Lecture Notes in Networks and Systems 95

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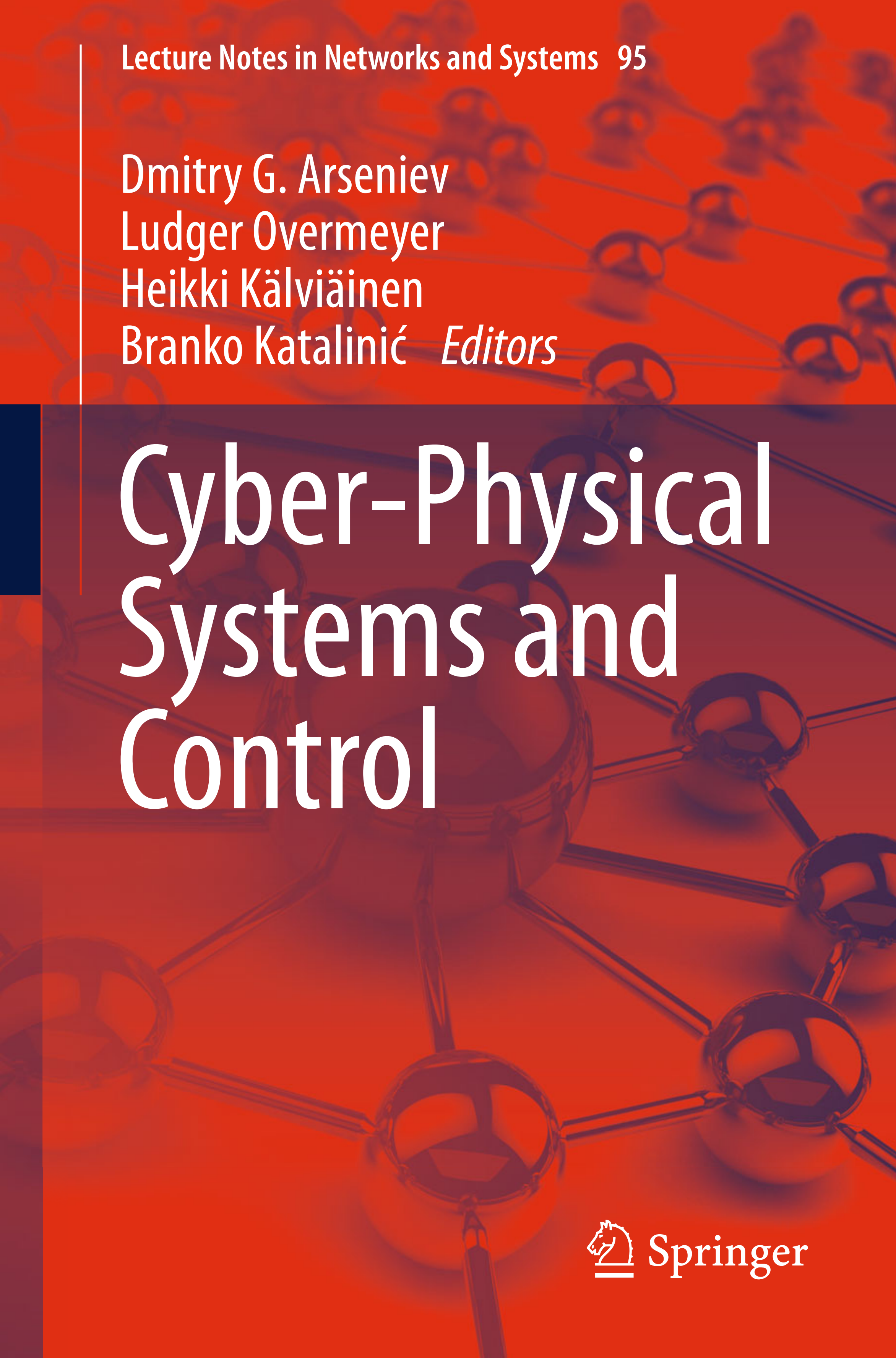
Cyber-Physical Systems and Control



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Preface

The International Conference on Cyber-Physical Systems and Control (CPS&C'2019) was held in Peter the Great St. Petersburg Polytechnic University, which in 2019 celebrates its 120th anniversary.

