STANDARDS FOR MONITORING AND CONTROL OF CYBER-PHYSICAL SYSTEMS

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Abstract: *The Industry 4.0 initiative imposes new requirements on cyber-physical systems in terms of interoperability, response time, communication capabilities, and more. A major approach to addressing these requirements is through the development and use of standard reference frameworks, architectures and models as well as the widespread and joint application of open industry standards. The aim of the article is to analyze the use of standards under the Fourth Industrial Revolution as well as to present and analyze some of the most applied standards in the field of monitoring and control of cyber-physical systems, such as AutomationML, OPC-UA, IEC-61449, IEC-61512. The reference architecture RAMI 4.0 was used to establish relationships and interactions between them.*

Keywords*:* CYBER-PHYSICAL SYSTEM, INDUSTRY-4.0, IEC-61499, AutomationML, OPC-UA, IEC-61512, IEC-62264

1. Introduction

The rapid development and broad penetration of information and communication technologies in the industry has led to the emergence of new industry development strategies with a view to enhancing its competitiveness, such as: the German Initiative “Industry 4.0” [1], the American “Smart Manufacturing” [2], the Chinese “Made in China 2025” [3], the Japanese IVI (Industrial Value Chain Initiative) [4], the Italian “Industrial National Plan 4.0” [5], etc. All of them aim "The complete transformation of the whole sphere of industrial production through merging of digital technology and Internet with conventional industry". Recent studies have shown that digitization of products and services can add more than 110 billion Euros a year to Europe in the next five years [6]. Successful implementation of all these initiatives is possible with the use of Cyber-Physical Systems (CPS) technologies, which are considered to be new types of systems that expand the capabilities of the physical world through computing, communications and control, and upgrading the electronic automation. The most important key topics in research, development and implementation are:

- Modeling, Simulation and Verification of CPS;
- Development and application of software process models in the development of CPS (Modeling of the development life cycle of CPS;
- Reference Frameworks and Architecture of CPS;
- Development of semantic service oriented architectures of CPS;
- Distributed control of CPS using advanced methods and algorithms;
- Interoperability in CPS and between them;
- Data analysis (big data) and decision making.

An important role for successfully dealing with the tasks in the above mentioned directions and integration of the received solutions is played by standardization. The development and adoption of standards reduces the risk to enterprises and encourages the adoption of new technologies, products and production methods. Standards for CPS include reference architecture, common services and functional models, semantics, security and safety standards, and standard interfaces for system-to-system interactions [7]. A survey on the “Prospects for Industrie 4.0” [8] confirms the importance of standardization for adoption of Industry 4.0. It is identified that the first greatest challenge connected with implementing the vision is the standardization as shown in Fig.1.

The main objective of the investigation proposed in this paper is to summarize and analyze the knowledge about standardization processes and standards needed in the field of monitoring and control of CPS. It is necessary to draw conclusions on the applicability of the existing standards in the field for the purposes of the Industry 4.0 initiative and to analyze the possibilities for their extension and joint use. The paper is organized in 4 parts. After the introduction, in part 2 a short overview of standardization processes in the context of Industry 4.0 is proposed. Part 3 presents an analysis of the most important standards for monitoring and control of CPS, based on different reference architectures, meta-models and models. Finally some conclusions in respect to interoperability of applications for monitoring and control are drawn.

Fig.1: *Challenges for the implementation of “Industry 4.0” [8]*

2. Standardization in the context of Industry 4.0

The major advantage of using standards is that they reflect the state of the art of research and technology development and promote mutual understanding and consensus among partners. Studies show that the contribution of standards to annual GDP growth varies from 0.3 to 1%. For Germany this impact is estimated at 1% of GDP, for France - 0.8% and for the UK only 0.3% [9].

