Combined approach for development of cyber-physical systems based on IEC 61512 and IEC 61499 standards

Daniela Tzakova, Idilia Batchkova, Yordan Belev
Dept. of Industrial Automation, University of Chemical Technology and Metallurgy
Bul. Kl. Ohridski 8, Sofia, Bulgaria

dtzakova@gmail.com, idilia@uctm.edu, yordanbelev@gmail.com,

***Abstract**: The transition to CPS is one of the great challenges of the "Industry 4.0". The core of cyber-physical systems is an effective control, associated with achievement of a high degree of adaptability, autonomy, functionality, reliability, security and usability. The paper presents a combined approach for development of cyber-physical systems based on the IEC-61512 and IEC-61499 standards represented as partial model of asset administration shell, according the reference architectural model RAMI4.0. The models allow the description of continuous production of finite quantities of materials (batches) from two distinct views – physical and control (cyber). The approach is enhanced in respect to the correctness and reliability achieved, by replacing the semi-formal models with using of Signal Interpreted Petri Nets supporting the verification processes.*

***Keywords**:* CYBER-PHYSICAL SYSTEM, INDUSTRY 4.0, RAMI 4.0, ADMINISTRATION SHELL, IEC-61499, IEC-61512

1. Introduction

The strategic initiative "Industry 4.0" [1] is related to the new industrial revolution and implies integration of Cyber-Physical Systems (CPS), the Internet of Things (IoT) and cloud computing leading to what is called "smart factory". The smart factories are flexible systems and machines following RAMI 4.0 structure, with functions distributed throughout the network, where participants interact across hierarchy levels, products are part of the network and there are communications among all participants. "Industry 4.0" focuses on the integrated use of advanced information and operational technologies, such as Internet of Things (IoT), cyber-physical systems, big data, data analytics and decision making, artificial intelligence and robotics, cloud and fog calculations, augmented reality and more. With a view to faster adoption of the new concept by industry, it is desirable to ensure a smooth transition to these new technologies, through the use of transitional technologies and standards, and reasonable investment to achieve the objectives, including integration between operation and information technologies. There are a number of prerequisites for this in the industry: embedded devices and controllers, wireless sensor networks, RFID technologies and more. While the hardware industry is relatively prepared for the transition to industrial IoT, software and architectures face serious challenges.

The transition to CPS is one of the great challenges of the "Industry 4.0". They refer to a new generation of engineered systems where cyber and physical components are strongly interconnected, each operating on different spatial and temporal scales, exhibiting multiple, distinct behaviours, and interacting in numerous ways that change depending on context [2]. The core of cyber-physical systems is an effective control, associated with achievement of a high degree of adaptability, autonomy, functionality, reliability, security and usability.

An important way to deal with the complexity, diversity and heterogeneity of cyber-physical systems is to use reference frameworks and architectures to achieve interoperability, simplify development and facilitate implementation. One of the most popular reference architectures is RAMI4.0 of the Industry 4.0 Working Group [3, 4], which supports the analysis and specification of domains, and facilitates the unification of methods used by various disciplines such as industrial engineering, control theory, communication and information technology, thus making possible their combined use. 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. Key elements in RAMI4.0 are the standards, which reduces the risk for enterprises and encourages the adoption of new technologies, products and production methods. The main advantage of using standards is that they reflect the state of research and technological development and promote mutual understanding and consensus between partners. Standards are used on the different levels of aggregation, covering different engineering topics and domains. An important step in the right direction is their joint use by setting up appropriate interfaces, or meta-models.

The main goal of the paper is the integrated and combined use of the standards IEC-61512 [5] and IEC-61499 [6, 7] based on the concept of RAMI4.0 for building a database, including Asset Administrative Shells (AAS). AAS is an implementation of the digital twin for Industry 4.0. It establishes cross-company interoperability, covering the complete life cycle of products, devices, machines and facilities enabling the integrated value chains. It is available for non-intelligent and intelligent products and is the digital basis for autonomous systems and Artificial Intelligence [8].