The CPS&C'2019 was dedicated to the 35th anniversary of the partnership relations between Peter the Great St. Petersburg Polytechnic University and Leibniz University of Hannover.

This conference draws upon the experience of previous major events that focused on information technologies, system analysis, engineering, and control and were hosted by Peter the Great St. Petersburg Polytechnic University in partnership with leading European and Russian academic institutions. The most significant in the series of these events were such annual events as the International Conference on System Analysis in Engineering and Control (since 1998), the Distributed Intelligent Systems and Technologies Workshop (since 2008), the International Scientific Symposium on Automated Systems and Technologies (since 2014), and the International Conference Network Cooperation in Science, Industry and Education (in 2016), each attended by hundreds of participants.

The cyber-physical systems (CPSs) are a new generation of control systems and techniques which help promote prospective interdisciplinary research. A wide range of theories and methodologies are being investigated and developed in this area to tackle various complex and challenging problems. Therefore, CPSs can be considered as a scientific and engineering discipline that is set to make an impact on future systems of industrial and social scale characterised by deep integration of real-time processing, sensing, and actuation into logical and physical heterogeneous domains.

The CPS&C'2019 aimed to bring together researchers and practitioners from all over the world and to reveal cross-cutting fundamental scientific and engineering principles that underline the integration of cyber and physical elements across all application fields.

Participants of the conference represented research institutions and universities from Austria, Belgium, Bulgaria, China, Finland, Germany, the Netherlands, Russia, Syria, Ukraine, the USA, and Vietnam.

The book of proceedings includes 75 papers, arranged into five chapters, namely: Keynote Papers, Fundamentals, Applications, Technologies, and Education and Social Aspects.

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Contents

Seamless Data Integration in a CPPS with Highly Heterogeneous Facilities - Architectures and Use Cases Executed in a Learning Factory

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Abstract. Facing the principal challenges of a Cyberphysical System (CPS) in a manufacturing environment by establishing an appropriate universal and scalable architecture the paper shows two explicit use cases of successfully established communication lines (horizontal and vertical) that integrate facilities derived from highly different domains, this all done at the Learning Factory at Graz University of Technology. In present time effective Cyberphysical Production Systems (CPPSs) live on the pervasive and seamless data integration of its data generators and receivers mainly facilitated by the Linkage Part of a CPPS. The connectivity, its semantic interoperability and the scalability need well-designed concepts and architectures because of the existence of too many standards and protocols. The challenge increases significantly if the network should be set up with facilities from many different suppliers and their proprietary standards. At the Learning Factory of Graz University of Technology the integration of most heterogeneous products at the office floor and at the shop floor is a major part of its research. The paper presents two solutions in form of “Use Cases,” representing an innovative concept for both the vertical and the horizontal integration. Usage of an Enterprise Service Bus at the office floor and the installation of the “KEPServerEX”- middleware at the shop floor are selected core approaches for creating a representative CPPS.

Keywords: CPS in manufacturing · Cyberphysical production systems · Learning factory · Heterogeneous IoT · Data capturing · Robot control · OPC UA · MindSphere · KEPServerEX · PdM WebConnector

1 CPPS – The CPS in Manufacturing Environments

Cyberphysical Systems (CPSs) are engineered systems that are built from and depend upon the integration of computational algorithms and physical components [19]. CPSs enable capability, adaptability, scalability, resiliency, safety, security and usability that will far exceed the simple embedded systems of today [13]. Typical and well-known applications of CPSs are the arenas of Smart Mobility, Smart Health, Smart Grid, Smart Cities and Smart Factory. All of them take their technical and economic advantage out

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of the seamless integration and interoperability of their real-world processes and their computed virtual processes. Such configurations are supposed to lead to higher transparency, enable a better understanding and end up in a well-grounded and faster decision taking, this all meant for improving the regarded system.

In concerns of manufacturing, a CPS turns into a Cyberphysical Production System (CPPS), which more or less carries the same principles and characteristics as a CPS but concentrates on the specific tasks of fulfilling future-oriented, competitive production processes. Such CPPS – or Smart Factories – have to regard also the duties of the whole supply chain, the quality management and many other service-oriented processes. A meaningful CPPS need its horizontal integration (shop floor integration) as well as the link to the commercial and supervising levels of a company with the need of a vertical integration (office floor integration).