The main shortcomings in standardization are related to the existence of too many standards and the lack of interoperability between them internationally, with the main reasons for this being the different culture, language and areas of use. Overcoming these shortcomings requires cooperation and coordination, the so-called harmonization process. In this regard, the White Paper on "Modernizing the Standardization of Information and Communication Technologies (ICT) in the EU" was adopted in 2009, where it stated that: "Standards are needed in the digital society to ensure the interoperability of networks and systems. In a digitally-driven society, ICT-related solutions are used in every economic sector as well as in our everyday life. These solutions, applications, and services must be able to communicate with each other, i.e. they must be interoperable. Interoperability requires standards“[10]. At a meeting of the European Commission in February 2010, the Expert Group on the Review of the European Standardization System (EXPRESS) presented its report

"Standardization for a Competitive and Innovative Europe: Vision 2020" [11]. In a document dated 4 February 2011, the European Council, on the basis of [11], confirms that standardization is an important framework for promoting private investment in innovative goods and services and that standardization processes need to be accelerated, simplified and modernized. This is an essential sign of the European economy that European standardization continues to adapt to the rapidly changing global reality and economic environment. In June 2011, the "Strategic Vision for the Development of European Standards by 2020" is published. It aims at improving and accelerating the sustainable growth of the European economy [9].

The basis for addressing the above-mentioned standardization issues is the use of standardized reference frameworks and architectures that help achieve interoperability at standards level. One of the most well-known reference architectures for Industry 4.0, which successfully launched these processes, is the reference architecture RAMI 4.0 [12]. The reference architectural model RAMI 4.0, shown in Fig.2, is three-dimensional and describes the crucial aspects of Industry 4.0. The "Hierarchy level" axis includes the hierarchy levels defined in the ISO/IEC-62264 standard, including all different functionalities in the factory. In the RAMI 4.0 the functionalities are extended to the "product" according IEC-61512 standard and to "connected world". The left horizontal axis represents the life cycle of the facilities and products, based on the IEC-62890 standard and the vertical axis represents the six layers for decomposing into its properties. The reference model allows a step-by-step migration from present into the world of Industry 4.0. RAMI 4.0 integrates different user perspectives and provides a common understanding of Industry 4.0 technologies. It is a foundation for the following next steps towards Industry 4.0: thing identification, unified semantics and common syntax for data, defining of QoS components, communication connections and protocols.

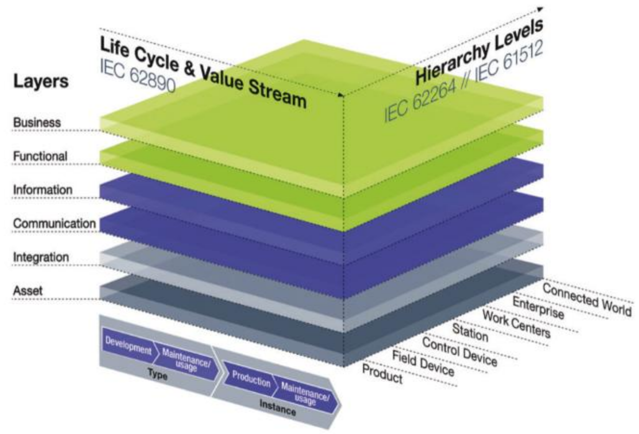

***Fig.2**: Activity model of quality operations management [12]*

The areas in which the interoperability of different standards based on RAMI 4.0 can be successfully launched are summarized and shown in Fig.3. With respect to monitoring and control of cyber-physical systems, the standards of great importance are from the following fields: "Engineering" (IEC-62714, IEC-62424, IEC-61131, IEC-61499), "Communication Layer" (IEC-62541) and "Hierarchical Levels" (IEC-61512, IEC-62264). They will be presented and analyzed in Part 4 of the paper.

3. Main trends in monitoring and control of CPS

The structural and behavioral complexity of cyber-physical systems poses great challenges in terms of the methods and environments for their design and analysis. It is necessary to develop the theoretical foundations of CPS, as well as to create software platforms with appropriately defined levels of abstraction, architecture, languages for modeling different aspects of CPS and transformations between these models. Especially important are methods that have to integrate the discrete dynamics of the computing part with the continuous dynamics of the physical part and the stochastic nature of communications, which must be expanded to cover a wider context. There are three main approaches to designing the CPS: Networked control systems, Hybrid control systems and Distributed hybrid control systems.

