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Cyber-physical production systems: Roots, expectations and R&D challenges

László Monostori[a,b*]

[a]Fraunhofer Project Center on Production Management and Informatics,
Institute of Computer Science and Control, Hungarian Academy of Sciences, Budapest 1111, Hungary, and
[b]Department of Manufacturing Science and Technology, Budapest University of Technology and Economics, Budapest, 1111, Hungary

* Corresponding author. Tel.: +36-1-279-6159; fax: +36-1-466-7503. *E-mail address:* laszlo.monostori@sztaki.mta.hu

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Abstract

One of the most significant directions in the development of computer science and information and communication technologies is represented by *Cyber-Physical Systems (CPSs)* which are systems of collaborating computational entities which are in intensive connection with the surrounding physical world and its on-going processes, providing and using, at the same time, data-accessing and data-processing services available on the internet. *Cyber-Physical Production Systems (CPPSs)*, relying on the newest and foreseeable further developments of computer science, information and communication technologies on the one hand, and of manufacturing science and technology, on the other, may lead to the 4th Industrial Revolution, frequently noted as *Industry 4.0*. The key-note will underline that there are significant roots generally – and particularly in the CIRP community – which point towards CPPSs. Expectations and the related new R&D challenges will be outlined.

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Keywords: Manufacturing systems, cyber-physical systems, distributed systems

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1. Introduction

Cyber-Physical Systems (*CPS*) are systems of collaborating computational entities which are in intensive connection with the surrounding physical world and its on-going processes, providing and using, at the same time, data-accessing and data-processing services available on the internet [1], [2], [3]. "The potential of CPS to change every aspect of life is enormous. Concepts such as autonomous cars, robotic surgery, intelligent buildings, smart electric grid, smart manufacturing, and implanted medical devises are just some of the practical examples that have already emerged [3]."

Cyber-Physical Production Systems (*CPPS*), relying on the newest and foreseeable further developments of computer science (CS), information and communication technologies (ITC), and manufacturing science and technology (MST) may lead to the 4th Industrial Revolution, frequently noted as Industry 4.0 [4]. According to the Federal Ministry of Education and Research, Germany (BMBF): "Industry is on the threshold of the fourth industrial revolution. Driven by the Internet, the real and virtual worlds are growing closer and closer together to form the Internet of Things. Industrial production of the future will be characterized by the strong individualization of products under the conditions of highly flexible (large series) production, the extensive integration of customers and business partners in business and value-added processes, and the linking of production and high-quality services leading to so-called hybrid products [4]".

In this paper, the parallel development of CS and ICT on one hand, and of manufacturing on the other, is described, pointing out the convergence of the two worlds, namely the virtual and physical ones. The concept of cyber-physical production systems is introduced in short, together with the high expectations towards them. The roots of CPPSs are also enumerated, and the main research challenges towards the realization of CPPS are highlighted.

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2. Interplay between CS, ICT and manufacturing automation

If we look through the development of computer science (CS), information and communication technologies (ICT) and manufacturing automation, a parallel development can be observed (Fig. 1). The development of computers led to the numerical control of machine tools and robots, the microprocessor were the heart of computer numerical control (CNC), the application of computer graphics resulted in computer-aided design (CAD) systems. The development of manufacturing systems was unimaginable without computer networks. The data of computer-integrated manufacturing (CIM) systems were stored in databases. The newest results of artificial intelligence (AI) and machine learning significantly contributed to the intelligent manufacturing systems (IMS). Computer vision algorithms were applied in robotics for recognizing the environment and the object to grasp. The internet revolutionized the cooperation of humans and systems (extended enterprises (EE), supply chain management (SCM) or production networks (PN)). Multi-agent systems were applied for realizing agent-based manufacturing and holonic manufacturing systems (HMS). Wireless communication, sensor networks and internet of things (IOT) made the development of high resolution manufacturing systems possible [5], and tracking and tracing solutions in production. Embedded systems helped in realizing product-service systems, while the semantic web solutions supported the interoperability of systems by using ontologies. Grid computing led to grid manufacturing, and similarly, cloud computing to cloud services to manufacturing.

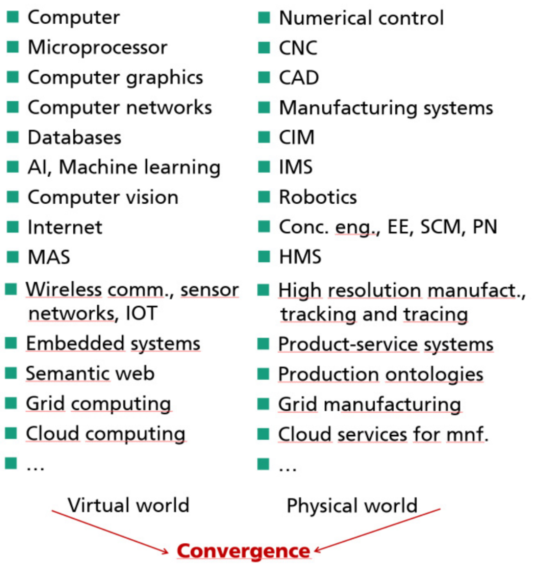

Fig. 1. Interplay between CS, ICT and manufacturing.

