MONITORING AND CONTROL OF CYBER-PHYSICAL SYSTEMS – THE BACKBONE OF INDUSTRY 4.0

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Abstract: *Monitoring and control of Cyber-Physical Systems (CPS) have many challenges related to the heterogeneous environment, the high degree of interaction between the components and the high requirements for functionality and scale. The paper presents an analysis of the state of the art in this area and proposes an approach for monitoring and control of CPS through the integration of the IEC-61499 based models for distributed control systems and the IEC-61512 standard providing domain specific models for design and control of batch production processes as well as the Signal- Interpreted Petri Nets used for the purpose of formal specification and verification of unit procedures. The approach is illustrated with an example of CPS for loading a batch tank and mixing of liquid flow.*

Keywords*:* CYBER-PHYSICAL SYSTEMS, INDUSTRY 4.0, MONITORING, CONTROL, IEC-61499, IEC-61512

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 that 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.

Cyber-physical systems (CPS) represent integration of computational and physical processes. They use embedded computers and networks for the purpose of monitoring and feedback control of physical processes [7]. Through cyber-physical systems, the physical world connects to the virtual world to form Internet of Things, Data, and Services. One of the most promising and challenging applications of CPS is the cyber-physical production system. Research in the field began in 2006 in the United States, when the President's Council of Advisers for Science and Technology (PCAST) identified research in the field of CPS as a national priority and hundreds of millions of dollars have been invested since then [8]. The European Industry Association ARTEMIS-IA [9] also focuses its interest on embedded systems and their evolution towards the CPS, with around € 2.7 billion invested so far, mainly in more than 50 projects under the European Framework Programs (7 Framework Program and Horizon 2020). It is commonly believed that the development and implementation of CPS should be based on a new scientific basis in order to build a bridge between sequential semantics and parallel physical world.

To meet the challenges of modern enterprises, CPS must meet certain requirements, which can be summarized as follows:

- The architecture of these systems must be decentralized, based on the knowledge product/resource;
- Interactions between the elements of these systems must be abstract, generalized and flexible;
- Control must be reactive and proactive;
- Control must be self-organizing.

The above requirements can be achieved using a range of approaches and methods from different scientific fields. Some of the key topics in research and development 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.

The main objective of the research is to develop and present an approach for monitoring and control of cyber-physical systems, based on defined requirements to the cyber-physical control systems. The paper is organized in 4 parts. After the introduction, in part 2 a short review and analysis of different approaches and methods for monitoring and control of cyber-physical systems is proposed. Part 3 presents the suggested approach based on the reference architecture and models of the IEC-61499 standard for distributed measurement and control systems [10], the standard IEC-61512 providing domain specific models for design and control of batch production processes [11] and the Signal Interpreted Petri Nets [12] as a tool for specification and verification of unit procedures. In Part 4 of the paper the approach is illustrated with an example from the domain of batch CPS. Finally some conclusions are made.

2. State of the art in monitoring and control of CPS

2.1. Basic requirements to the CPS

Cyber-physical systems can be seen as successors of the steam engine governor, emerging during the Industrial Revolution in the eighteenth century and closely related to the emergence and development of control theory. The subsequent advance in the field of computer, computing and communications technologies causes the Information Technology revolution, and their convergence with control and automation has led to the emergence of so-called cyber-physical systems. The use of key enabling technologies such as: ubiquitous embedded computing, sensing, wireless networking technologies, multi-objective optimization, decision-making tools, specification and verification technologies are paramount to the development of smarter, more flexible, reliable and efficient cyber-physical systems. Some of the most important features that distinguish today's cyber-systems from older generation control systems are defined in [13] as:

- Much larger scale of CPS;
- CPS components operate in a heterogeneous environment;
- CPS components interact with each other in a very complex manner;
- CPSs should be highly extensible for new functionalities, and flexible for runtime adaptation.

