REFERENCE FRAMEWORK AND ARCHITECTURE FOR DEVELOPMENT OF CYBER-PHYSICAL SYSTEMS

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***Abstract**: The strategic initiative Industry 4.0 implies integration of Cyber-Physical Systems (CPS), Internet of Things (IoT) and cloud computing, leading to what is called "smart factory". The lack of theoretical foundation and methodologies creates barriers that may hamper the adoption, commercialization, and market success of the new CPS applications. The reference frameworks and architectures support 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. The paper presents an analysis of the benefits and use of reference frameworks and architectures in the development of CPS. Standardized meta-models of reference frameworks and architectures are presented. Particular attention is paid to the NIST reference framework and architecture of CPS, with a view to establishing a methodology for development of Cyber-Physical Production Systems.*

***Keywords**:* CYBER-PHYSICAL SYSTEM, REFERENCE FRAMEWORK, REFERENCE ARCHITECTURE, META-MODELS, INDUSTRY 4.0

1. Introduction

The European Commission's strategy for European Reindustrialization aims of increasing the industrial sector's share of gross value added in the European Union to 20% in 2020, based on European strengths in the fields of engineering, automotive, aeronautics, etc. [1]. The only way in which the manufacturing sector's share of the economy can ultimately be increased is if it achieves faster sustainable growth than the other sectors (especially services) [2]. The Industry 4.0 platform is an initiative of the German Federal Government to support German industry in the transition to digital production with intelligent, digital networks and systems that enable largely self-control and self-management of manufacturing processes [3, 4]. Especially strong is the focus of Industry 4.0 on the functions of future intelligent, adaptive and predictive technical systems that need to be self-optimizing, self-configurable and self-diagnosable, enabling cognitive information processing and intelligent networking in continuous interactions with environment. That is why the strategic initiative Industry 4.0 implies integration of Cyber-Physical Systems (CPS), the Internet of Things (IoT) and cloud computing, leading to what is called "smart factory".

CPS are physical and engineered systems whose operations are monitored, coordinated, controlled and integrated by a computing and communication core [6]. 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 effective control, associated with achievement of a high degree of adaptability, autonomy, functionality, reliability, security and usability is the core of cyber-physical systems. The synergy between cyber and physical systems can be both at the nano-level and also at the level of "system of systems". The Strategic Research Co-operation Plan [7] points out that European industry should take advantage of the opportunities resulting from the wider application of the CPS concept as one of the key technological options (capabilities). 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 [8]. The development of CPS is much more than the union of computation and physical systems and in order to apply the principles of CPS to new applications, new approaches, methods, algorithms, techniques and tools are needed, which will support the process of analysis and design of CPS, on the basis of a widely accepted reference framework or architecture. Establishing an excellent science foundation and close cooperation between researchers in the field of CPS is a prerequisite for increased competitiveness and a means to address the major challenges.

While the hardware industry is relatively well prepared for the transition to CPSs, there are serious challenges to software and architectures. An important step in the right direction is the use of reference frameworks and architectures which aim to achieve interoperability, simplify development, and facilitate performance. Some of the most popular reference architectures, used in the domain of CPSs are: RAMI4.0 [9], IIRA [10], IoT-A [11]. None of these frameworks and architectures, however, takes into account the specificities of cyber-physical systems. While IoT-A focuses on the functional and informational aspects of architecture, RAMI4.0 of the Working Group ”Industry 4.0” and IIRA of the Industrial Internet Consortium are all focused on the industry. There are some similarities and cross cutting points between the last two reference architectures, and there is an agreement between the participating organizations to accurately identify the interoperability characteristics between the two architectural paradigms and try to align them and define the standardization requirements by using common testbeds. Subject of consideration and analysis in this paper are the reference framework and architecture of CPS proposed by the National Institute of Standards and Technologies (NIST) of USA, which offers concrete solutions especially to the CPS, taking into account their specific characteristics [12, 13].