***Fig.3:** Key domains for standardization*

The fundamental requirements for introducing CPS in industry are specified by [13] as follows:

- Adaptable to heterogeneous environments: integration with cutting-edge information systems, smart-devices and the existing environment (from old PLCs to smart object embedded in computing power).
- Capable of working in distributed networks: they should gather, transfer and store in a reliable manner all the information provided by smart sensors and actuators through the use of the IoT.
- Based on a modular open architecture: the interoperability has to be ensured across different platforms provided by several vendors along the value chain.
- Incorporate human interfaces (HW & SW based): integration of user-friendly and reliable service to make decision makers aware about the real time situation of the factory.
- Fault tolerant: given by the encapsulation of models to activate prediction control loop and correctness of automation systems.

4. Short analysis of standards for monitoring and control of CPS

4.1. IEC-62714 Standard (AutomationML)

The IEC-62714 Standard or also known as AutomationML (AML – Automation Markup Language) is an international and free of charge standard proposing neutral data format based on XML for storage and exchange of engineering information about industrial automation systems [14]. It covers information about the plant structure (topology, geometry and kinematics) and the plant behaviour (logic). The standard ensures a common understanding of exchanged data through explicit common semantics for all data to be exchanged. AML covers the data contents from different information sets as shown in Fig.4, combining the following data formats:

- CAEX (IEC-62424) – for description of system hierarchies and attributes of system elements and devices;
- COLLADA (Standard of KHRONOS Group) - describing geometry und kinematic information;
- PLCopen XML (Standard of PLCopen for modelling of IEC 61131 projects) for describing of behavior information models.

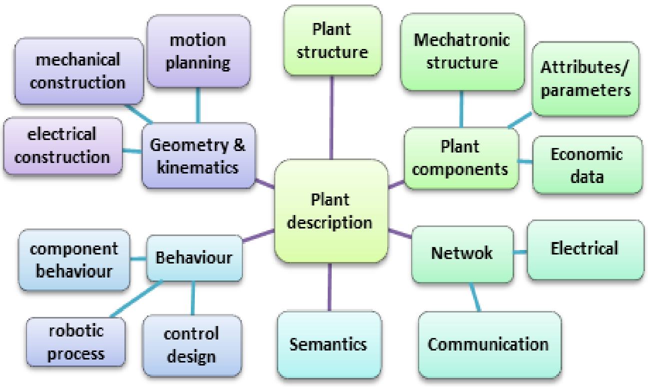

Fig.4: Basic information sets covered in IEC-62714

4.2.IEC-62541 (OPC-UA)

The IEC-62541 Standard [15] or OPC-UA (Open Platform Communication – Undefined Architecture) is a new generation of OPC that replaces DCOM communication specific TCP/IP protocols enabling OPC in any operation system and can be implemented in all languages. OPC UA offers a fully networked, object-oriented concept for the namespace, including metadata for object description. The OPC UA specification defines a service-oriented architecture (SOA) with a set of services described in Part 4 of the standard. The information models in OPC UA form a layered structure, shown in the Fig.5, where the lowest level is the base Information Model. Above the base model the service-specific information model extensions for Data Access, Alarms & Conditions, Programs, Historical Access and Aggregates are located. Above the composition of general information models, the companion specifications are defined. The next layer are companion specifications which are domain-specific information models On the uppermost level of the OPC UA structure, highly specified information models are defined by different companies or vendors for use in their specific products. The composition of information models can be extended.