The main idea of IEC-61512 is to separate product knowledge from the equipment used and to describe a batch process in different grades of detail from chemical and control engineering points of view based on 7 different models using semi-formal technique. The second standard that is combined is IEC-61499 standard. It is a standard for design and implementation of distributed controllers. As its predecessor IEC 61131, it provides a framework for hardware and software aspects of controllers. It defines various models for system, device, resource, and application level. For application design IEC 61499 introduces new kinds of function blocks (FBs).

The main aim of the paper is to suggest a combined approach for development of cyber-physical systems based on the IEC-61512 standard for batch control and IEC-61499 standard for development of distributed control applications. The approach takes in to account the last achievements in the reference architectural model development included in DIN SPEC 91345. After the introduction a short analysis of related standards is undertaken in part 2. The last part of the paper presents the combined approach for development of CPS for batch control using IEC-61499 and IEC-61512 Standards. Finally some conclusions are done.

2. Related works

2.1. Reference architectural model for Industry 4.0 (RAMI 4.0)

The reference architectural model RAMI 4.0 is one of the most well-known reference architectures for Industry 4.0 [4]. The framework of RAMI 4.0, shown in Fig.1, 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.

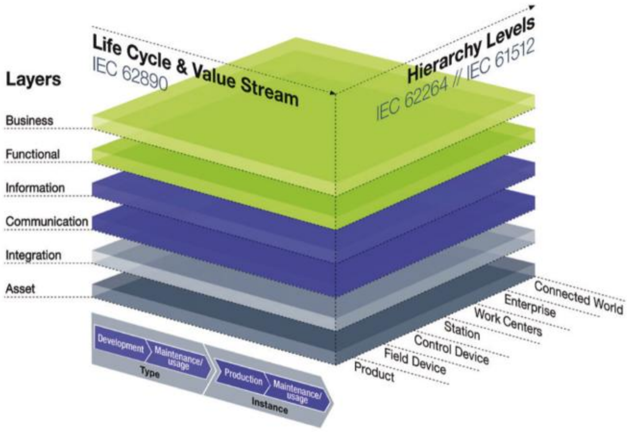

Fig.1: *Activity model of quality operations management [3]*

In RAMI 4.0, the concept of I4.0 component is defined and may be considered as a specific case of CPS. Each I4.0 component, as shown in Fig.2, consists of physical part (asset) and cyber part, named "administrative shell" (AS), which is a digital representation of asset. AS offers dedicated information, functionalities and internal and/or external services, and includes two parts: manifest and component manager. Manifest features externally accessible set of meta-information that reflects the uniqueness of I4.0 component. The resource manager guides the services and access to them, described in hierarchically organized sub-models. The sub-models are two kinds: generic and specific. The generic sub-models are static models and represent mandatory information, such as: index data item, property value statement, documentation and communication. The properties of sub-models are formatted corresponding chosen standardized data format (eCl@ss, Common Data Dictionary (IEC 61360-4), IEC 61987 (Process automation), etc.). The AS includes a communication interface for providing outside access to functions and data.

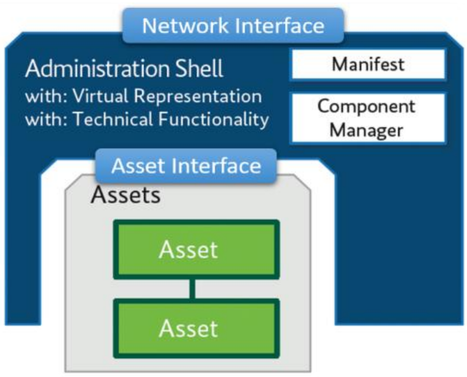

Fig.2: *I4.0 component [3]*

2.2. Short overview of IEC-61512 standard

The IEC-61512 standard [5] also known as ANSI/ISA S88.01 is a basic and well accepted standard in the area of batch process industry, providing domain specific models for design and control of batch production processes. The standard is shortly known as S88. Its structure gives a frame for clearly definition of processes and product requirements. The modular structure of the standard is applicable to all types of control systems and promotes reusability through breaking up the systems into smaller components. The standard provides a guideline for designing batch control applications for manual as well as automatically controlled processes. The three control types in batch manufacturing are basic, procedural and coordination. These control types are applied to the control and equipment modules. To examine the relation between equipment and procedural control, IEC-61512 standard defines a hierarchy of four types of recipes, i.e. general, site, master and control recipe.