1.1 Typical Setup and Components of a CPPS

The setup of a CPPS always is specific depending on its industrial sector; nevertheless there always can be detected the same three categories of elements: the Physical Part, the Cyber Part and the Linkage Part. Undoubtedly, the latter belongs to the most challenging of them.

Regarding the physical world a CPPS is typically made by tool machines, welding units, robots, shuttles, presses, tools, sensors, and actuators, as well as means of metrology and logistics. It is mainly represented and visible at the shop floor but contains also the IT-infrastructure hardware with computers, servers, monitors, gateways and all kinds of connecting devices.

The cyber part of the CPPS mainly consists of software and assisting tools for planning, modelling, analyzing, simulating and forecasting the relevant processes. These are engineering tools CAD, CAM, and CAE, followed by business administration tools like PLM, ERP, MES and ending up with high-level software applications that provide services for data capturing, cloud computing, safety and security utilities. The “digital twin” – representing either the full process or only an important section out of it – should be mentioned here as one of the most popular cyber elements of a CPPS.

The last and highly essential part for a successful CPPS, the Linkage Part, is the set and the match of communication standards and protocols, the usage of appropriate field busses, middleware and a suitable control system. Only with these enablers based on an appropriate architecture the whole system can turn into a living and effective CPPS. “Interoperability goes beyond technology [28].”

1.2 Actual Status and Challenges of a Sound CPPS

Designing the architecture of a CPPS is not bound to the restricted communication lines of the traditional automation pyramid any longer, decentralization and completely new control loops can take place ongoing [17]. Nevertheless, the challenges for the establishment of a well working CPPS did not really decrease. The reasons for this are manifold, the expectations towards it quite often are over exaggerated [16].

The brownfield situation, where facilities of older generations cannot even offer any interface for communication, is not going to be discussed in this paper. However, even the focus on green field applications, where up-to-date technology promises advanced communication features and interoperability between systems, the realization of a fully integrated CPPS likely becomes hard work.

The big variety and complexity of a CPPS already derives from the necessity of so many different components, devices and facilities and consequently the high variety of suppliers. So it is no surprise that for all these future elements of the CPPS, the same standardized programming tools and interfaces are not automatically given. At this stage, the repeatedly mentioned lack of standards has to be commented on. The reality shows that it is quite the opposite: there is a much too high number of upcoming standards that are mainly all incompatible (see e.g.: IEC 61158 with 19(!) different field busses [18]).

So it is even hard for suppliers of such “things” to decide which communication standards there should be offered, not to speak about the customers that are confronted with an uncontrolled growth of possibilities, especially when being at the start of establishing a CPPS.

In the meantime, selected architectures, communication standards and protocols including valid and semantic descriptions of the data [6] come out on top (e.g. OPC-UA, MT-Connect, MQTT). Service-Oriented Architectures (SOAs) have become powerful tools for creating open and scalable CPPSs in order to integrate so many foreign worlds. Nevertheless, there is still a lot of work to do in alignments for achieving the desired full horizontal and vertical integration [29]. Especially the add-ons of a modern structured cognitive production system – this accompanied with the demands of increasingly time-critical, safety- and security-oriented processes – turn out to be more than a challenge [23, 24].

2 Research in the CPPS of a Learning Factory

2.1 Introduction of the Research Field Smartfactory@tugraz

The smartfactory@tugraz (brand name for the Learning Factory at Graz University of Technology) provides various technological and CPPS-related topics for its researchers and visitors. There is established a full range production line for producing wave gears in diverse variants as objects demonstrator. The production of these variants follows a lot-size-1 sequence in order to show the capabilities of the OT and IT for acting agile. The fundamental facilities of the smartfactory@tugraz are three tool machines, a tool measurement device, a coordinate measurement machine, an assembly line with six robots, one screwing and two pressing units and an AGV for intralogistics services (Fig. 1).

Fig. 1. Insight of the Learning Factory smartfactory@tugraz in Graz, Austria

2.2 Working with Heterogeneous Facilities and Data Formats

Whilst industrial companies deeply avoid working with heterogeneous vendors of facilities and IT standards because of high integration and education efforts, the smartfactory@tugraz intentionally builds up a highly heterogeneous environment for manufacturing and assembly in order to face exactly these scientific challenges when going into research and development.