2.2. Reference architecture of CPS

NIST and in particular the created CPS Public Working Group offers a reference architecture of CPS, shown in Fig.1, consisting of 6 layers and even more transversals capabilities, each of which is included in each layer [14]. The first layer “physical systems” includes all the engineered devices. The sensors on the second layer acquire data from the physical systems, and transmit that information to the next layer and actuators receive data from the control components and act on the physical systems in an adequate way. Monitor and control systems at the third layer consist of hardware and software components, which acquire data from sensors, perform local processing and control the actuators in order to reach the wanted state in the physical systems. The forth layer “Data analytics” includes software for processing, filtering and storing the information from different control components. It is also possible to include software for pattern recognition, decision-making, predictive analysis and machine-learning. The fifth layer (Modeling, Optimization and Simulation) develops and maintains dynamic computing models. The sixth layer (business and consumer goals) refers to the measurable objectives defined by the users to be achieved. In this paper the focus is on the third layer, as in the next section the current state of the art in the field of CPS monitoring and control will be analyzed.

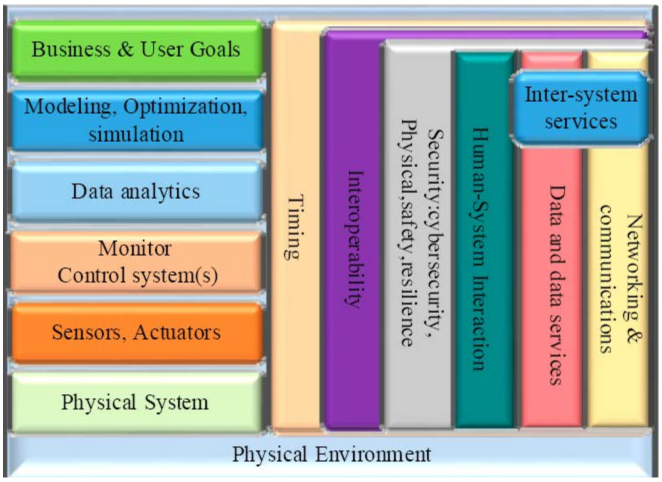

***Fig.1:** NIST Reference architecture of CPS [14]*

2.3. 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 - The emphasis on these approaches is on the communication between the different components of the system. There are two main approaches for data acquisition from the physical part of the CPS: timed driven and event driven sampling. The latter approach requires continuous monitoring of the physical system. Compromise approach, the so-called self-triggering approach, is related to the determination of safe intervals during which the physical system is not observed and the time when the data is collected. Particular attention is also paid to methods of addressing the effect of delayed network signals, such as scheduling or stability analysis methods. Other important tasks that seek a solution, especially from the field of control theory, are to determine the optimal placement of computations and to deal with the availability of channels with very low data rates. An overview of networked CPS is given in [15].
- Hybrid control systems that emphasize their continuous and discrete dynamics. Various approaches are known, among which the most popular are hybrid automata using different mathematical formalizations to reflect the transition between discrete states and the evolution of the continuous states over the time. Among the most frequently used are finite state machines and timed automata, bisimulation, transition systems, linear hybrid automata (LHA), rectangular hybrid automata (RHA), temporal logic and others. It should be noted that there are a lot of software tools that allow the synthesis of control systems and their formal verification, such as UPPAAL, HyTech, etc. Some analysis of these approaches are presented in [13, 16];
- Distributed hybrid systems – One of the most often applied approaches uses software platform, called middleware, which uses an appropriate abstraction of complex systems and offers architecture for the rapid deployment of CPS applications [17]. The successfully applied architectures include: component-based, service-oriented, agent-based, and the CPS 5C (connection, conversion, cyber, cognition and configuration) architectures [18]. Another successfully applied approach is based on the Embedded Virtual Machine (EVM) and uses a modular architecture that separates the tasks from the unreliable physical part allowing the integration of system components and their run-time reconfiguration [19]. Other successful approaches use specialized programming languages such as Giatto, Esterel, Signal, etc. or the Model Driven Development (MDD) approaches. MDD [20] are some of the most promising and challenging approaches for development and maintenance of highly distributed control systems such as CPS. Here the systems are presented as models that conform to meta-models, and the model transformations are used to manipulate the various representations. The main difference from other development methods based on models is that MDD uses models as inputs to parameterized implementation generators, i.e. implementation is (semi)automatically generated from the models.

In the next section of the paper an analysis of the IEC 61499 standard in respect to its application for development of distributed monitoring and control for CPS is presented and an approach for these purposes is proposed.