The paper is organized in 4 parts. After the introduction, in part 2 some research activities and peculiarities by the development of CPS are summarized. Part 3 represent an analysis of the basic definitions and meta-models of reference frameworks and architectures are presented and discussed. The standards connected to these meta-models do not comply with the characteristics of CPS. Part 3 proposes an analysis of the suggested from the NIST PWG Framework and Reference Architecture of CPS. Finally some conclusions are made.

2. Short analysis of the research on development of CPS

Research and development in the domain of CPS is of great importance for 5 key areas in Europe - transport, energy, well-being, industry, and infrastructures. One of the most promising and challenging applications of CPS are the cyber-physical production systems (CPPS). Research in the field began in 2006 in the US when the Council of Science and Technology Advisors (PCAST) identified research in the field of CPS as a national priority and since then hundreds of millions of dollars have been invested in research [14]. The European Industrial Association ARTEMIS-IA [15] also focuses its interest on embedded systems and their evolution towards the CPS, with research amounting to around € 2.7 billion, mainly in more than 50 projects under the European Framework Programs (7 Framework Program and Horizon 2020). It is widely believed that the development and deployment of CPS should be based on a new scientific basis that will bridge the successive semantics and the parallel physical world. In this connection, the research is also focused on 3 European Horizon 2020 projects under the Co-ordination and Assistance Action Scheme - Road2CPS, TAMS4CPS and sCorPiuS. The main objective of the Road2CPS project is to create a road map for technologies and applications that identifies and describes the main technological areas and related research priorities that support the development of reliable CPSs as well as specific technologies, needs and barriers for their successful implementation in different application areas [16]. The TAMS4CPS (Transatlantic Modeling and Simulation of CPS) project (2014-2017) promotes strategic EU-US cooperation on modeling and simulation for CPS [17]. The consortium is developing in 2017 a "Strategic Research and Cooperation Program", which is expected to provide the basis for joint activities in the coming years. The aim of the ScorPiuS project is to present a definitive road map for research that identifies and describes the research priorities and formulates strategic and technological recommendations for adopting the CPS in industry, optimizes the impact on large, small and medium-sized enterprises [18].

The design of CPS requires knowledge on the dynamics of computers, software, networks, and physical processes. The main challenges in the development of cyber-physical systems have different nature and may be grouped in different categories, such as technical, organizational and social. To organizational challenges belong the standardization and issues connected with regulations and legislation. Till now, there is not a universally accepted and/or standardized reference framework or architecture for development of CPS. Different reference models and Standards for interoperability of different systems are needed. The most important social challenges are connected to the Computer – human interactions and interface design. The technical challenges in the design and analysis of CPS stem from the need to build a bridge between sequential semantics and parallel physical world and are connected with the following engineering domains:

- Modelling, development and realization of CPS components and systems;
- Validation, verification and testing of the models at different levels of abstraction;
- Maintenance and evolution of the introduced CPS components and systems.

3. Basic Definitions and meta-models

3.1. Definition and meta-model of Reference Framework

The framework is considered as a logical structure for classifying and organizing complex information. It is a set of pre-defined views, interests, key stakeholders, and viewpoint compliance rules that are set to capture the common practice of describing architecture in particular areas or user communities [19]. The framework meta-model is shown in Fig.1. Some of the best-known frameworks in the domain of Enterprise systems are: CIMOSA, GRAI-GIM, PERA, ZACHMAN, ARIS, TOGAF, C4ISR/DODAF and their GERAM summary (ISO-19439, ISO-15704).