Summarizing, the results of CS and ICT undoubtedly contributed to the development in production, but this was not a one-way street: the importance and highly complex nature of production gave newer and newer challenges for the representatives of other disciplines.

As we look at this parallel, mutually inspiring development a kind of convergence can be observed, namely between the virtual and physical worlds (Fig. 1).

2.1. Cyber-physical production systems (CPPS)

CPPS consist of autonomous and cooperative elements and sub-systems that are getting into connection with each other in situation dependent ways, on and across all levels of production, from processes through machines up to production and logistics networks. Modelling their operation and also forecasting their emergent behavior raise a series of basic and application-oriented research tasks, not to mention the control of any level of these systems. The fundamental question is to explore the relations of autonomy, cooperation, optimization and responsiveness. Integration of analytical and simulation-based approaches can be projected to become more significant than ever. One must face the challenges of operating sensor networks, handling big bulks of data, as well as the questions of information retrieval, representation, and interpretation, with special emphasis on security aspects. Novel modes of man-machine communication are to be realized in the course of establishing CPPS.

CPPS partly break with the traditional automation pyramid (left side of Fig. 2). The typical control and field levels still exist which includes common PLCs close to the technical processes to be able to provide the highest performance for critical control loops, while in the other, higher levels of the hierarchy a more decentralized way of functioning is characteristic in CPPS.

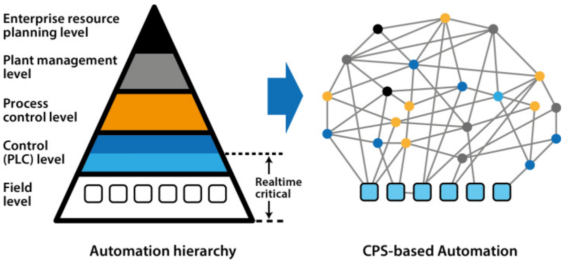

Fig. 2. Decomposition of the automation hierarchy with distributed services [6].

CPPS will enable and support the communication between humans, machines and products alike. The elements of a CPPS are able to acquisition and process data, and can self-control certain tasks and interact with humans via interfaces (Fig. 3).

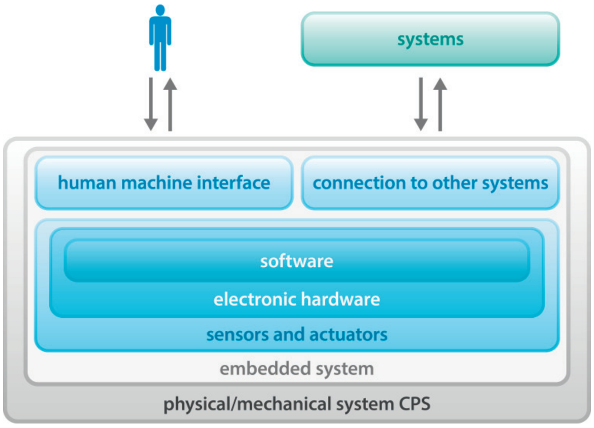

Fig. 3. Interaction between humans and machines in cyber-physical systems [7].

3. Expectations towards CPS and CPPS

Expectations are manifolds, sometimes over exaggerated:

- robustness at every level,
- self-organization, self-maintenance, self-repair, generally, self-X,
- safety,
- remote diagnosis,
- real-time control,
- autonomous navigation,
- transparency,
- predictability,
- efficiency
- model correctness, etc.

Through CPS, the development of new business models, new services are expected which may change many aspects of our life. The potential application fields are almost endless: air- and ground-traffic; discrete and continuous production systems; logistics; medical science, energy production, infrastructure surrounding us, entertainment, and we could keep on enumerating. Through cyber-physical approaches, they could result in smart cities, production-, communication-, logistic- and energy systems; furthermore, they could contribute to creating new quality of life. In the latter case we may either talk about cyber-physical society, which already includes human, social, cultural spheres as well, above the physical- and cyber spaces.

As to CPPS, many see the opportunity for the fourth industrial revolution in it (Fig. 4). The first industrial revolution is contributed to the first mechanical loom, from 1764, the second to the Ford assembly belt from 1913, the third to the first PLC in 1968. It is envisioned that CPPS can bring a similar big jump as the above mentioned breakthrough inventions.

4. Roots of CPPS in manufacturing

As in the case of many revolutions, there are some significant previous phenomena which in a way ring in the big changes. In the coming space, some former developments in production will be enumerated, with special emphasis on the reported results within the International Academy for Production Engineering CIRP, which can be considered as roots of CPPSs.

