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Enabling Connectivity of Cyber-Physical Production Systems: A Conceptual Framework

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Abstract

Inside smart factories, Cyber-Physical Systems (CPS) have to be synchronized one with another and with the external world to share information and trigger actions. In this work, the conceptual development of such a network to implement a Smart Factory at the Mini-Factory Laboratory of the Free University of Bolzano is presented. The objective is to set up a framework for an Industrial Internet System (IIS), first by homogenizing and integrating the communication systems of the end-nodes of the laboratory, i.e., sensors, robots, etc., through the necessary hardware and middleware, and second, by constructing a centralized backbone network where all valuable information is collected for further big data analysis.

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Keywords: Industry 4.0, Cyber-Physical Systems, Cyber-Physical Production Systems, Internet of Things, Industrial Internet System, Smart Manufacturing, Manufacturing Systems

1. Introduction

In the last years the industrial sector of the European Union has experienced a partial recovery with respect to its contraction experimented during the last economic crisis. However, this recovery is still low and fragile [1]. The

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effect of the displacement of manufacturing activities to lower labour cost regions are yet visible, causing a drastic decrement in the production of labour intensive products. Then, since the industrial sector represents about the 19% of the GDP of the EU [2], it has a significant contribution to all economic sectors. To assure sustainable growth and competitiveness, as well as to provide a way to re-industrialize previously deindustrialized areas, the trend of Industry 4.0 proposes a series of innovations in manufacturing and logistics, which promise a new horizon in economic growth. Small and medium-sized enterprises represent the backbone of Europe's economy and the key to Europe's competitiveness [3]. Thus, it is important to develop specific approaches for this dimension of enterprises to introduce and apply emerging Industry 4.0 technologies in their production processes. The name Industry 4.0 refers to the fourth industrial revolution [4], where Internet of Things (IoT) and Internet of Services (IoS) will enable the integration of all the instances of horizontal and vertical value chain of the product [5]. At the Free University of Bolzano we are addressing the issue of connectivity in Industry 4.0, setting up a Smart Factory at our 'mini-factory laboratory' to investigate industry 4.0 concepts with a special focus on small and medium sized enterprises (SMEs). In this paper, we present a first framework to the connectivity structure of an IIS to implement a Cyber-Physical Production System (CPPS). After the presentation of the research methodology in Section 2, Section 3 introduces a short literature review of Industry 4.0 and CPPS focused in connectivity. After that, in Section 4, we introduce a conceptual framework of the different functional domains that should be connected inside a CPPS and the system architecture. In Section 5, we present the current state of the mini-factory laboratory and the planned transformation into a smart factory environment. The paper ends with a brief conclusion and outlook for future research activities in the mini-factory lab.

2. Research Methodology

With the endeavor of implementing a Smart Factory, we started a literature collection from different academic sources as Google Scholar and Scopus to define the fundamental Industry 4.0 concepts we would to implement in our laboratory (briefly described in Section 5). We used several key words as "cyber-physical systems communication" and "cyber-physical systems integration" as well as citations to retrieve documents. Following [5-7], we focused the literature review on connectivity and its implementation. Concepts as interoperability, Industrial Internet Systems and others commented in Section 4, appeared as fundamental and also drove our literature collection shaping new questions for our research. In Section 5 we describe the application of those concepts in our laboratory, where we have given the first steps to develop an IIS.

The research question which currently employs many researchers is as follows: How can Business Domain and the physical production system consisting of machines with different controls be efficiently linked in the laboratory?

3. Industry 4.0 and Cyber-Physical Production Systems – roots and future challenges

There are several approaches to define Industry 4.0. We desire cite two characteristics, which underline importance in connectivity [5, 6]. First, Industry 4.0 relies in vertical integration of the manufacturing process. It breaks with the traditional automation pyramid, proposing a more distributed and collaborative architecture [7]. Second, it relies on horizontal integration of all the value chain, from customer requirements to product architectures and production [6, 8], allowing the creation of a new kind of added value. The core concept underneath these integrations is the Internet of Things that will allow merging seamlessly two domains that were traditionally disjoint, specifically, the Information Technology (IT) and Operational Technology (OT) domains. Combining the methodologies which support physical value creation and manufacturing processes (OT) with those related to information processing (IT), bears the challenge of providing physical objects that traditionally lie in industrial environments with (i) cognitive, (ii) perception or actuation, (iii) communication and (iv) autonomy capabilities [9]. Machines, sensors, other objects have long been endowed with cognitive perception and actuation thanks to small and dedicated computer systems called Embedded Systems (ES). When arbitrary objects are catered with the above described properties (i)-(iv), they become Cyber Physical Systems (CPS), which are the building blocks of the fundamental entities of Industry 4.0, the Smart Factory [10, 11]. The definition of CPS may vary from authors, but they may be understood as ES with actuating and/or sensing capacity, endowed with advanced communication skills [7, 12]. This last element is fundamental. Classical ES may communicate with low-level communication protocols like SPI or I2C, meanwhile a CPS is capable to stablish more structured connections like TCP/IP or PROFIBUS and it may accept structured streams of information. This is a key point of CPS: they are designed to stay connected and work inside a body of CPS where high-structured information is constantly exchanged [13]. For this reason Smart Factories are essentially Cyber-Physical Production Systems, i.e., a body of autonomous and cooperative elements connected with each other at all levels of the production system [14].

