstations. Process plans are prepared off-line by the production-engineering department by deciding the best technological solution for product manufacture, taking into account the available process equipment and the required tools and fixtures. In some cases, routing alternatives can be included in process plans by providing optional routes at some point of the process plan in order to have more flexibility. Since one or more operations can be performed at the same workstation, the sequence of workstations that the product has to "visit" to be produced is not described in the process routing: the transportation routing is devoted to this purpose and is composed of an ordered sequence of workstations to be visited.

The structure of MSO is described using the UML (Unified Modeling Language) (UML1.4.2 – ISO/IEC 19501:2005) and implemented with the Visual Paradigm software tool (www.visual-paradigm.com). Within the eScop research project the operating implementation of MSO has been made by translating its UML description into OWL.

Application example

Within the European Artemis project eScop, a CPS test-bed environment for manufacturing is being implemented, as it will be illustrated by briefly explaining the objectives and the architecture of such research project. eScop stands for Embedded systems for Service-based Control of Open manufacturing and Process automation. The project aims at overcoming the current problems of system integration at shop-floor control level by semantically integrating embedded devices and applications based on open standards. The central concept of eScop is to combine the power of embedded systems with an ontology-driven service-based architecture for realizing a fully open automated manufacturing environment.

The true innovation of the proposed solution is the merge of the power of ontology knowledge and SOA control approaches that allows the control to be automatically configured by the ontology knowledge content, while embedded systems allow this architecture to work.

Referring to Fig. 3, in which the eScop general architecture is presented, the logical levels that have been previously represented in Fig. 2 in a generic way can be recognized. The MSO is reported as eScop MSO and it supports the configuration description and the technological process view within the eScop architecture. In particular, looking to the eScop architecture (Fig. 3), three main control layers are visible: PHL denotes the PHysical Layer, RPL stands for the RePresentation Layer and ORL denotes the ORchestration Layer. Furthermore, the complementary INTerface (INT) and VISualization (VIS) layers complete the architecture. The layers are interconnected with round arrowhead connectors, showing information flow among the layers via web-service. The content and purpose of the layers are the following:

- The PHL (physical layer) contains service-enabled embedded devices (RTU, Remote Terminal Units) that control the shop floor equipmen;
- The RPL (representation layer) is made of two components: i) Ontology Service, which queries and updates the MSO knowledge base, and ii) the MSO itself, which is the Manufacturing Systems Ontology. The eScop MSO reflects the manufacturing system's current status in real time and it is updated and queried by the physical and the orchestration layers;
- The ORL (orchestration layer) is also made of 2 components: i) Service Composer, which receives task needs and decides how to orchestrate the sys-

tem, and ii) Orchestrator service which executes the orchestration process;

- In addition, the visualization layer is also connected to the MSO for real time visualization of the manufacturing system status.

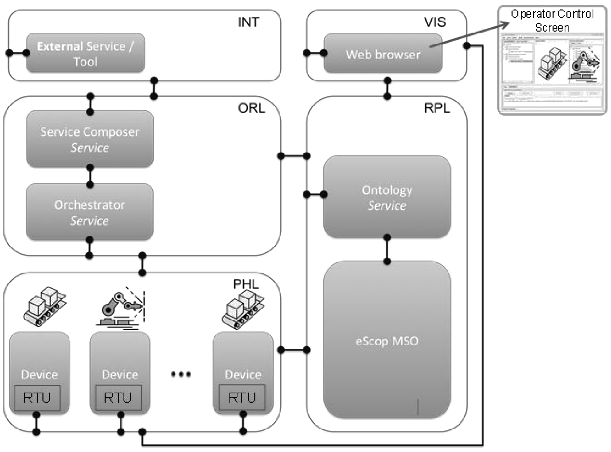

Fig. 3. eScop architecture.

The result of such architecture is a modular, fully open solution for the operational control of manufacturing equipment allowing:

- Easy and fast commissioning of new plants;
- Achievement of "plug & produce" inclusion of new equipment;
- Replacement of traditional control based on hierarchical hardware architecture, by a single level cohort of embedded systems and a series of software control levels.

For more information about the eScop architecture please refer to [23] and to the eScop project web site.

Conclusions

The building of CPS applications to real world problems and especially to the complex environments of manufacturing and production, requires domain knowledge, thus some important challenges emerge for future research:

- Ontologies seem to be the right tool to implement knowledge and integrate it in CPS applications for manufacturing. Are they?
- How must ontologies be used for storing the manufacturing domain knowledge?
- Should this knowledge be divided in levels (e.g. general knowledge, sectorial knowledge, specific knowledge) for being successfully implemented in ontologies for a given application domain?
- What about software ontologies implementation and integration in CPS solutions?

This research has been partially supported by funding from the ARTEMIS Joint Undertaking under grant agreement no 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. Thanks are due to Prof. L. Tanca and Prof. F.A. Schreiber of DEIB, Politecnico di Milano for their valuable consulting support.

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