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Industrial automation based on cyber-physical systems technologies: Prototype implementations and challenges

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ABSTRACT

Cyber-Physical Systems (CPS) is an emergent approach that focuses on the integration of computational applications with physical devices, being designed as a network of interacting cyber and physical elements. CPS control and monitor real-world physical infrastructures and thus is starting having a high impact in industrial automation. As such design, implementation and operation of CPS and management of the resulting automation infrastructure is of key importance for the industry. In this work, an overview of key aspects of industrial CPS, their technologies and emerging directions, as well as challenges for their implementation is presented. Based on the hands-on experiences gathered from four European innovation projects over the last decade (i.e. SOCRADES, IMC-AESOP, GRACE and ARUM), a key challenges have been identified and a prioritization and timeline are pointed out with the aim to increase Technology Readiness Levels and lead to their usage in industrial automation environments.

1. Introduction

In the last couple of decades the traditional paradigms adopted for industrial automation are becoming increasingly inadequate to accommodate emerging technology and business needs of manufacturing players. Changing conditions, constraint industrial companies running their business, as they face strong pressure related to the cost, quality and customization of products in highly flexible and responsive production systems [1]. This market and business evolution is generating a need for more flexible and scalable production systems which should be able to handle agile fluctuation with highly product variability at reasonable cost with real-time reactivity. The "collaborative automation" paradigm [58] is a major one supported by the industry, where the aim is the development and implementation of tools and methods to achieve flexible, reconfigurable, scalable, interoperable network-enabled collaboration between decentralized and distributed embedded devices and systems. This trend has been accompanied by a technological evolution characterized by the penetration of computational capabilities, i.e., data and information processing, into the mechatronics, transforming gradually the traditional shop floor into an ecosystem, where networked systems are composed by smart embedded devices and systems, as well as by customers and business partners in business and value processes, interacting with both physical and organizational environment, pursuing well-defined system goals.

Under the label of Cyber-Physical Systems (CPS) and more precisely their applicability in the industrial domain – hence referred to as Industrial Cyber-Physical Systems (ICPS) – key innovation actions have been started in various programs, e.g., the Industrial Internet [2] and German "Industrie 4.0" initiative [3–5]. Communities in several domains are actively working towards designing, implementing and assessing suitable engineering approaches for the realization of the CPS. These approaches are supported by enhancing and developing the necessary technological basis to facilitate the realization of the addressed trends in Industrial Automation, as well as in other emerging application domains, such as smart grids, smart buildings, smart transportation, smart healthcare, and particularly in smart manufacturing [6,7].

In this context, this paper introduces the major features of a set of industrial CPS prototype implementations supporting the realization of the collaborative automation paradigm [8] based

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on the use of Multi-Agent Systems (MAS) and Service-Oriented Architectures (SOA), enriched with insights from social and biological systems, such as swarm intelligence, self-organization and chaos theory. Moreover, some complementary technology enablers, such as wireless sensor networks, augmented reality and cloud computing, are considered to support the operation of the ICPS in ubiquitous environments, where the re-configuration appears naturally like "drag-and-drop" applications and complexity is handled by background services.

The gathered experience in several European research and development (R&D) projects is used to illustrate some of the achievements in the area and to address new challenges. Particularly, the major results of four selected European Innovation projects are reported i.e.:

- The European Innovation Project SOCRADES – Service-oriented Cross-layer Infrastructure for Distributed Smart Embedded Devices – [9], highlighting the introduction of the service-oriented architecture paradigm into the industrial automation environment.
- The European Innovation Project GRACE – inteGration of pRocess and quAlity Control using multi-agEnt technology – [10] highlighting the use of agent technology to integrate quality and process control aiming the improvement of the production efficiency and product customization.
- The European Innovation project IMC-AESOP – Architecture for Service-oriented Process, Monitoring and Control – [11], highlighting the application of the service-oriented paradigm to develop and implement the next-generation industrial SCADA (Supervisory Control and Data Acquisition) and DCS (Distributed Control Systems) systems.
- The European innovation project ARUM – Adaptive Production Management – [12], highlighting the integration of agent-based planning and scheduling tools using the service-oriented paradigm to respond faster to unexpected events during the ramp-up production of complex and highly customized products.