Currently, Industry 4.0 and CPPS are on their infancy. Several challenges and gaps must be addressed to make the fourth industrial revolution a reality. For example, advantages on electronics and miniaturization have shifted the main concerns of the development of ES from the management of limited resources to the interaction between the electronic platform, the software and the physical world [12, 15]. It is important to develop future frameworks and models for cyber physical systems to enable a cloud-based production on demand in manufacturing networks [16-18]. Also, the coordination of heterogeneous systems with multiple models, methods, and actors is quite hard, and has been a research argument for a while [15, 19]. The main concern of this work is how to design a Smart Factory exploiting the cognitive and communication capabilities of the CPS present in the 'mini-factory laboratory'. The premise is that this can be achieved through the realization of a common communication network with a set of common protocols. This will allow a suitable coordination and orchestration of all the cyber-physical elements in the laboratory and serve as the basis for a subsequent generalization of the framework approach.

4. Framework of an Industrial Internet System for CPPS

To achieve coordination and orchestration of the cyber-physical capabilities of a distributed body of CPS it is mandatory having a correct structure and organization of the communication functions. Following this idea, the functional components of a CPPS and their interactions, must be endowed with a structure that makes it possible to address specific concerns, which are qualitatively distinct. For this structure, we refer to the Industrial Internet Reference Architecture [20], which, under the so called 'Functional Viewpoint' introduces the concept of functional domains to simplify the development of IISs (see Fig. 1). This decomposition underlines important building blocks, which are neither complete nor minimum to describe all the functional components inside an IIS. Rather, this decomposition is a starting point for conceptualizing a concrete functional architecture. At the same time, each domain behaves different granularities and time scales, but they can be hierarchically organized from high-level intelligence, where strategic planning and decision making is done, to low level control where OT directly shapes the physical world.

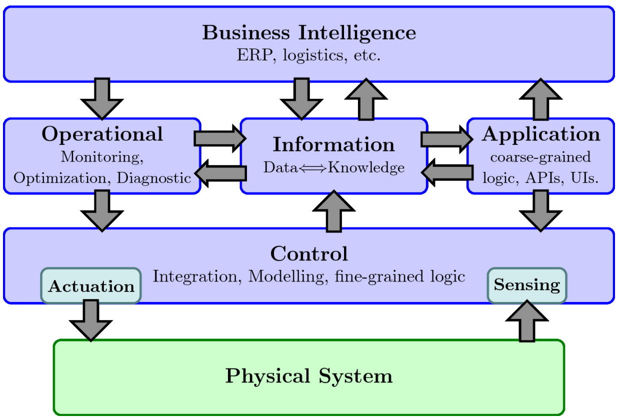

Fig. 1. The functional Domains [20].

The functional viewpoint introduces the following domains: (i) The Control Domain comprise low level OT and low level control loops like LQG and PID, (ii) The Operation Domain contains functional capabilities to enable operability of the hardware on the control domain, (iii) The Information Domain collects information from all domains and provides high-level analysis and intelligence about the overall system, (iv) The Application Domain applies coarse grained logic and provides high-level abstraction comments which are implements in APIs and UIs, (v) The Business Domain refers to the functional components of the upper layers of the automation pyramid as ERP and high level decision making systems.

We may understand IIS as an Industrial IoT system, which is the product of the digital connection of these functional domains. This is possible only after enabling two qualitatively different features. On the one hand, we say to have integrability of elements when they can communicate using compatible or common signals and protocols. On the other hand, we call interoperability the capability to exchange mutually intelligible information [21]. This difference may be better understood after identifying the technological platform, which enable these features.

