AGENT-BASED DEVELOPMENT OF CYBER-PHYSICAL SYSTEMS FOR PROCESS CONTROL IN THE CONTEXT OF INDUSTRY 4.0

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Abstract: *In order to achieve its goal in using intelligent adaptive and predictive technical systems with self-X functions and cognitive information processing in continuous interaction with environment, the Industry 4.0 initiative implies integration of Cyber-Physical Systems (CPS), the Internet of Things (IoT) and cloud computing leading to what is called "smart factory". This, in turn, faces the CPS with new challenges in terms of increasing the degree of distribution, autonomy, mobility, communication and security of the systems and their components, as well as expanding their functionality in the direction of data analytics, information and knowledge extraction, and increasing their intelligence. This paper discusses and analyses the CPS in the context of Industry 4.0 and the main trends in the development of process automation and control in order to suggest an appropriate and advanced agent based approach for development of CPS for process control. The proposed approach is based on using the following standards – from one side the IEC61499 Standard for agent specification and from other side the IEC62264 and IEC 61512 Standards for defining the different kind of agents in the control system. The presented approaches are illustrated with a partly presented example of development of Injector control system. Finally some conclusions are made.*

Keywords*:* CYBER-PHYSICAL SYSTEM, INDUSTRY-4.0, AGENTS, PROCESS CONTROL, ONTOLOGY

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 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 [2, 3]. 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 interaction 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 [4]. 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 [5] 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 [6]. 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 methods and tools are needed. 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.

CPS integrate computing, networking and physical dynamics, as distinguished by a high degree of heterogeneity and parallelism. As a result, the software design techniques are insufficient. New approaches, methods, algorithms and techniques are needed, which will support the process of analysis and design of CPS. The concept of CPS is tightly linked with agent based systems in respect to their basic properties such as: autonomy, sociability, reactivity, proactivity and mobility. Different approaches and methods are used in order to guarantee the useful features of agents in various applications areas of CPS, such as modeling, monitoring, control, diagnostics etc. An important conclusion to be drawn from the analysis of the approach is that the results are more successful when the agent based approach is combined with other approaches, methods and tools.

The main aim of the paper is based on an analysis of CPS in the context of Industry 4.0 and the main challenges in the field of process control and automation to summarize the basic assumptions and capabilities of using an agent based approach for development of CPS for process control. Some results are presented and discussed. The paper is organized in 4 parts. After the introduction, in part 2, a short analysis of the requirements to the CPS in context of Industry 4.0 is proposed. Part 3 discusses the main challenges to process automation and control according to the European Roadmap for process automation [7]. In the next part a short survey of the agent based approaches for control and automation is presented. The last part presents an idea for development of CPS for process control based on agents using IEC-61499, IEC-62264 and IEC 61512 Standards. Finally some conclusions are made.

2. An Analysis of the CPS in the context of Industry 4.0

The advent of control systems in industry started in the era of the first industrial revolution and was characterized by the use of mechanical devices, such as the steam engine governor. The growing number of implemented control systems has led to the emergence and development of the first analysis methods of control theory. The advent of electricity, which is connected to the second industrial revolution led to the replacement of mechanical control devices with electromechanical and their enormous and diverse use in the existing and new emerging industrial branches. With the emergence of the first microprocessors in the seventies began the development and introduction of digital control systems. This has led to the advent of the new levels of control such as DCS, SCADA, MES, the purpose of which is to process and aggregate huge amounts of data from various sensors, releasing the person from multiple control system setup operations, and set him more responsible tasks related to monitoring and optimization of production systems. Unfortunately, however, the theory of computer-based control is underdeveloped. The main task of the theory of cyber-physical systems is to fill this gap.

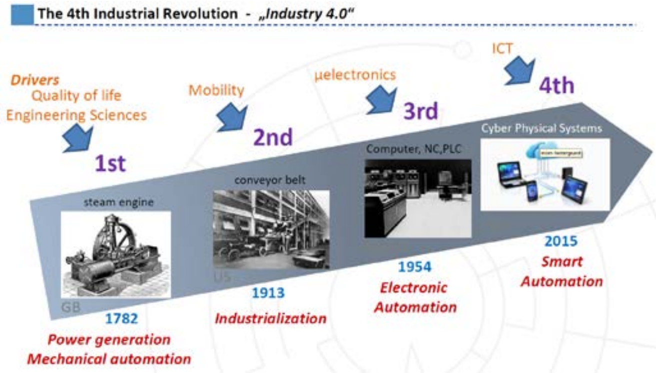

Fig.1: Industrial revolutions and Automation

The fundamental requirements for introducing CPS in industry are specified by [8] 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.