The main idea of IEC-61512 is to separate product knowledge from the equipment used. The philosophy of IEC-61512 is shown in Fig.3. To describe a batch process in different grades of detail from chemical and control engineering points of view, IEC-61512 proposes a set of seven models as shown in Fig.4. 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. As all models in IEC-61512, the control recipe is built in a hierarchical way. Phases (not shown in Fig.4) 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. Operations are organized in unit procedures which are assigned to a specific class of plant units. A unit procedure describes a series of operations providing a high level function. Finally, unit procedures are combined to procedures describing the interaction of plant units. S88 introduces the semi-formal design language Procedure Function Chart (PFC). It enables the designer to graphically describe the organization of operations, unit-procedures and procedures using basic elements. In Fig.4 the PFC are replaced by Signal-Interpreted Petri Nets (SIPN). They provide more details for analysis and verification in a formal way. The IEC 61499 based methodology is used to implement the control scenario. They will be shortly presented in the next paragraphs.

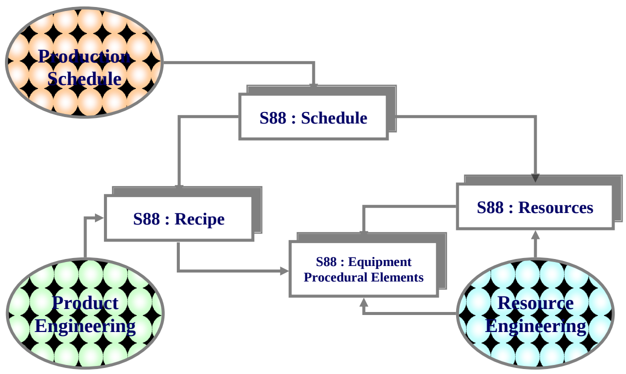

Fig.3: *The philosophy of IEC-61512*

IEC-61512 defines several models describing the equipment, process and procedure hierarchies necessary to make batches as it is shown in Fig.4. The physical model describes the equipment necessary to make a batch and is divided into two organization parts: "Enterprise", including enterprise, site and area, and "Equipment" composed of process cell, unit, equipment module, control module. Subject of the research proposed in this paper is the "Equipment" part. A process cell contains all of the equipment, including units, required to make batches. Batching activities are focused on units, defined as "a collection of process and control equipment, and the associated control logic that carry out one or more major processing activities” [5]. An equipment module according IEC-61512 is “a functional group of equipment that can carry out a finite number of specific minor processing activities”. This module can be made up of control modules or other equipment module. In some cases, equipment modules can replace control modules. Control modules are treated as basic elements of the IEC-61512 physical hierarchy. They are defined as “collections of sensors, actuators, other control modules and associated process equipment that, from the point of view of control, is operated as a single entity” [5]. Examples of control modules may be valves, pumps, PID, PLC, sensors.