The Open Systems Interconnection reference model (OSI model) defines seven layers that make up a framework of how information travels up and down between physical hardware devices and applications running on user desktops [22]. In what follows, we describe how to achieve integrability and interoperability on the OSI model in a way that is convenient for our particular case (see Fig. 2).

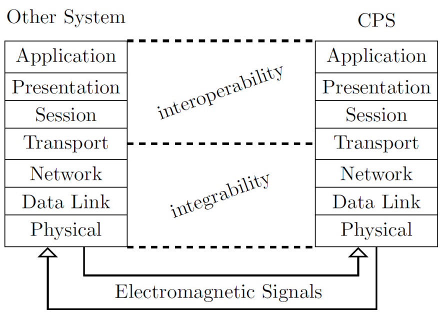

Fig. 2. The OSI model of bit transport.

At the application layer, a computer interprets the bit sequences as high-structured information. By example, the sequence of task for a robotic arm in a hybrid manufacturing station is better represented in a certain way, where positions and velocities are easily addressed. But, due to the complexity of communication on computer systems, that digital representation can't be transmitted as it is. Instead, some bite sequences may be split and more information must be added. This process of travelling down on the OSI model is called encapsulation, and the reverse process decapsulation [23]. Integrability is assured with the possibility of conveying correctly bite sequences from one system to another. In our case, we reach integrability establishing communication at the OSI transport layer. Interoperability refers to the interpretation of these bite sequences as high-structured information at the upper OSI layers. This comprise two different features, (i) syntax and (ii) semantics. The first deals with data formats, i.e., which sequences of bites are mapped to symbols. The second deals with methods to interpret these sequences of symbols.

Since 1960's several communication technologies where implemented to assure integrability and interoperability between CPS and ES. They have been known as Machine to Machine (M2M) communication technologies, and were principally used to send orders, receive measures and eventually configure devices, everything at low level [24]. In the Smart Factory this communication scheme changes qualitatively. As CPS have both self awareness and self control capabilities, they may send and receive more structured information streams with its impression of itself, to operate high-level task in a smart way, and communicate with other CPS to coordinate operations. Consequently, in Smart Factories the cognitive capabilities of each CPS may take a part in the global orchestration of the CPPS. However, to achieve the IIS we need to address two further considerations.

First, several systems may lack on cyber-physical capabilities. ES, actuators and sensors with low level communication capabilities may be necessary for specific application and should be connected to the CPPS. The solutions to this problem are manifold and we focus on two possible methods. On the one hand, we can build a CPS wrapping, i.e., an electronic suit which connects with the system of interest and provides to it cyber-physical capabilities [6, 19]. On the other hand, we can design a communication interface to connect the high-level communication system of the CPPS to a low level communication of the system of interest.

Secondly, the communication technologies presented in a CPPS may be very different. In actual IIS a heterogeneous set of technologies are combined, from low-power wireless, like ZigBee or 6LoWPAN, to legacy connections like serial RS-232. Each technology is suitable for specific tasks and has its own quality of service as velocity and reliability. Consequently, it is necessary to aggregate the CPS of the production system to the same network using the correct combination of technologies. We address this problem from the perspective of the physical topology of the communication hardware, and choose the ‘Three Tier Architecture’, sketched in Fig. 3. It consists in a logical subdivision of the nodes presented in the CPPS's network in three ‘tiers’ in accordance with their communication needs and functional domains. At the lower level, we have the ‘Edge Tier’, which implements most of the control domain components. In this Tier a Proximity Network connects sensors, actuators CPS and other elements in a bunch of heterogeneous communication technologies which are connected to the same baseline. The ‘Platform Tier’ implements most of the information and operation domains and the ‘Enterprise Tier’ implements most of the business domain. In our model, the last two tiers are connected to the Edge Tier through the so called Access Network, which, contrary to the Proximity Network, do not have the same constrains that can be found on the factory floor and connects qualitatively different systems.

Note that this architecture does not only splits functional components in accordance with the necessary technologies for communication. It also splits the decisional task into different levels. At the enterprise Tier, strategic and high level decisions, which are characteristic of the business functional domain, are taken. At the platform tier, the granularity becomes thinner, and more technical aspects are considered to introduce commands into the system. Finally, in the edge tier, low level feedback control system relies.