As for the shop floor the three tool machines are equipped with PLCs from Mitsubishi once and Sinumerik 840D sl twice. Its data protocols are MT-Connect and OPC-UA. Furthermore, there is a multisource fleet of robots coming from Stäubli, Fanuc, Kuka and Universal Robots, most of them communicate with “OPC-UA,” but Fanuc, e.g., carries the drivers for the “GE Ethernet.”

At the office floor, the learning factory is working with three major software packages also coming from three different suppliers, the PLM from Siemens, the ERP from proALPHA and the MES from Solidat. Also, in this case there is a confrontation with the problem: how can a seamless data flow be realized starting from the PLM, going down to ERP and MES to the shop floor and back? How can data capturing from such different machinery work? How can these data be transferred to diverse cloud applications for analysis purposes?

3 IT-Network Architecture of the Learning Factory

In general, the IT network architecture of the smartfactory@tugraz [29] consists of two major parts: the “Office Floor” and the “Shop Floor”. As a principal for creating a scalable and expandable solution, the Service-Oriented Architecture (SOA) was set as the basic approach. As long as both major parts have their specific requirements (e.g. real time execution and safety options preferably at the shop floor, security and outbound connectivity feature more at the office floor), the implementations (see Fig. 2) will be regarded separately.

At the Office Floor an Enterprise Service Bus (ESB) with the name “PdM WebConnector (PWC)” integrates and conducts the data exchange between the software domains of PLM, ERP and MES. This is highly relevant because one of the commands of the Learning Factory is that any master data is allowed to be put into the system only once. Going on this master data must be available for all participating clients in the CPPS in a consistent manner. The PWC enables this required connectivity in executing data mediation, data mapping and data transformation.

At the Shop Floor at a final stage – from the Connectivity Platform upwards – OPC UA is used as a communication standard. The strengths of OPC UA standard definitely lie in the modelling of informations for vertical and horizontal communication by providing semantic interoperability and the advanced data security [4, 18, 22]. Also, at the machine level there are mainly devices with OPC UA protocol but not only, because the Learning Factory intentionally wants also to show the way of integration with heterogeneous participants. This all is done via mighty middleware located at the server of the Connectivity Platform (see Sect. 4.2 for more details).

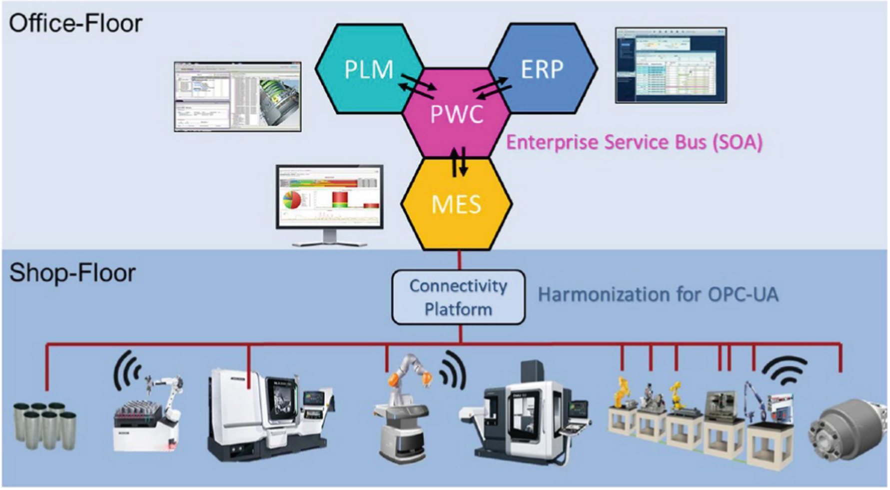

Fig. 2. General architecture of the Learning Factory

4 Use Cases of Mastering Heterogeneous Environments

For a Learning Factory the research in finding solutions for a consistent data flow and the interoperability of all its CPPS “Things” must end up in proven and robust implementations that could be demonstrated for students and interested industrials. That is why the smartfactory@tugraz has been setting up a couple of so-called “Use Cases” that all follow a certain choreography for best didactic transformations.