3. An approach for monitoring and control of CPS based on IEC-61499 standard

3.1. Analysis of IEC-61499 standard in respect to CPS

Contemporary CPSs are characterized by their high dimension and complexity, including a variety of decision-making capabilities and control logic. The degree of communication of these systems with physical processes, based on algorithms with increased efficiency and robustness, also increases. The amount of logic-based programming code far exceeds traditional control algorithms.

The IEC 61499 standard 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.2. 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.

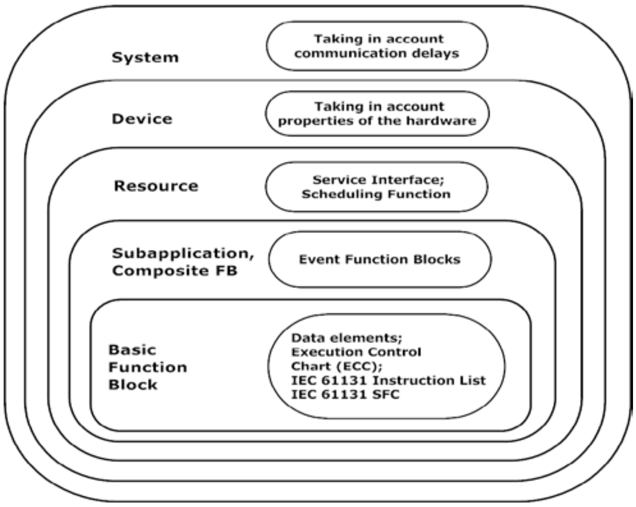

Fig.2. *Basic models in IEC61499*

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.

There are several engineering environments supporting the development of control systems based on the IEC-61499 standard. The most popular and most commonly used open source environment is the FBDK (Function Block Development Kit) [21]. The product is developed by Rockwell Automation and allows the definition of basic and composite functional blocks, resources, devices, and system configurations. XML format and Java interface are used to support the visual testing of the developed models. In the FBDK environment there is a library of different functional blocks, resources and devices, as well as graphical interfaces and simulation capabilities. Other known environments are 4DIAC [22], FBench [23], ISaGRAF [24], and nxtStudio [25]. 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 immateriality of development tools and the lack of a sophisticated integrated development environment (IDE) and integrated design methodologies to facilitate the component-based development of automation systems throughout the development life cycle.

The main advantages of the standard with regard to CPS can be summarized as follows:

- IEC-61499 allows the integration of time-triggered mechanism with event-triggered systems, based on SIFB;
- The IEC-61499 based reference architecture and models supports the reusability of developed components of CPS and shortens the time for their development and configuration;
- The achieved distributed control structure facilitates the reconfigurability of the system through inserting, deleting and replacing IEC-61499 based functional components;
- The suggested models allow the creation of library with IEC-61499 based reusable components for the different application domains.

The main shortcomings in the implementation of the standard with regard to CPS are the following:

- IEC-61499 does not provide opportunities for verification of control logic, both in the design phase and after online reconfiguration;
- It does not allow modeling of the physical part of the system;
- There is no possibility of performing parallel control logic;
- There is a need to improve the execution semantics, in order to independent from deployment platforms (deterministic) and to address the real-time constraints [26];
- Lack of modern interfaces for communication with the upper management and control levels;
- Middleware for Real-Time Communications enabling distributed elaboration of signals and cognitive functions of CPS.

3.2. Short description of the suggested approach

The proposed approach for monitoring and control of CPS 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), which are used as a tool for formal verification of the correctness in the behavior of the developed 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 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 - the procedural control of each unit procedure
- Mapping of model to an IEC 61499 based application - The SIPN model with regard to the functional component is mapped into IEC-61499 by using some rules.