The design of the 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 no a reference framework 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:

- Modeling, 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.

Industry 4.0's vision requires revision of the approaches for development and use of CPS concerning the following areas:

- In respect to the decentralization in order to integrate the Cyber-Physical Systems (CPS) with cloud computing infrastructures using a high-level architecture for IoT systems, such as this of OpenFog Consortium or FAR-EDGE Reference Architecture [9].
- Empowering decentralization using edge computing that moves some part of computing from the cloud to its edge nodes supporting real-time interactions and scalable analytics;
- 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;
- Digital representation of all information and services from and about the physical systems using the concept of Administrative Shell and I4.0 component as a specific case of CPS [10].
- Need for new planning procedures for CPS;
- The Industry 4.0 vision requires smaller, more intelligent and modularized cyber-physical entities that are function-oriented.

3. Main trends in process automation and control

The European roadmap for industrial process automation is developed by the ProcessIT.EU Center of innovation Excellence and formulates the trends, visions and long range goals in industrial process automation, categorizes them into a set of research and development areas and concretises the visions and long range goals into a number of ideal concepts that form the direction of development, proposed in this roadmap [7]. The study also found that automation services predominate over hardware and automation software, which directs attention to the used engineering tools and their efficiency. The roadmap envisions also some technical solutions and methods, summarized in Fig.2, which are of high importance to meet the main challenges of process control and automation. Among these solutions, with particular luminance, three main points stand out:

- The future development of automation and process control systems relies on the use of approaches and methods of cyber-physical systems with a view to achieve collaborative automation and a dynamic virtual twin of the system, available in a real time;
- Secondly, the need for adapting and using the technologies of the Internet of Things to achieve distributed automation and control systems;
- The third major point is the massive need of standards and their use in the development of hardware, software, platforms, network communications and transparency of information.

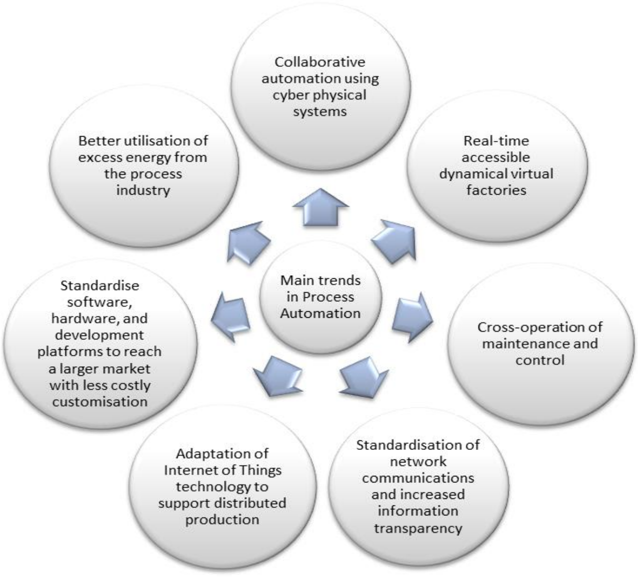

Fig.2: Main trends in Process automation

4. Short overview of agent based development of control systems

Jennings and Wooldridge [11] have defined an agent as "a computer system situated in some environment and capable of autonomous action in this environment, in order to meet its design objectives". Software agents may be seen as building blocks for virtual environments which augment the reality. They have the following main properties and characteristcs [12]:

- autonomy: agents encapsulate some state (that is not accessible to other agents), and make decisions about what to do, based on this state, without the direct intervention of humans or others;

- socialability (interactivity): agents interact with other agents (and possibly humans) via some kind of agent-communication language, and typically have the ability to engage in social activities (such as cooperative problem solving or negotiation) in order to achieve their goals;
- reactivity: agents are situated in an environment, (which may be the physical world, a user via a graphical user interface, a collection of other agents, the Internet, or perhaps many of these combined), and are able to perceive this environment (through the use of potentially imperfect sensors), and are able to respond in a timely fashion to changes that occur in it;
- pro-activeness: agents do not simply act in response to their environment, they are able to exhibit goal-directed behaviour by taking the initiative;
- mobility: agents can transport themself across different systems architectures and platforms.