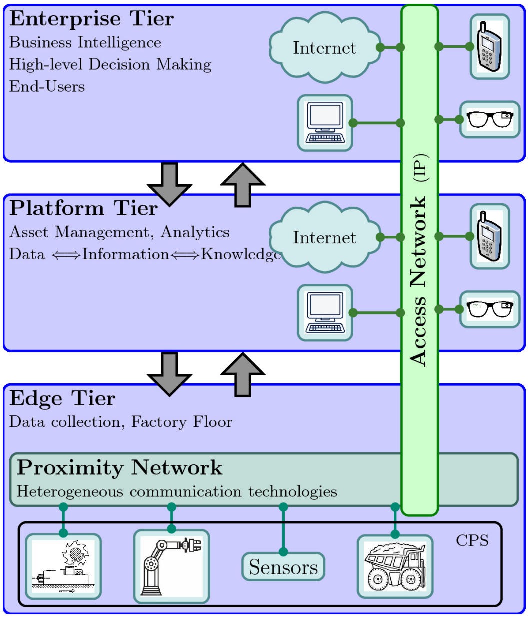

Fig. 3. Three Tier Architecture [20].

5. Application of the IIS concept in the mini factory laboratory

At the mini-factory laboratory of the Free University of Bozen-Bolzano, we are implementing a first prototype of an IIS. At the moment, we have three CPS (see Fig. 4):

- UR3 lightweight robot produced by Universal Robots: it is designed for both, assembly and workbench tasks, where the payload don't exceeds 3 kg. It is a 6-axis manipulator constituted by and anthropomorphic base and a three axis wrist. The robot has a workspace of 500mm and is equipped with a gripper. Also, it is controlled by a Mini-ITX PC with a Linux system installed which runs, as a daemon, the low-level robot controller called URControl. A visual interface is available through a touch screen pendant, providing a GUI called PolyScope. The controller has a Network Interface Card (NIC) with IEEE 802.3u 100BASE-TX Ethernet capability [25]. The URControl daemon provides TCP/IP control interface based in the PolyScript language.
- Adept Cobra i600: it is a four axis manipulator with a SCARA base and one additional wrist-like joint. It is designed for several industrial applications where the payload does not exceed 5.5kg, and have a workspace capable of reaching 800mm. It is controlled by an Adept SmartController EX which has a NIC with IEEE 802.3u 100BASE-TX compatible Ethernet capability. The controller runs an operative system developed by adept called V+OS, which provides a control interface based in the V+ language.
- Adept Quattro: it is a four arm delta robot designed for industrial high-speed applications like packaging. It has the same controller as the Adept Cobra i600 robot.

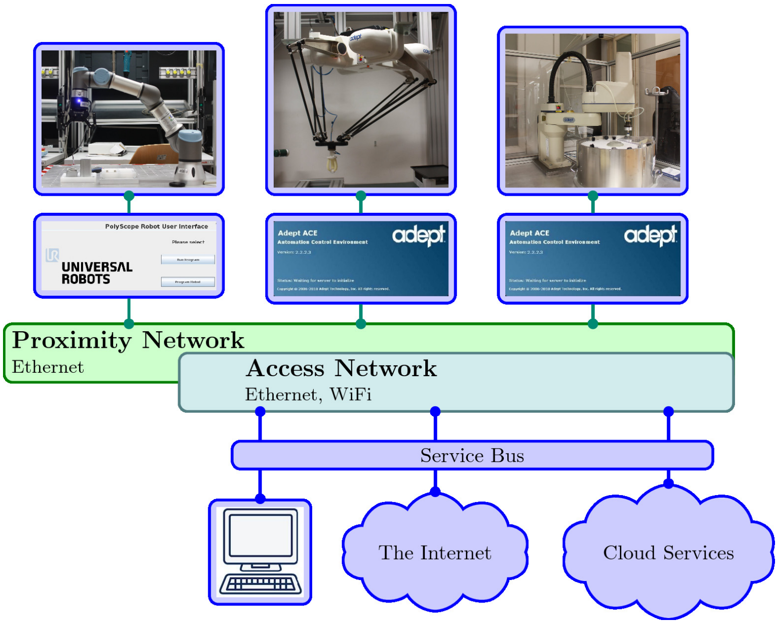

Fig. 4. Current state of the mini-factory network.

Each robot consists of the arm and its controller. All these systems have remarkable cyber-physical properties as important processing capacity on their controllers (cognitive), self-awareness of joint positions, temperatures and torques (perception), and capability of establishing Ethernet communications with a TCP/IP protocol (communication).