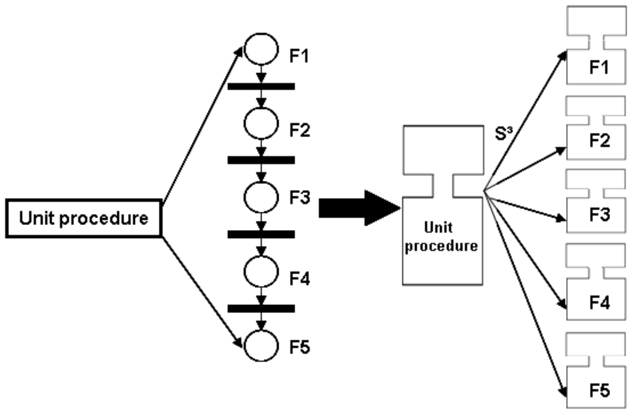

Fig.3: *Basic models in IEC-61499*

4. Case study: Functional component of batch CPS

4.1. Short description of the CPS

The goal of the described case study 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 physical system, called "Loading" is shown in Fig.5-1 and includes equipment for pumping a batch tank with liquid feed and its optimal mixing. The informal specification of unit procedure is shown in Fig.4.

1. VP-01(1) || VA-06(1) || VA-07(1) || VA-09(1) || PV-01 (1)– *"for vacuum creation purpose"*
2. **IF** PI2.04 = 280 mbar **THEN** VA-08(1) || PIC01 is "automatic mode"
3. **IF** dPIC-01= 25 mbar **THEN** dPIC01 is "automatic mode"
4. **IF** LS2.01 = Lmin (300 l) **THEN** dPIC-01 - "manual mode"
5. **IF** PIC.01 ≥ 200 mbar **THEN** VP-01(0) || PIC01 – "manual mode" || PV-01 (0)
6. **IF** PIC1.01 = 0 mbar **THEN** VA-06 (0) || VA-07 (0) || VA-08 (0)
7. **IF** PI2.03=0mbar **THEN** VA-09 (0)

Fig.4: *Informal specification of unit procedure*

The SIPN model of the unit procedure is shown in Fig.5-2. It is modelled by six places and five transitions. Places with a circle shape show the related component, which is valid if it has a token. For valve, 1 means opened and 0 closed. For pump, 1 means turned-on and 0 turned-off. Besides, level sensor is mapped into transition (i.e. bar), while the time condition is represented at the arc (i.e. directed arrow). The unit procedure will be reused for a new batch process.

Mixture Control is a component which is responsible to control the route of liquid feed to distillation cube. The FB composes four valves and two pumps. It is responsible to open and to close the route to the distillation cube. The reuse of FB valve is three times, of FB pump is one time. The implementation of Mixture Control in a composite FB is shown in Fig.5-3 and Fig.5-4. As a starting point, the elements of SIPN model represent the schedule model of the "Loading" unit control are interpreted by FB's identity. S^3 technique is applied with corresponding FBs (Scheduler, Selector, and Synchronizer) to control the component based on the given component schedule. The component schedule representation uses the following SOP (Scheduler of Operations), SOP_Setup = [21, 1, 2]; SOP_Stop = [12, 26].

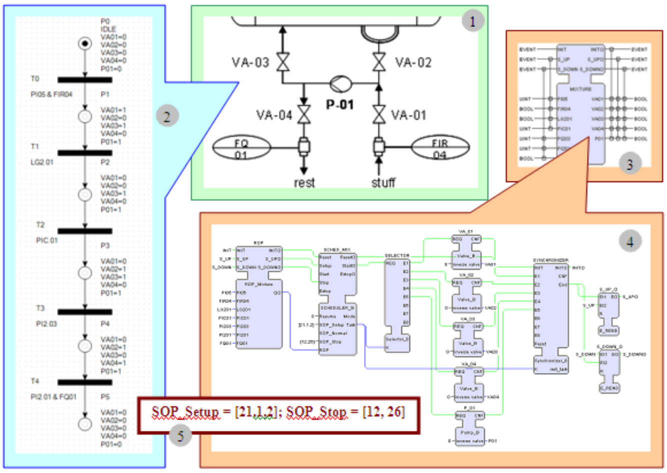

Fig.5: *Illustration of the case study*

5. Conclusions

One of the main benefits of the proposed approach is that the development of cyber components for the related physical components is influenced by some common properties in Batch Control in order to improve flexibility. It is achieved by using generic re-usable control components that can be reused to control different equipments and processes with similar functionality. The suggested formal specification and verification using SIPN satisfies the following three important for the CPS requirements: (1) find conflicting outputs especially in parallel executions, (2) find undesired output combinations (e.g. referring to a combination of opened valves that is forbidden in the current setting), (3) verification of specified flow.

6. References

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