In this paper there should be introduced two Use Cases that correlate with the topic “Integration of heterogeneous facilities”. One will be a representative for the horizontal integration and a second one for the vertical integration. The titles of these Use Cases are:

- Foreign Domain-Guided Control of Robots;
- Cloud-Oriented Data Capturing at High Diversity.

4.1 Foreign Domain-Guided Control of Robots

When buying a robot companies must pay attention to the programming, operating and maintenance skills of the inhouse workers in order to keep education, training and operating efforts low. This consequently leads to a monoculture of infrastructure instead of decisions for an even better and more appropriate type of machinery.

This Use Case is a specialty for working with robots from different suppliers though not being educated or experienced in a broad band of knowledge in all these products. The only requirement for this is to be acquainted with the TIA-Portal (by Siemens) or the programming of Sinumerik 840D sl. With these skills alone, it is possible to actually program and run robots of Kuka, Stäubli and Denso types (Yaskawa is in preparation). Figure 3 shows the set up for achieving the required interoperability with an example connecting a Stäubli robot.

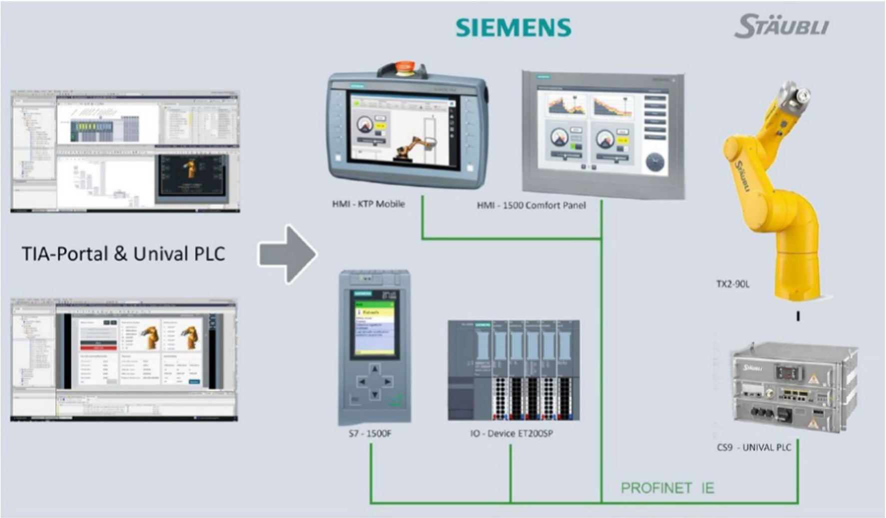

Fig. 3. Data flow from user interface at tool machine to the robot

The interoperability between the Stäubli robot and a standard industrial PLC – in this case Simatic or Sinumerik – is based on the Stäubli product “uniVAL PLC”. (Kuka, Denso and Yaskawa provide comparable products). It connects the additional necessary components like the PLC (S7-1500F), the I/O device (ET 200SP) and both variants of HMI (small, mobile, with emergency switch OR big and multifunctional) via Profinet. The programming of the working routines is done via either HMI or the TIA Portal. In case of an off-line programming, the program is directly transferred to the PLC. One PLC can control up to five different robots.

In case of running the Stäubli robot from the HMI of a tool machine, the principles and connections are the same. The HMI of the tool machine then is conformed to the "HMI 1500 comfort panel" of the diagram in Fig. 3. This shown case receives realistic importance especially when tool machines are going to be equipped with robots for loading and unloading parts and tools.

4.2 Cloud-Oriented Data Capturing from Facilities with a High Diversity in Protocols and Drivers

The goal of this Use Case is successful verification of data capturing though meeting highly heterogeneous data generators at the shop floor and transferring these data into specified clouds with the purpose for ongoing data analytics. Final output of this conception of data capturing is the enhancement of production efficiency and maintenance processes.

Aside the general challenge of allocation and distribution of correct data in a CPPS, another central problem is the standardization of data collection [31]. This task particularly requires new approaches if the addressed data generators are highly heterogeneous like it is done at smartfactory @tugraz with intention. Actually the infrastructure at the shop floor (see Fig. 4) is made up by machinery and robotics with not only the OPC-UA standard but also an MT-Connect protocol and the Fanuc robots, which do not run on Profinet but on the GE Ethernet field bus and its proprietary drivers.