This paper is organized as follows. Section 2 describes the basics of the CPS paradigm as a suitable approach to implement the vision for the smart and adaptive factories for the future. Section 3 introduces an high-level view to realize industrial CPS solutions based on MAS principles combined with several technologies, namely SOA and cloud systems, and considering biological inspiration. Section 4 describes four use cases where these concepts were prototype implemented in real industrial scenarios, summarizing the Technology Readiness Levels (TRL) achieved by these industrial prototypes. Section 5 makes a comparative analysis of these use cases and identifies some challenges for approaching the increase of those TRLs. Finally, Section 6 rounds up the paper and presents the conclusions.

2. The emergence of CPS

The term "Cyber-Physical Systems" (CPS) coined in 2006 in a high-level working group[1] composed of selected experts from the USA and European Union, advocates the co-existence of cyber and physical elements with a common goal. Embedded systems have been developed over the past decades, however CPS explicitly pose a focus on the integration of computation with physical processes [13]. Generally, CPS are nowadays designed as a network of interacting cyber and physical elements.

[1] NSF Workshop on Cyber-Physical Systems, October 16–17, 2006, Austin, Texas, http://varma.ece.cmu.edu/cps/.

In the last years, requirements and overall complexity in the areas of utilization of CPS has increased dramatically. The later is correlated to the pursuit for flexibility, customization, interaction and provision of new functionalities in industrial settings. Currently, there is a technology push into complexity, with everything getting smart, e.g., phones, houses, cars, aircrafts, factories, cities etc. As an example, the functionalities and consequently complexity associated can be seen by a system comparison e.g. of the early past century plane controls in Charles Lindbergh's "Spirit of St. Louis" and a modern Airbus A380 aircraft. Although both have the common goal of flying, this could be realized by monitoring a couple of sensors in the "Spirit of St. Louis", which nowadays translates to thousands of sensors in A380, which is impossible to assess for humans. However, with the automation and creation of high-level key performance indicators from the sensor data, this can still stay manageable at high level, although not all interworking are directly seen nor understood by its operators. Although complexity may have its advantages, hiding it from the end-users and managing it, results to grand challenges. As an example, in our cars, the complexity is hidden from the driver, as she/he just needs to handle a limited number of controls to operate the system, without being exposed to its complex networks of sensors and actuators distributed all through the mechanic infrastructure.

Particularly in manufacturing automation, markets are imposing strong changing conditions, where the customization of products requires the use of flexible automation infrastructures. Moreover, the application of flexible automation cannot completely guarantee respecting the time to market requirements, compared with the usual short time on the market of the manufactured products. This situation lies to the necessity of developing and implementing, in a complementary manner to the addressed flexibility, fast and manageable reconfigurability of the automation systems. This means, the reconfigurability of mechatronic (physical part of the automated objects) and of the automation software (cyber part of the automated objects).

As depicted in Fig. 1 (adjusted from Ref. [14]), there are several areas that share common ground, e.g., software agents, Internet of Things, CPS, cooperating objects etc. These have co-evolved over the last decades, and although some of these are used interchangeably (in places), there are differences among them. In our view, what differentiates them is the varying mix of the degree of physical and feature elements that creates the right recipe for a specific area. For instance, Cooperating Objects [14] focus mostly on the cooperation aspects while considering the rest of the available features only as enabling factors to achieve cooperation. Other approaches, e.g., Internet of Things, focus mostly on the interaction and integration part while cooperation is optional. Similarly, CPS may pose a different mix of the key features and depend on their utilization domain. CPS consider the computational decisional components that use the shared knowledge and information from physical processes to provide intelligence, responsiveness and adaptation. In conclusion, the differentiating factor among all areas, is not the distinct characteristics but which of them they employ (depending on the scenario) and at which degree.

CPS in industrial infrastructures deal also with the combination of mechatronics, communication and information technologies to control distributed physical processes and systems, designed as a network of interacting software and hardware devices and systems, many of them with a higher level of decision-making capabilities in both aspects: "autonomic" with self-decision processes [15] and "collaborative" [14] with negotiation-based decision processes. CPS can be considered as smart systems that use cyber technologies embedded in and interacting with physical components, featuring a tight combination of computational and physical elements, integrating computation, communication and control over an information system (integration of computation