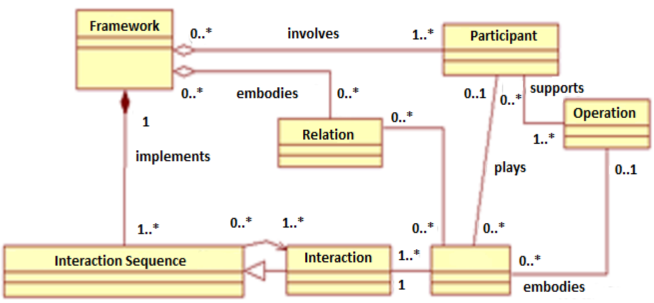

Fig.1: *Framework meta-model [19]*

3.2. Definition and meta-model of Reference architecture

The Reference architecture, in turn, represents a fundamental organization of a system consisting of components, the relationships between them and the environment surrounding them, and the principles governing their design and development. It is based on the notion of view, defined as a description of a system from the perspective of multiple related concepts. As such, the view consists of one or more patterns. The Reference Architecture is a standardized, common architecture describing all systems in a particular area, based on limitations in the reference requirements, specifying the syntax and semantics of high-level components. It is reusable, expandable, and configurable, is the basis for creating partial (reusable) and specific architectures and models. Elements of the reference architecture are: model (topology), configuration, architecture diagram, dependency diagram, description of the interfaces between components, constraints. Reference architectures are intellectual paradigms that support the analysis, correct discussion and specification of an area, 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. The reference architecture meta-model is shown in Fig.2.

The IEEE 1471 (2000) [20] standard, adopted and extended from ISO as ISO/IEC 42010 (2011) [21] referring to the recommended practice for architectural description of software-intensive systems, defines architecture as a fundamental organization of a system consisting of components, relationships between them and the environment that surrounds them and the principles guiding its design and evolution. The conceptual framework of the reference architecture according to ISO/IEC 42010 (2011) is presented in Fig.2. An architectural description is directed to the system's stakeholders in order to answer their architectural concerns about the system and is organized into one or more views of the system. The view is defined as a description of a system from the perspective of a related set of concerns. As such, the view consists of one or more architecture models. Each view addresses one or more concerns of the stakeholders. The architectural views are the actual description of the system. Each view corresponds to exactly one viewpoint. Viewpoints define the resources and rules for constructing views. Each viewpoint used in an architectural description is "declared" before use. Viewpoints are not system specific, unlike the stakeholders and views. Concerns drive the selection of the viewpoints to be used and each concern is addressed by some architectural view.

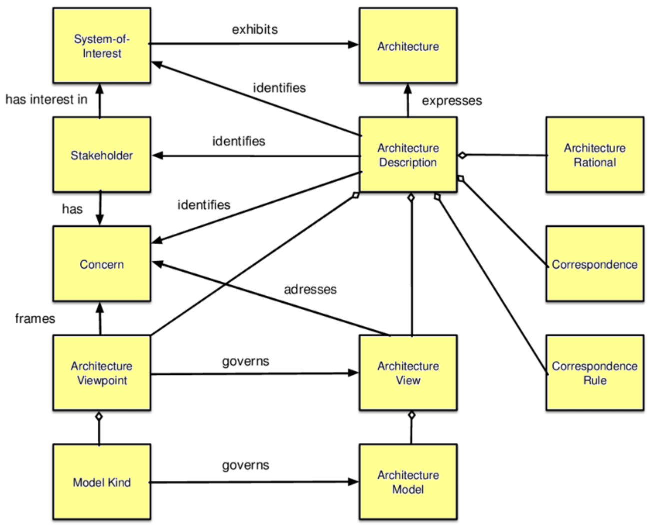

Fig.2: *Reference architecture meta-model [21]*

3.3. Definitions of Reference model and meta-models

Many of the current information systems are built using the so-called reference models. The reference model is a generally valid conceptual model used at the same semantic level. The main task of reference models is to speed up (rationalize) the design of different types of models through a common solution. The use of reference models is motivated by the design paradigm through reuse. Reference models speed up the modeling process by creating repositories from models for important processes and structures. The benefits of using reference models increase significantly, when they are generalized in relevant reference frameworks and architectures.