With the target to unify all protocols of the shop floor for the OPC-UA standard (preferred because of its most flexible, powerful and secure features) before finally uploading it to diverse cloud applications there could be found a powerful middleware with the name "KEPServerEX" (see Ref. [11]). It fulfills the desired alignment of data formats by structuring, renaming and converting the raw data from their former exchange format. It provides access to more than 150 protocols (proprietary and IT-protocols) and enables communication with devices and systems from all major automation vendors. This additionally ensures the important scalability of such an architecture. With this tool the add-on of any facility of any origin can be done quite easily without irritation of the existing architecture.

Within the architecture of the smartfactory@tugraz with all this data, there will be addressed two clouds. First, there is the open IoT platform "MindSphere" that collects and saves all defined data from the shop floor in a big data table. Before entering the "MindSphere" cloud all data coming from the "KEPServerEX" Server have to pass a gate called "Mind Connect Box" (see Fig. 4). Access to the data stored in MindSphere is operated via certain Apps which do not necessarily need to be of Siemens origin but can be programmed by any company or user. A second and parallel cloud application with an Apache Hadoop infrastructure is set up by the partner T-Systems in order to provide support in terms of Big Data Analytics.

Figure 4 (right side) shows that even data coming from facilities already equipped with OPC UA protocol run via the KEPServerEX Server though its data would not need any data transformation anyway. The reason for this preferred routing is, firstly, the possible use of the additional KEPServerEX functions in managing the defaults and parameters for the data capturing of the whole shop floor and, secondly, the possibility to have all (!) devices interconnected for data transfer.

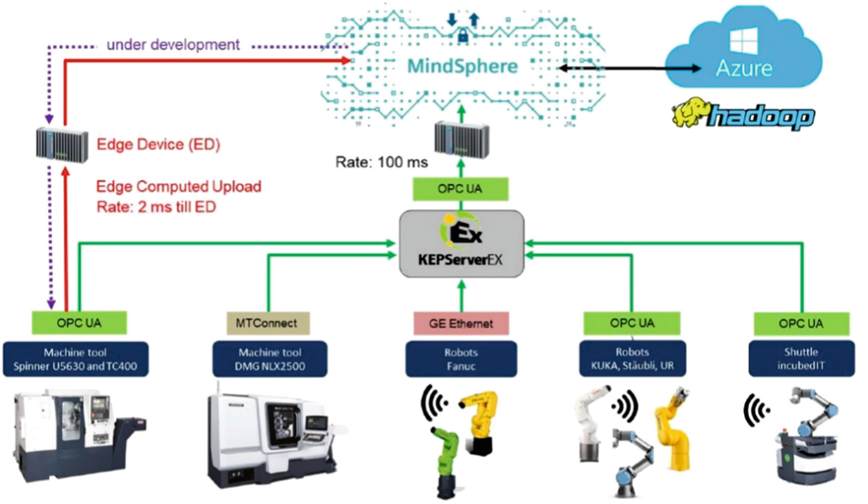

Fig. 4. Middleware “KEPServerEx” for harmonizing and translating diverse protocols

The data flow at the outer left side shows a direct connection to the clouds via short-cutting the KEPServerEX Server. This application is bound to additional preconditions. First, the integrated facility must work on Sinumerik 840D sl and, second, there is the need of an additional Siemens Edge Device, mostly applied directly at the machine. This Edge Device includes functionalities of the otherwise usual “Mind Connect Box” as a pre-processor before entering MindSphere. The only reason and advantage of such a solution is the high possible data transfer rate of only 2 ms instead of normally 100 ms.

5 Conclusions

Effective CPPSs live on the pervasive and seamless data integration of its data generators and receivers (Things) mainly facilitated by the Linkage Part of a CPPS. The connectivity, its semantic interoperability and the scalability need well designed concepts and architectures not because of lacking standards and protocols but – just the opposite – the existence of too many of them. The challenge increases significantly if the network should be set up with facilities from many different suppliers and their proprietary standards.