CPS may be modeled as Multi Agent Systems (MAS), which may be defined as "a loosely coupled network of problem solvers (agents) that work together to solve problems that are beyond the individual capabilities or knowledge of each problem solver" [13]. The agent community has considerable interest in developing methods and techniques for specifying, modelling, implementing and verifying of MAS for development of CPS in the different applications domains, but so far no standardized methodology has been recognized. Several object-oriented methodologies have been suggested for agent-oriented analysis and design, based on UML. Important drawbacks of using UML to model MAS are the modelling of agent communications as method invocations and the absence of references to the mental state of the agents. To overcome these drawbacks, the UML notations are extended to reflect the characteristic properties of the agents. Successfully extensions of UML are achieved in AUML, GAIA, MESSAGE/UML, AgentUML, Prometheus, etc. Some of them are based on FIPA standard (http://www.fipa.org) suggesting an agent reference model for creation, registration, location, communication, migration and retirement of agents. Recently are also available some specialized tools for lightweight devices, such as DSML4MAS (http://dsml4mas.sourceforge.net/), FIPA-OS, ASEME (for Eclipse), Tropos (http://www.troposproject.org/), INGENIAS (http://sourceforge.net/projects/ingenias/), Jade-Leap, etc. However, there are limitations and drawbacks, associated with the variety of devices and communication protocols, specific for CPS. As well there are some agent-based development environments especially for the CPS domain, as for example: THOMAS, MaRV, ALZ-MAS, CodeBlu, etc.

The actually state of the industrial application of agent technology in CPS is proposed in [14] and the current efforts and challenges for their wider applicability are discussed. The review also shows that the adoption of agent technology in industrial applications is critical in respect to real time constraints and this implies the use of technologies for real-time control as for example the IEC-61499 standard. The agent based technologies are more appropriate for the higher levels in order to provide intelligence and responsiveness.

5. An approach for agent based development of process control system as CPS

As shown in the previous section the concept of CPS is tightly linked with multi-agent systems, however there is not an existing methodology for applying agents to the cyber-physical domain of process control. We suggest using the design principles for development of agent based CPS, defined in [14] and illustrated in Fig.3. They link the high level design abstraction and principles with the final implementation.

There are many different standards associated with the Industry 4.0 vision in order to achieve interoperable and scalable solutions based on the integration of smart agents in industrial CPS environments. This study uses three of them in order to start an approach for development of CPS for process control, connected with improving the adaptability, autonomy, efficiency, functionality, reliability, safety, and usability of such systems. For solving real time control tasks, the IEC 61499 standard [15] is adopted, which defines the basic concepts and models for design of distributed process measurement and control systems. It is based on the concept of function block as a main building block of an application and may be used in the design of re-usable intelligent software components. Distributed automation systems could be modeled in cyber-physical way by introducing concurrent model of computations in the IEC-61499 standard. By applying the cyber-physical view with the IEC-61499, control, communication and physical plant in distributed automation systems are covered in one graphical modeling langauge.

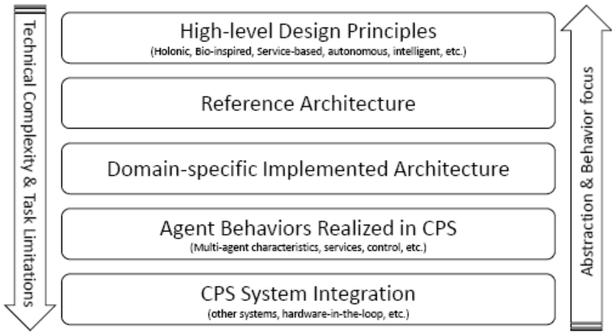

Fig.3: Design principles for agent-based CPS [14]

In cyber-physical systems, there are stronger communications between components and new communication standards and approaches are needed because of the exchange of heterogeneous information. A promising approach in this direction is the use of ontologies, describing the semantics of information and achieving a comprehensible exchange of information. It is extremely important to reuse existing ontologies in automation such as ontology of automation devices, reconfigurable mechatronic systems, diagnostics, and so on. Other important requirements for ontologies used are their modularity, enabling their efficient reuse, refinement and extension; the use of a common standard language for their description, as well as a common automation vocabulary that facilitates the alignment of individual modules to satisfy different requirements.

Both standards IEC-61512 and IEC-62264 are used to create ontology for the automation domain. The IEC-61512 standard [16] provides domain specific models and terminology for design and control of batch production processes and may help to explain the relationships between them. The standard also defined the data models that describe batch control as applied in the process industries, data structures for facilitating communications within and between batch control implementations and language guidelines for representing recipes. The IEC-62264 standard [17] for Enterprise-control system integration defines the terms and models between the enterprise business systems and factory floor control systems. The most important and old parts of the standard include models and terminology, objects and attributes for enterprise-control system and activity models of manufacturing operations management systems. In Fig.4 is shown the "equipment module" of the "manufacturing ontology", structured according to the hierarchical model of the equipment defined by the two standards: IEC-62264 and the IEC-61512.