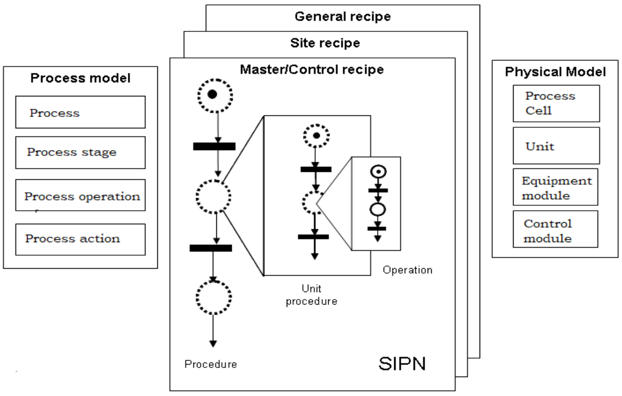

Fig.4: *Simplify view of IEC-61512 structure*

2.3. Short overview of IEC-61499 standard

The IEC-61499 standard [6] defines the basic concepts and reference architecture for the design of reusable and component-based distributed control systems (Fig.5). At the heart of the standard is the concept of "function block" (FB) as a basic structural unit of the application. The term “Function Block” is defined by Lewis as: “an abstract mechanism that allows encapsulation of industrial algorithms in a form that can be easily understood and applied by an engineer who is not skilled in the implementation of complex algorithms” [7]. The standard defines three types of function blocks: basic, composite and service interface. The basic function block is presented by an input and an output interface composed of input and output events and data. The internal view of a basic function block includes an Execution Control Chart (ECC), internal data and internal algorithms. The ECC is a state machine used to control the execution of algorithms associated to the function block. A function block is characterized by its type name and instance name, which are used to identify a function block. The event and data inputs and outputs are required for the interconnection of different function blocks to function block systems, while the ECC, internal data and internal algorithm describe the internal behavior of the function block. The kernel of the Basic function block is its Execution Control Chart. An ECC consist of states, transitions and actions, which invokes the execution of the algorithms, which are associated to the ECC states, in response to event inputs.

IEC-61499 standard defines 3 types of reference models, on the basis of which a distributed control system can be designed at different phases of its life cycle: system model, device model and resource model. The system model specifies the distribution of an application between devices, and a single device can perform multiple applications. Devices are containers of resources that make it possible to run function blocks on the network independently. The resource model specifies the location where an application is running, providing the basic resources for doing so. Although the industry is aware of the benefits of using IEC 61499, this standard has not yet been widely applied in the industry. The main reasons for this are the immaturity of the development tools and the lack of a sophisticated integrated development environment (IDE) and integrated design methodologies that facilitate component-based development of automation systems throughout the whole development lifecycle. There are several engineering environments that support the development of control systems based on the IEC6199 standard among which the 4DIAC tool has special ambitions to meet the requirements of Industry 4.0 [9].

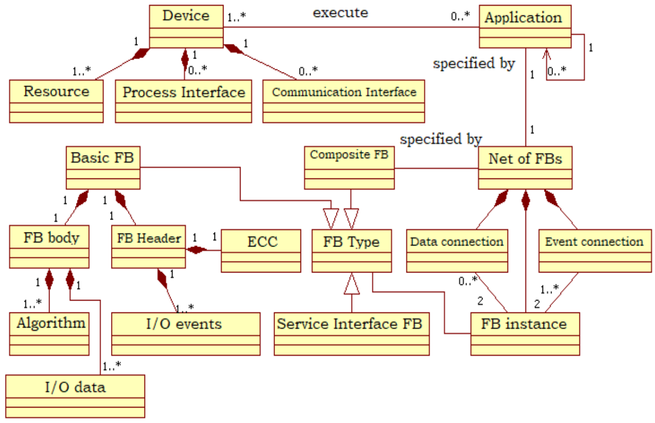

Fig.5: *Reference architecture of IEC-61499 standard*

3. Combined approach for development of CPS based on IEC 61512 and IEC 61499 Standards

The basic idea of the approach is to allow the chemical engineer to specify his knowledge using S88 while at the same time giving the control engineer the opportunity to use IEC 61499 to design and implement the needed logic controllers. The goal is to provide highly reusable components concerning batch process and an easy way to reconfigure their executions. As a result, the control strategy can be flexibly managed. The proposed approach supports the development of reusable software components based on the combined use of three different formalisms: the IEC-61499 standard for distributed process measurement and control systems, the IEC-61512 standard for batch control and the Signal Interpreted Petri Nets (SIPN), used as a tool for formal verification of the correctness in the behavior of the developed I4.0 components or CPS. IEC-61512 provides domain specific models for design and control of batch production processes. The models allow the description of continuous production of finite quantities of materials (batches) from two distinct views – physical and control (cyber). The approach is illustrated in Fig.6, and includes the following steps:

- Functional component development - each physical component as for example pressure sensor, temperature sensor, level sensor, valve and pump, has corresponding cyber component (i.e. functional component). If several components are employed for an equipment or unit module, their software components are then compounded as a composite component. The functional component can be instantiated several times;
- Control recipe modeling using SIPN that is an extension of Condition-Event nets which allow process interfacing by output signal assignments associated with places and input signal evaluation in Boolean expressions attached to transitions [10]. The procedural control of each unit procedure 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. The extension of SIPN with time and hierarchical structures gives opportunity for fully description of control system functionality and requirements;
- The designed formal SIPN model may be checked for correctness before its implementation through automatically constructed different types of Reachability Graphs (RG), transparent analysis or transformations to timed automata. The focus is oriented more and more to formal specification

languages such as temporal logic and formal verification methods such as the famous model checking.

