IEC 61499 BASED CONTROL OF CYBER-PHYSICAL SYSTEMS

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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 and analyses different combined approaches for control of CPS based on IEC-61499 standard. The approaches are divided in two groups. The first group of approaches combines IEC-61499 standard with advanced methods of software engineering, such as formal methods and model-driven development, based on UML/SysML. The second group uses other standards as IEC-61512 and PLCopen to be combined with IEC-61499 standard in order to improve the development lifecycle of cyber-physical systems.*

***Keywords**:* CYBER-PHYSICAL SYSTEM, INDUSTRY 4.0, IEC-61499, IEC-61512, PLCopen, UML/SysML

1. Introduction

The global competition between enterprises and the new production strategies adopted by enterprises require the need for a new type of information and control systems, characterized by a high degree of horizontal and vertical integration, as well as self-organizing characteristics, in order to quickly adapt to changes and disturbances from the environment. Cyber-Physical Systems (CPS) is a very appropriate concept. They are physical and engineered systems whose operations are monitored, coordinated, controlled and integrated by a computing and communication core [1]. They are unique in that the components can be distributed both spatially and temporally, and include complex networks of feedback controllers and real time communication. The impact of CPS is revolutionary and pervasive as stated by CPS Public Working Group at NIST (National Institute of Standards and Technology) [2] as the development of these systems is related to the emergence of autonomous vehicles, smart grids, smart cities and homes, robots, smart medical devices, telemedicine, Internet of Things (IoT) etc. Some of the main nonfunctional properties distinguishing CPS are: real time, reconfigurability, scalability, context-awareness, interoperability, resilience and security. The synergy between cyber and physical systems can be both at the nano-level and also at the level of "system of systems". Still, however the science is owed to CPS; the lack of theoretical foundation and methodologies creates barriers that may hamper the adoption, commercialization, and market success of new CPS applications [3].

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.

An option to deal with these requirements is due to the rapid development of electronics, information and communication technologies, which has led to the emergence of a number of new technical tools and innovations such as: fieldbus, smart devices (with built-in microprocessors), fuzzy programmable controllers and more. Other way is the replacement of the centralized structure of information and control systems with the distributed ones, which has significantly greater advantages than the centralized ones. A natural reaction to these changes is also the IEC-61499 Standard for development of distributed systems for process measurement and control [4, 5].

One of the ways to tackle the challenges facing today's cyber-physical systems, associated with achieving a high degree of interoperability, agility and reconfigurability, is the transition from a centralized architecture of information and control systems to a distributed one. Promising trend in this direction is the implementation of the IEC-61499 standard, offering reference architecture and models for development of distributed control systems. The main aim of the paper is to summarize and compare different approaches for development of IEC-61499 based cyber-physical systems through their combination with other different approaches and advanced methods of software engineering. After the introduction a short analysis of control for CPS and IEC-61499 standard is undertaken in part 2. In part 3 different combined approaches for IEC-61499 based control of CPS are presented and discussed. Finally some conclusions are done.

2. Short analysis of CPS and IEC-61499 standard

2.1. Control in 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 [6].

- 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 [7, 8];

• 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 [9]. The successfully applied architectures include: component-based, service-oriented, agent-based, and the CPS 5C (connection, conversion, cyber, cognition and configuration) architectures [10]. 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 [11]. Other successful approaches use specialized programming languages such as Giatto, Esterel, Signal, etc. or the Model Driven Development (MDD) approaches. MDD [12] 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.

2.2. Short overview of IEC-61499 standard

The IEC-61499 standard [4] defines the basic concepts and reference architecture for the design of reusable and component-based distributed control systems. At the heart of the standard, the concept of "function block" (FB) is the basic structural unit of the application. The function block can be used to define reusable software components that, based on a chosen methodology, can be used to design complex, decentralized, distributed control systems. 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” [5]. The standard defines three basic types of function blocks: basic, composite and service interface and 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. There are several engineering environments that support the development of control systems based on the IEC6199 standard such as for example FBDK (Function Block Development Kit) [13], 4DIAC [14], FBench [15], ISaGRAF [16] and nxtStudio [17]. 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.

The main advantages of the standard with respect to CPS can be summarized as follows:
• IEC-61499 standard allows the integration of a time-triggered mechanism with SIFB-based event triggered systems;
• The reference architecture and models based on IEC-61499 standard support the reuse of the developed CPS components and shorten their development and configuration time;
• The distributed control structure achieved, facilitates the reconfiguration of the system by inserting, deleting and replacing functional components based on IEC-61499 standard;
• The models offered allow the creation of a library of IEC-61499 based reusable components for different application areas.