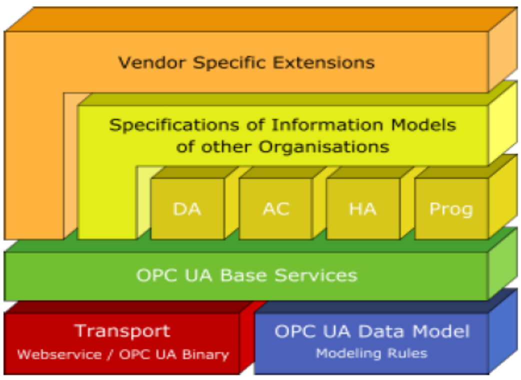

Fig.5: Layered structure of information models in OPC UA [16]

4.3. IEC-61499 standard

The IEC 61499 standard [17] defines different reference models supporting the design of distributed control systems at physical, logical and conceptual levels and from different viewpoints. The key models of an IEC 61499 based distributed control system are system, device, resource and application models as shown in Fig.6. All these models are based on the Function Block (FB) concept. Three different kinds of FBs are defined: basic (BFB), composite (CFB) for encapsulation of complex functionality through networks of BFB and service interface function block (SIFB) for providing interfaces for unidirectional (publish/subscribe) and bi-directional (client/server) communications as well for resource or device management. An application model is a network of FBs and may be executed by one or more devices, including one or more resources. Resource models provide support for program execution by their scheduling part, communication and process interfaces. A device is a control unit having one or more processors that defines specified function for the purposes of automaton and has two types of interfaces - process and communication in order to communicate with the process and other devices on the network respectively. The system model consists of a number of devices, with global or local communication links between them. From the above said it is clear that combining encapsulation of functionality, component-based design and event-driven execution and distribution accelerates and facilitates significantly the dynamic reconfiguration of control systems.

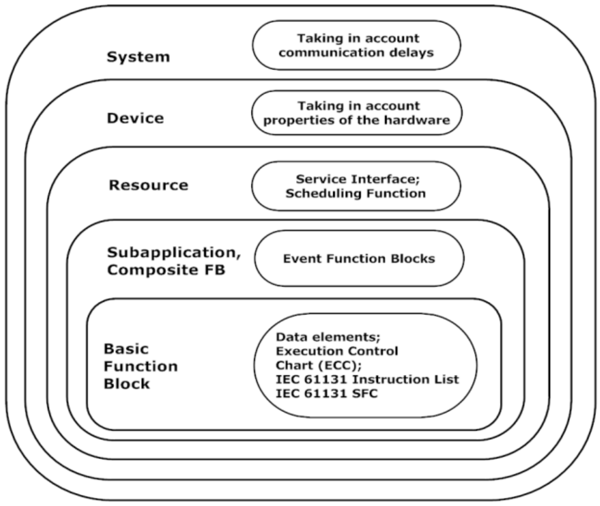

Fig.6: Basic models in IEC61499

Extra for the configuration purposes the so-called Management SIFBs are also considered in the standard. They enable the management of devices, resources and applications as it is possible to define and use 6 operations - create, initialize, start, stop, delete and query and to provide notification of changes in availability and status of data types, function block types and instances, connections among function block instances (IEC TC65/WG6, 2005). Thereby IEC 61499 provides the basic interfaces to support dynamic reconfiguration, but the mechanisms to do it are still under development.

4.3.IEC-61512 Standard

The IEC-61512 Standard [18] or also known ISA S88 provides a guideline for design of batch control systems. It defines basic terminology and a set of descriptive models. The main idea is to separate product knowledge from the equipment used. To describe a batch process in different grades of detail from chemical and control engineering points of view, the standard proposes a set of seven models as shown in Fig.7.

Taking the process view, design starts with a process model containing the (abstract) chemical knowledge of the process to be realized. From general recipe to control recipe this model is stepwise substantiated (i.e. adapted to the batch plant). The resulting control recipe describes which actions have to be taken in which order to reach the desired process. The control view (or equipment view) is described with the physical control model, dealing with sensor and actuator signals, and its abstractions, equipment control and control recipe. The control recipe is the meeting point of the two points of view. It is also the starting point for the proposed approach and will be explained in detail in the following. As all models in S88, the control recipe is built in a hierarchical way. Phases are considered as elementary steps in the control recipe and cannot be decomposed. A phase describes a basic function of the given plant such as dosing, stirring or heating. Collections of phases performed in a specified order (sequential and/or parallel) are operations.