- Mapping of model to an IEC 61499 based application (SIPN2IEC61499) - The SIPN model with regard to the functional component is mapped into IEC-61499 based component using some rules.

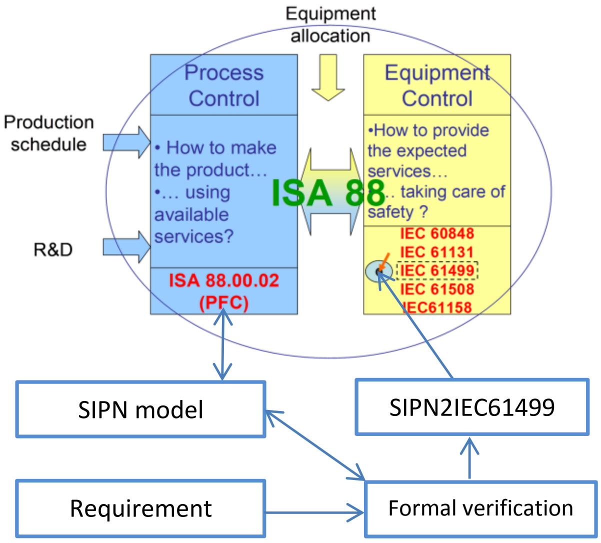

Fig.6: *Illustration of the combined approach*

IEC-61512 and IEC-61499 standards may be used within the asset administration shell in order to specify properties and property values as shown in Fig.7. The meta-model of AAS is based on the concept of partial models having unique global identifiers and a set of well-defined attributes and properties. The partial models characterize different aspects or functions (mixing, heating, reacting) of the asset, in different domains such as communication, engineering, security, process control, etc.

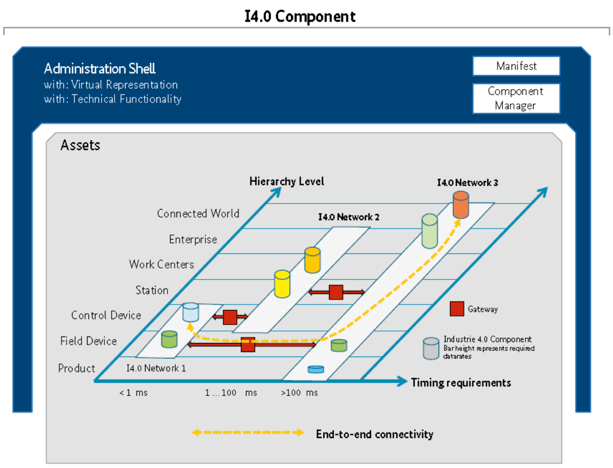

Fig.7: *Illustration of network-based communication as an asset*

4. CONCLUSIONS

The combined use of the IEC-61499 standard results in a significant improvement in the quality, safety and efficiency of the designed CPS. The main advantages of the suggested approach with respect to CPS can be summarized as follows:

- Important advantage of the proposed approach resulting from the use of SIPN models and their formalization is the ability to verify and validate the models, as well as to increase the security and safety of the applications. Using the SIPN model it is possible to check for consistent control on operation level, i.e. to guarantee that the order of phase execution fits to the specification of the plant.
- IEC-61499 standard allows the integration of a time-triggered mechanism with SIFB-based event triggered systems;
- The reference architecture and models based on IEC61512 and IEC-61499 standards support the reuse of the developed CPS components and shorten their development and configuration time;
- The models offered allow the creation of libraries of reusable components for different application areas based on both standards.
- The distributed control structure achieved, facilitates the reconfiguration of the system by inserting, deleting and replacing functional components based on IEC-61499 standard;

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