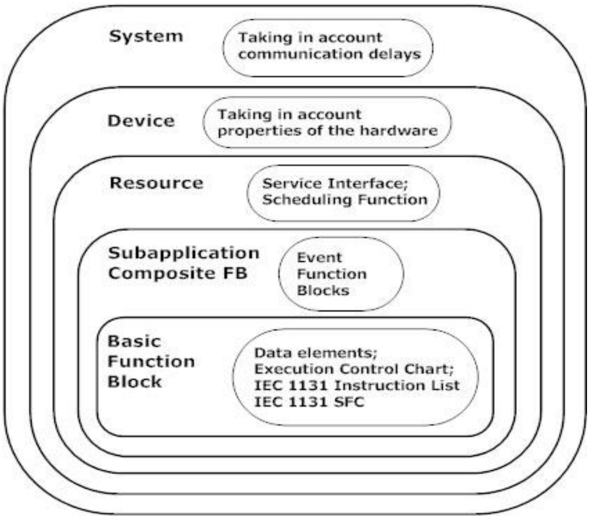

Fig.1: *Overview of IEC-61499 based models*

3. Short analysis of the combined IEC-61499 based approaches in the field of CPS

3.1. Classification of the approaches

Fig.2 summarizes the approaches proposed, which aim to increase the potential for implementation of the standard and increase the efficiency and quality of the developments, which can be divided into two groups:

• Approaches representing a combination of IEC-61499 based models with advanced software engineering approaches and tools, such as formal specification and verification methods, the use of agile models in software development processes, the use of UML/ SysML to extend development stages, or as an alternative to the design of IEC-61499 based control systems;

• Approaches that combine the concept of the standard with the successes achieved in the control of specific production areas, such as batch control (ANSI / ISA S88 - ISO-61512 standard [18]) and the PLCopen motion control initiative based on the IEC standard - 61131-3 [19].

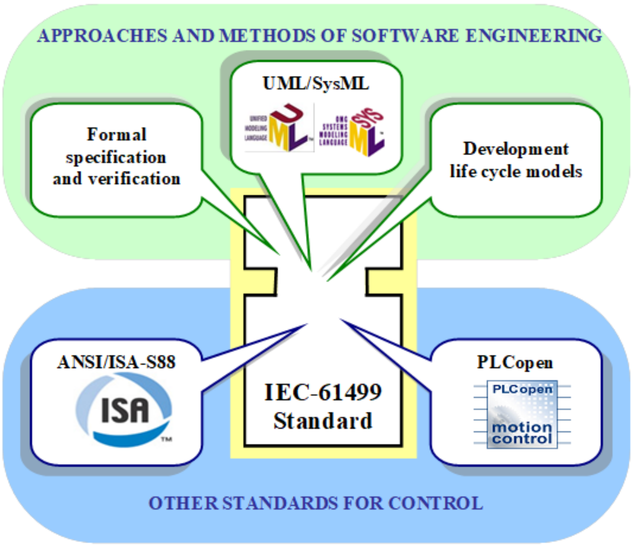

Fig.2: *Systematization of approaches for the development of IEC-61499 based management systems*

The next part of the paper presents the ideas of only a subset of approaches using software engineering achievements, which in the last part of the report will be illustrated with a specific example.

3.2. IEC-61499 based approaches combined with software engineering methods

A. Combined approach using IEC-61499 standard and formal specification

Combining the concept of IEC-61499 standard with the capabilities offered by the formal specification and verification approaches, leads to a significant increase in development efficiency due to the fact that, at relatively early stages, the specified control system can be verified based on the application of different formal methods and approaches. Fig.3 illustrates in a general way the idea of engaging in the development of the stages of formal specification and verification of models using the model checking method. It should be noted that this approach can be implemented with various formal methods and software. For example, in [20, 21], for the purpose of the formal specification of the system, Petri SIPN networks were selected, and for its verification the possibilities for transforming the network into a timed automata and NuSMV product implementing the model checking method using BDD diagram and SAT method. Alternatively, NuSMV may be replaced with UPPAAL, as demonstrated in [22]. This product can also be used on its own by specifying the control system model with timed automata, and the requirements may be defined using temporal logic.