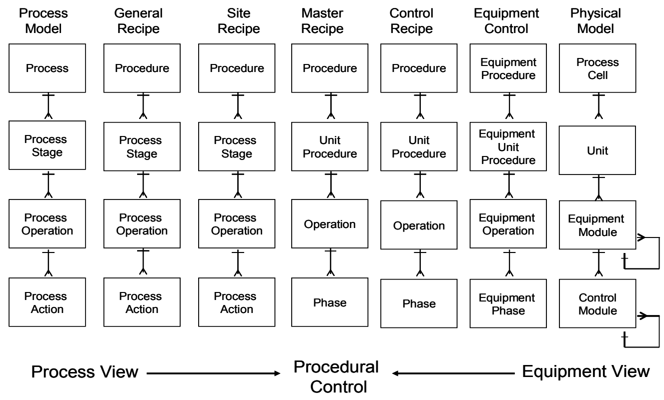

Fig.7: *Process and equipment view of IEC-61512 [18]*

4.4. IEC-62264 Standard

ISO/IEC 62264 (ANSI/ISA-S95) series of standards [19, 20] offer the technology and a vendor independent way to exchange data and information. These standards are an agreement between leading companies (SAP AG, Eli Lilly, The Foxboro Co., Hewlett-Packard, Honeywell, Rockwell Automation, IBM Corp., Oracle Corp., ABB etc.) to create a common framework and guidelines for design and integration of systems. The standard ISO/IEC 62264 facilitate to separate business process from production processes and to separate the exchanged information from specific implementation of manufacturing systems and specific implementations of the business systems. The standard provides standard models and terminology for describing the interfaces between the business systems of an enterprise and its manufacturing-control systems (Fig.8). Activities related to manufacturing operations management (Level 3) integrate planning and logistics (level 4) and control functions defined on Level 2.

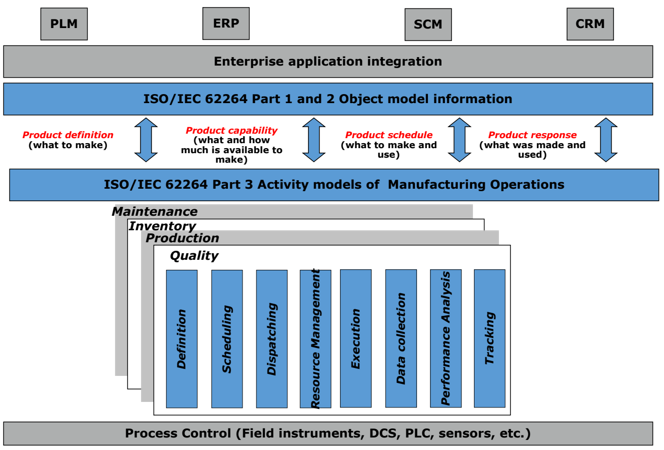

Fig.8: *ISO/IEC-62264 Manufacturing Architecture [21]*

5. Conclusions

The CPS require the development and use of new methods and techniques for design and integration, based on the use of open industry standards related to the achievement of full integration of heterogeneous products and systems from different perspectives and points of view. None of the standards discussed in this paper is able alone to address the challenges faced by monitoring and control in CPS. The use of RAMI 4.0 reference architecture ensures compatibility of the presented standards and significantly improves the performance and quality of the development.

Industry 4.0 vision requires revision of the approaches for development and use of CPS concerning the decentralization in order to integrate the Cyber-Physical Systems (CPS) with cloud computing infrastructures, and to empower decentralization using edge computing that moves some part of computing from the cloud to its edge nodes, supporting real-time interactions and scalable analytics, or the application of new disruptive key enabling technologies in factory automation like DLT (Distributed Ledger Technology) and Smart Contracts (ISO-20022) changing the paradigm of messaging. All thise new trends in the development of CPS will impose new challenges to ensure the interoperability at the level of standards.

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