At the Learning Factory of Graz University of Technology, the integration of most heterogeneous products at the office floor and at the shop floor is a major part of its research. The paper presents two solutions in the form of "Use Cases", one representing an innovative concept for the vertical and another for the horizontal integration. Usage an Enterprise Service Bus at the office floor and the installation of the middleware "KEPServerEX" in the shop floor are the selected core approaches for creating a representative CPPS.

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Physics of Mind – A Cognitive Approach to Intelligent Control Theory

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Abstract. Control of structurally-complex industrial and technological objects belongs to the class of problems of intelligent control, which demands making decisions in states of uncertainty. Further development of this industry will be associated with technologies of intelligent control based on knowledge. Such technologies use methods, models, and algorithms extracting and accumulating knowledge needed to find optimal decisions. Intelligent control theory is based on learning surrounding world and adapting to changes in the process of reaching the defined goal. In this paper we consider a cognitive approach to learning developed following the human cognitive ability and a scientific method of physics. The cognitive approach opens new wide directions towards control of industrial objects and situations that are not well structured and difficult to formalize, especially in real-life circumstances with significant uncertainty. A class of cognitive model control agents based on the principles of learning is described in the paper. Cognitive agents are such kind of agents that are learning from their surrounding and modifying their actions to achieve the goals; this type of agents enables solving problems in a wide area of control in the presence of uncertainty.

Keywords: Artificial Intelligence · Theory of control · Cognitive models · Cognitive agents · Hierarchy of industrial or technical systems · Cyber-physical system

1 Introduction

Artificial Intelligence (AI) and Intelligent System (IS) are central notions in current theory of control system [1]. Intelligent system is capable to function autonomously, by learning its surrounding, adapting to changes, and reaching defined goals [7]. Other researchers consider as key to intelligence the ability to accumulate knowledge, define aims, and plan actions [1]. At present, widely used is the notion of cognitive agent, i.e., such a kind of agent that is learning the surrounding and modifying its actions to achieve the goals [7, 15]. Cognitive agents capable of reaching goals in varying situations are the most perspective class of mathematical models of intelligent control [1, 11–13].

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A key principle of intelligent control is control based on knowledge [9]. Existence of knowledge of how to make the best control decisions in the presence of uncertainty is the foundation of intelligence. Thus learning, or accumulation of knowledge is the foundation of intelligent control [8, 14].

There are two aspects of knowledge that agents use for making good decisions. First, the agent must be in a possession of rules for making good decisions. Second, surrounding circumstances are changing, therefore agents should be able to adapt to these changes. Future intelligent systems will combine learning from data by estimating probability densities with learning from a language text. These ideas were previously discussed in the works of the authors [3–8, 10].

It is assumed that the intelligent control agent receives certain information about the current state of the surrounding, defined as situation Si, as well as actively uses the data to interact with the surrounding. Knowledge of regularities, determining the cause-effect relationship between events in a specific situation and enabling to predict various situations or controlled objects development, is the base that a control agent uses to elaborate efficient strategies for making the best – optimal-control decisions. This information exactly refers to the knowledge or representations of control agent cognitive capacities.

Cognitive control agents key characteristics are the autonomous character and purposefulness of actions. This means autonomous commands execution based on a targeted, problem-oriented reasoning. As the main characteristics of a cognitive intelligent agent are also considered autonomous, in which the intelligence is associated with autonomous perception and reasoning, with making decisions and actions in the states of uncertainty of the surrounding. In this case, critical for a cognitive agent becomes its ability to acquire knowledge through learning: that is, the ability to learn. Such ability requires the possibility to extract, accumulate and apply knowledge used for control. Such cognitive agents are able to learn and to be aware of their surrounding and adapt to it, and change it on the account of knowledge accumulated in the functioning process and acquired skills. A cognitive process is a process by which an autonomous artificial system perceives the surrounding, gains experience through learning, predicts the result of the events, acts and adapts to changes in the surrounding.

2 Formulation of the Problem

We consider a cyber-physical system that controls the hierarchy of industrial or technical systems [5]. Possible system states are estimated by clustering available data (x_1, …, x_n), where x_n are characteristics of agents and states of technical systems.