The design and development of CPS is significantly different from the systems and applications that are considered in this frameworks and architectures. Some of the significant differences are related to the following features of CPS such as the existing strong connections between cyber and physical parts; the open nature of CPS and the higher risk of unexpected behaviour; the need a specific interoperability methodology; the importance of trustworthiness due to the significant impact of CPS on the physical world; and include time-sensitive components and timing is a central architectural concern. CPSs are heterogeneous and complex, mostly systems of systems, able to change their goals, used in various applications, which must be freely composable, adaptable to different computational models, supporting variety of communication modes and interacting with their operating environment.

The next part of the paper presents and analyses the NIST reference framework and architecture of the CPS, which are built on the above-mentioned standardized frameworks and architectures taking into account the specificities of the CPS.

4. Reference framework, architectures and meta-models of CPS

3.1. Reference framework of CPS

The reference framework, suggested by NIST [12] and illustrated in Fig.3, has the goal to support the understanding and development of new and existing CPS and of comprehensive standards and metrics base for CPS. The role of the reference framework for achieving interoperability is also important. The framework will help to create a reference language for describing CPS and to help create tools, standards, and applications. Basic elements of NIST Framework of CPS are domains, concerns grouped in aspects for representing facets, properties. They are formulated based on different perspectives, represented by the following subgroups from experts: Vocabulary and Reference Architecture, Cybersecurity and Privacy, Timing and Synchronization, Data Interoperability, and Use Cases.

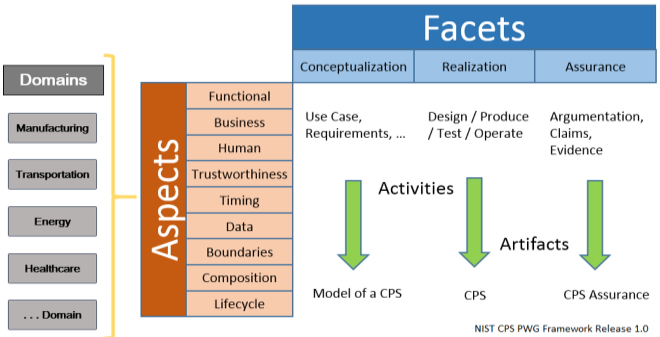

Fig.3: *Reference Framework of CPS [12]*

The framework is supposed for concrete domains, as shown in Fig.3. "Domains" represent the different application areas of CPS as shown in Fig.3. "Facets" are views on CPS in the system engineering process and contain well-defined activities and artifacts (outputs) for addressing concerns. Three types of facets are defined: conceptualization, realization and assurance. The conceptualization facet contains activities describing the high-level goals, functional requirements, and organization of CPS and has as output the conceptual model of the CPS. As an example, the main activities and their corresponding artifacts for conceptualization facet are shown in Fig.4. The realization facet comprises the activities in the following phases of the development life cycle of CPS - detailed engineering design, production, implementation, and operation. Its output is the CPS. The assurance facet includes activities for analysis and confidence that the CPS built in the realization facet satisfies the model developed in the conceptualization facet. This facet generates as output the CPS assurance. "Concerns" are interests in a system relevant to one or more stakeholders and "aspects" are high-level groupings of cross-cutting concerns. The aspects defined in the framework are: Functional, Business, Human, Trustworthiness, Timing, Data, Boundaries, Composability and Lifecycle. "Properties" are assertions directed to the concerns including different requirements, design elements, tests, and assessments. The main concerns of the aspect "trustworthiness" are shown in Fig.5. For example "reliability", according to the definitions in framework, brings together concerns related to the "ability of CPS to deliver stable and predictable performance in expected conditions", while "resilience" unites concerns related to the "ability of CPS to withstand instability, unexpected conditions, and gracefully return to predictable, but possibly degraded, performance".