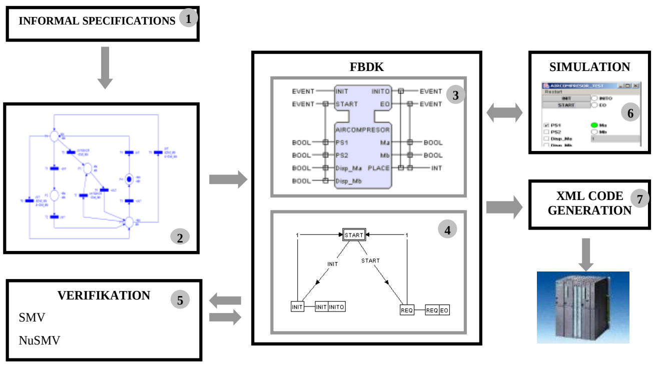

Fig.3: *Combined approach using IEC-61499 standard and formal specification*

B. Combined approach using IEC-61499 standard and UML/SysML.

The unified UML modeling language [23] and its profile for system engineering SysML [24] can be used in various ways in the development phases of IEC-61499 based control systems. A detailed overview of these approaches is presented in [25]. The approaches proposed by the authors differ in the degree of development of UML models, the development environment, and the version of UML used or the additional inclusion of SysML. For example, [26] proposes an approach using the UML1.4 version, based on IBM's Rational Rose programming environments and the UML-MAST profile, which aims at modeling the real-time characteristics of the system. Old versions of UML are also used in [27, 28], but in these cases the use of CORFU engineering environment, directly related to the IEC-61499 based FBDK development environment, is proposed for development purposes. The development of the UML language and the creation of a SysML profile for system engineering improve the language's usability in real-time systems development, enabling it to cover the entire development lifecycle. In this regard, different approaches with and without the help of the SysML profile in the Telelogic Rhapsody environment currently owned by IBM have been explored [29, 30]. It should be noted that the approaches proposed are applicable to both discrete and continuous systems. Significant is the success in the formalization of UML and the ability to verify and validate the proposed models at different phases of their development, which is a challenge to further improving and refining the approaches proposed. An attempt is also made to design a multi-agent control system based on the IEC-61499 standard and using UML/SysML [31].

3.3. IEC-61499 based approaches combined with other standards

A. Combined approach using IEC-61499 standard and ANSI ISA S88 (IEC)

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 is illustrated in fig.4, 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 - 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.

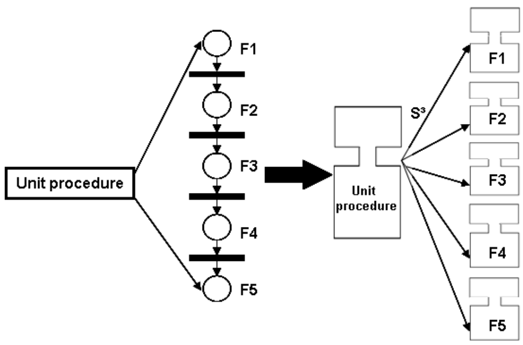

Fig.4: *Basic models in IEC-61499*

B. Combined approach using IEC-61499 standard and PLCopen (IEC-61131)

Within PLCopen, there are rich libraries of functional blocks, algorithms, control systems and development environments based on the IEC 61131-3 standard. It is essential to be able to use these developments in the design process of distributed control systems based on IEC 61499 standard. There are two main approaches to do this:

• Inclusion of IEC 61131-3 based algorithms as an integral part of the IEC 61499-based FB algorithms [5];

• Transformation of the function block based on the standard IEC 61131-3 into a functionally compatible IEC 61499 based function block.

In the second approach, the data (input or output) that are Boolean for the IEC 61131-3 based block is transformed into events (respectively input or output), as shown in Fig.5.

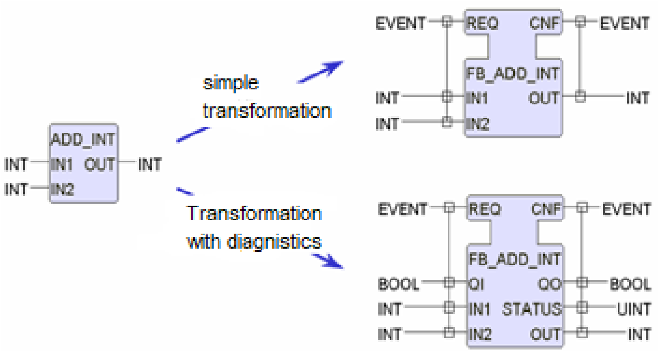

***Fig.5:** Transformation of PLCopen to IEC 61499 Standard*

4. CONCLUSIONS

The combined use of the IEC-61499 standard results in a significant improvement in the quality, safety and efficiency of the designed GSP. However, there are still some obstacles and disadvantages that can be summarized as follows:

- IEC-61499 standard does not provide verification capabilities for the control logic, either at the design stage or after online reconfiguration;
- The standard does not allow modeling of the physical part of the system;
- There is no possibility for parallel control logic;
- The implementation semantics need to be improved to be independent of deployment platforms (deterministic) and to respond to real-time constraints;
- Lack of advanced interfaces for communication with the upper levels of management and control;
- Lack of middleware for real-time messaging that enables the distributed development of CPS signals and cognitive functions.

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