A powerful clustering method is dynamic logics (DL), using the Gaussian mixture model [6]. In this model, every cluster m is characterized by a Gaussian likelihood:

$$l(n|m) = \left(\frac{1}{2\pi}\right)^{0.5d} |C_m|^{-0.5} \exp\left[-\frac{1}{2}(x_n - M_m)^T C_m^{-1}(x_n - M_m)\right].$$

Here M and C are the mean and covariance parameters of the Gaussian likelihood. In addition, every cluster is characterized by its rate:

$$r_m = N_m/N,$$

where N_m is the number of data points belonging to the cluster and N is the total number of data points.

DL algorithm for estimating likelihood parameters starts with arbitrary values of unknown parameters r, M, C.

The next step is to compute association variables:

$$f(m|n) = \frac{r_m l(n|m)}{\sum\limits_{m'} r_{m'} l(n|m')}.$$

Using these association variables data points in the cluster and rates are computed:

$$N_m = \sum\nolimits_n f(m|n), \; r_m = N_m/N.$$

Next, the mean value is computed:

$$M_m = (1/N_m)\sum_n f(m|n)x_n,$$

as well as the covariance:

$$C_m = (1/N_m)\sum_n f(m|n)(x_n - M_m)^T(x_n - M_m).$$

Having parameters of clusters, it is possible to evaluate the total likelihood of all defined clusters. The total number of clusters will be defined by maximizing the total likelihood.

The clusters make up the system states; they are denoted by:

$$S = \; <s_1, \ldots, s_m> .$$

These estimated states represent one aspect of knowledge. Another aspect of knowledge consists of selecting control actions $u(t)$ at every moment t.

A control action $u(t)$ transforms the state $s(t)$ into $s(t+1)$. Beginning with the initial state $s(1)$ at the moment $t = 1$, the system goes to the state $u(1)s(1) = s(2)$.

The results of actions $u(t)$ at every state si are considered to be known; they are derived from the system model. We also know the system gain $g(i, j)$ derived from transforming any state s_i into s_j. The system goes through the following states

$$s(1), u(1)s(1) = s(2), u(2)s(2) = s(3), \ldots, u(T)s(T) = s(final).$$

The optimal control, therefore, consists of maximizing the total gain over the time T:

$$G(T) = g(t = 1, t = 2) + g(t = 2, t = 3) + \ldots + g(t = T, t = final).$$

This gain is maximized by selecting actions $u(1), u(2), \ldots, u(T)$ at every moment t.

3 Cognitive Control Agent

Cognition, considered in the context of the agents' ability to make conclusions about things and events in the world around them, as well as the ability to learn its surrounding, are the most important characteristics of the intelligent control concept [3]. We suppose that cognitive agents that are capable of automatic accumulation and use of knowledge for making better control decisions, represent the next step in the development of distributed control systems. Such agents have adaptive capabilities that provide efficient activity of devices and systems in a dynamically changing surrounding.

An agent's knowledge represents its awareness of the surrounding and itself. We consider the knowledge of the i-th agent as its ability to display the current situation S_t, defining agent's interaction with the surrounding or a controlled object, as some action A_t:

$$\psi_i : S_i \rightarrow A_i,$$

which, in its turn, is directed to the agent's (or system of agents) reaching the defined goal, i.e., target state:

$$S_G = f(S_t, A_i). \tag{1}$$

The current situation S_i is perceived by an agent through its receptors, i.e., sensors, as a certain set of measured during the time interval $t_i, (i = 1, 2, \ldots, m)$ values, i.e., parameters/signs $z_k(t_l), k = 1, \ldots, K$ which are the base for making a certain evaluation Q_t of the current state or the surrounding of the controlled object:

$$\tilde{Q}_t \cong S_i,$$

where estimation of current state $\tilde{Q}_t$ may be evaluated by feature vectors Z_{ti} as:

$$\tilde{Q}_t \equiv Z_{ti} = [z_1(t), \ldots, z_k(t)]^T, \ldots$$

In the essence, transition to a new state reflects agent's achievement of certain equation $\varphi \equiv \{R_1\}$, which is defining the f-transformation operator of the current situation S_i, represented in a specific way of a characteristics of the "agent-surrounding" state or the "controlled object" $Q = \{q_k\}$, to the control command U triggering the controlling rules. In this context, we consider the knowledge of a ψ agent A_i as a multitude of rules $\{R\}$ defining the displays of "signs of situation" (controlled object states) in action (set of control decisions):