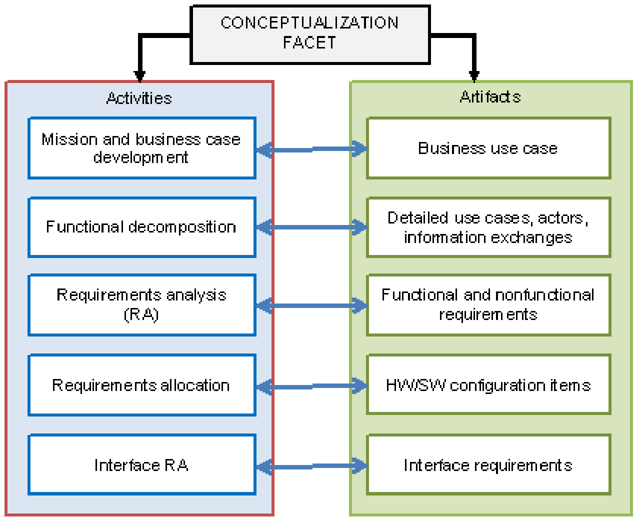

Fig.4: *Activities and Artifacts of Conceptualization facet*

The development process includes 4 steps: i) Identification of domains; ii) Identification of cross-cutting concerns (societal, business, technical, etc.); iii) Analysis of cross-cutting concerns to produce aspects; iv) Addressing concerns (aspects) through activities and artifacts according the fundamental facets of conceptualization, realization, and assurance.

Fig.5: *Concerns of the aspect "Trustworthiness"*

3.2. Reference architecture of CPS

NIST and in particular the created CPS Public Working Group offer a reference architecture of CPS, shown in Fig.6, consisting of 6 layers and even more transversals capabilities, each of which is included in each layer [13]. 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.

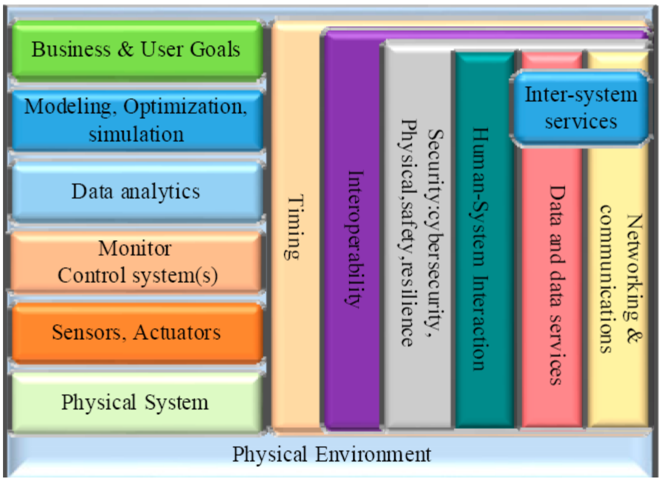

Fig.6: *NIST Reference architecture of CPS [13]*

5. CONCLUSIONS

The importance of the CPS and their applications will grow more and more rapidly. However, disclosure of the full capabilities of the CPS can only be realized if they are built of interoperable components, supported by reference frameworks and architectures. The creation and use of a widely accepted and consensual CPS reference framework provides a common basis for the development of CPS, their safe and secure combining, testing and offering of interoperable CPS. Other benefits of using the framework are the enhancement of research developments in the domain, improvement of their quality, reliability and easy integration with other products and services.

The NIST CPS reference framework uses the concepts of facets and aspects to support the development of a methodology for CPS analysis based on the identification of activities in the particular facets, which are implemented in a coordinated approach, directed to the concerns through the whole lifecycle. For this purpose different models of the development lifecycle can be used. The developer's goal is to use the framework as a reference language for describing the CPS and to develop tools, standards, and applications. One of the main issues that the framework needs to address, due to the strong commitment of CPS to the Internet of Things and Industry 4.0, is to achieve interoperability with the corresponding frameworks and architectures IIRA, IoT-A and RAMI4.0.

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