In particular, the UR3 robot is a so called force limited robot. That means that its control system may be configured for safe physical human-robot interaction (pHRI) as a collaborative robot with which a person can share the same workspace. As described in the previous sections, the UR3 as a CPS may take part on the coordination and orchestration of the CPPS by autonomously keeping a behavior, which is safe for pHRI. Moreover, because its controller is very similar to a desktop computer with a very flexible operative system, and the URControl daemon may be accessed by POSIX sockets, it is perfectly possible to enhance its autonomy by developing new software.

Because each CPS's communication capabilities, the problem of integrability is solved with a wired 100BASE-TX Ethernet Proximity Network. The main challenge is to achieve interoperability between the CPSs to communicate seamlessly with the other functional domains. Basically, we need a bridge between the applications running on each component of the mini-factory laboratory. This problem of interfacing several applications is solved through a so called Enterprise Service Bus (ESB). The equivalent on manufacturing systems is called Manufacturing Service Bus (MSB), and we develop such software infrastructure as an object oriented API written in C++ (see Fig. 5). In the actual state, we are able to connect to the TCP/IP listening socket available on the UR3 robot, and we are currently developing a similar system on the V+ language used by the Adept robots to communicate in a homogeneous manner between the nodes of the lab.

At the level of the control domain, we have the hardware of the robots and their controllers as well as the software running on them and the internal loop control at of the robots. In our case, the interface between the control and the other domains is furnished by the application domain. In fact, it provides the MSB, which will allow defining the coarse-grained logic of the system through its API.

The information and operational domain are currently under construction. These depend on the application domain just in the API for information gathering, but for specific function we can implement direct communication with the CPS when necessary. The operational domain have the Flexim simulation software and other optimization tools from optimal control theory (see Fig. 5).

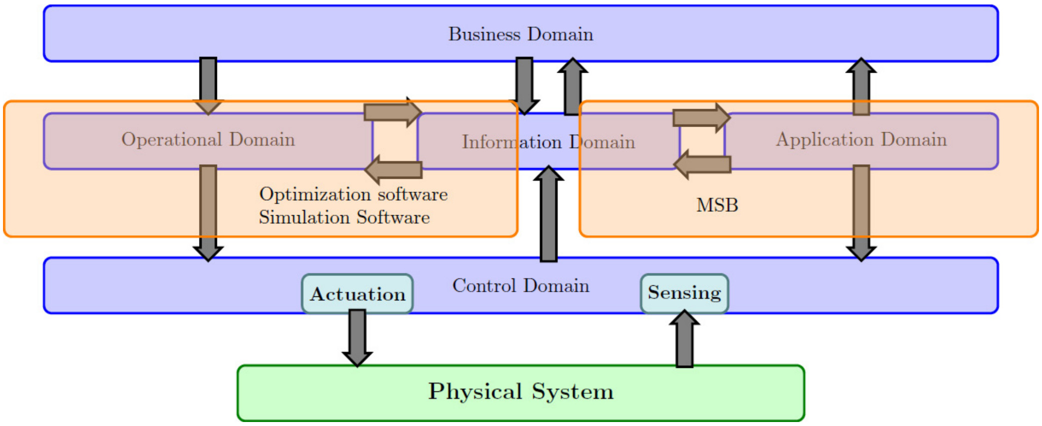

Fig. 5. Functional Domains on the Mini-factory.

6. Conclusion and prospective

We presented a theoretical framework for a first implementation of an IIS for CPPS. The different actors in such production systems were aggregated in different conceptual domains in agreement with their functionalities and characteristics. The main concern was to enable integrability and interoperability between the different actors of the system. In the mini-factory laboratory the first steps to solve that concern have been implemented through the realization of a conceptual framework and realizing a proximity and an access network in a wired IP 100BASE-TX Ethernet network. On the other hand, there still remain key issues to be addressed. In particular the autonomy of each CPS needs important features that we did not address in this work. An MSB is a key component for the composition of the cognitive capabilities inside a body of CPSs, but there are still several question to be answered about the interoperability of such complex application layers. Another important issue is the behavior of the overall system by the interaction of each actor, when a global goal is requested. Finally, but not the last unaddressed issue, we have not addressed is the management of all the amount of data available in our network. This last issue deals with Big Data and opens the possibility of e.g. predictive maintenance. These issues are limitation of our current work, but represents prospective for our future research.

This work is a first step to build up a smart factory in the mini-factory laboratory realizing an IIS to enable connectivity of CPPS. In a second step, the shown framework will be realized to continue with case study research in the laboratory focusing on the special requirements of SMEs. However, in this work some important arguments were not discussed such as security and resilience. These are future lines of research that we will address.

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