In Fig.5 an intelligent agent based approach for process control of Injector, based on the IEC-61512 standard is partly illustrated. Common intelligent cyber components have been built and reused for different application. The components are managed in a control recipe that describes their execution schedule. Furthermore, IEC 61499 Standard is adopted as an application framework in which the functional components are implemented as IEC 61499 based function blocks (FB). The operation schedule of the controlled components is then implemented according IEC 61499, based on Scheduler-Selector-Synchronizer (S^3) architecture and a special kind of Petri nets models describing the sequence of control execution may be used in order to verify of algorithm.

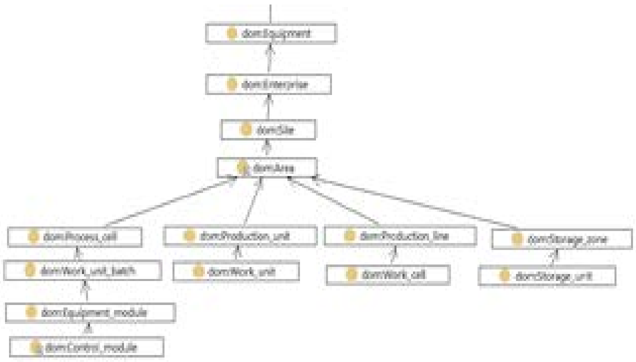

Fig.4: ''Equipment module'' of the "manufacturing ontology"

6. Conclusions

The presented approach is still at an early stage of development. There are a number of extensions to automation ontologies based on other existing standards and developed ontologies. An important step in the right direction is also related to the communication protocols and interfaces used. The discussion around the fusion of MAS and SOA is connected with enhancing some basic features of the CSP, such as adaptability, flexibility, interoperability and modularity. Moreover CPS systems must be improved in respect to service discovery, self-organization, rich knowledge representations and context-awareness.

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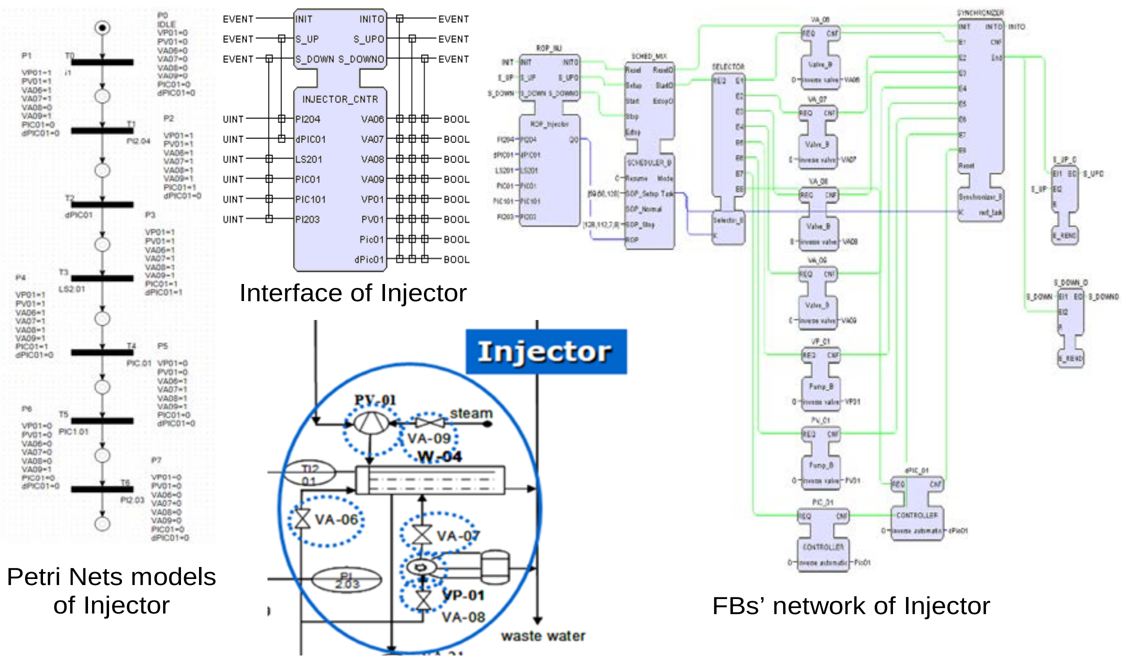

Fig.5: Control components of Injector CPS