- Intelligent manufacturing systems (IMS) which were expected to solve, within certain limits, unprecedented, unforeseen problems on the basis even of incomplete and imprecise information [8], [9]. Artificial intelligence and machine learning methods play a significant role here [10], [11].
- Biological manufacturing systems (BMS) which are based

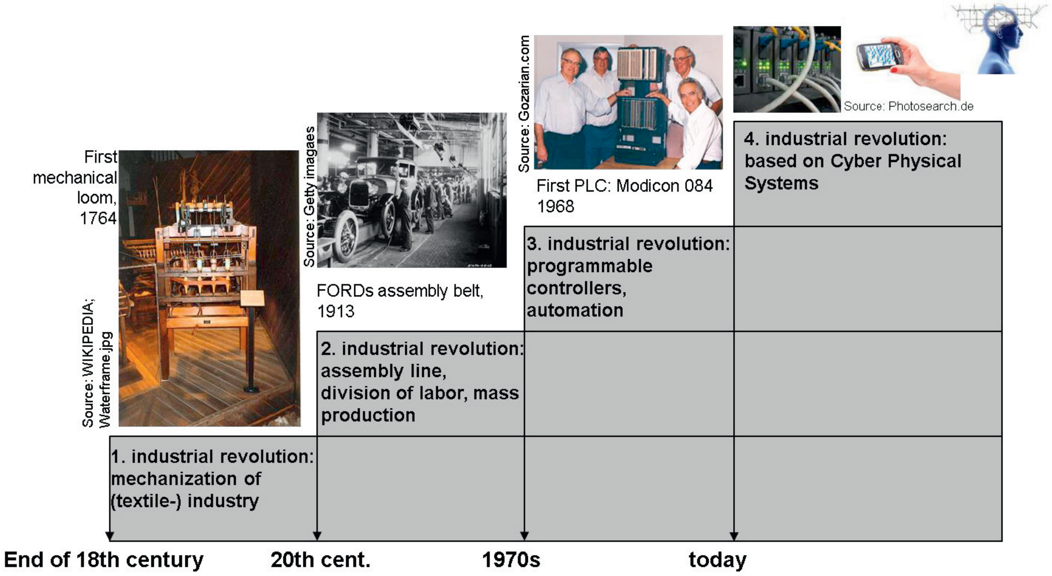

Fig. 4. CPPS as the fourth industrial revolution (after [4], courtesy of O.Sauer)

on biologically inspired ideas such as self-growth, self-organization, adaptation and evolution [12].

- Reconfigurable manufacturing systems (RMS), where the components are reconfigurable machines and reconfigurable controllers [13].
- Digital factories (DF), the mapping of most of the technical and business processes into the digital world [14], [15], [16].
- Holonic manufacturing systems (HMS), agent-based manufacturing, where the two main characteristics of the entities are autonomy and cooperation [17], [18], [19], [20], [21].
- Emergent synthesis methodologies [22].
- Production networks [23].
- Changeable production structures [24].
- Cooperative, responsive manufacturing enterprises [25].
- Co-evolution of products, processes and production systems [26][26].
- Complexity handling in engineering and manufacturing [26].

All of these cornerstones address at least one but mostly several issues which are highly related to the R&D challenges raised by CPPSs.

5. R&D challenges

The expectations towards CPS and CPPS are versatile and enormous: robustness, autonomy, self-organization, self-maintenance, self-repair, transparency, predictability, efficiency, interoperability, global tracking and tracing, only to name a few. Though there are very important developments in cooperative control, multi-agent systems (MAS), complex adaptive systems (CAS), emergent systems, sensor networks, data mining, etc., even a partial fulfilment of these expectations would represent real challenges for the research community.

In the coming space only some of the R&D challenges are outlined from the much bigger set of research fields which are related to CPPS:

- *Context-adaptive and (at least partially) autonomous systems*. Methods for comprehensive, continuous context awareness, for recognition, analysis and interpretation of plans and intentions of objects, systems and participating users, for model creation for application field and domain and for self-awareness in terms of knowledge about own situation, status and options for action are to be developed.
- *Cooperative production systems*. New theoretical results are to be achieved and the development of efficient algorithms for consensus seeking, cooperative learning and distributed detection is required.
- *Identification and prediction of dynamical systems*. The extension of the available identification and prediction methods is required, as well as, development of new ones which can be applied under mild assumptions on the dynamical system, as well as, the disturbance process.
- *Robust scheduling*. New results are to be achieved in handling production disturbances in the course of schedule execution.
- *Fusion of real and virtual systems*. The development of new structures and methods are required which support the fusion of the virtual and real sub-systems in order to reach an intelligent production system which is robust in a changing, uncertain environment. Novel reference architectures and models of integrated virtual and real production subsystems; the synchronization of the virtual and real modules of production systems and their role-specific interaction; and context-adaptive, resource efficient shop floor control algorithms are needed.
- *Human-machine (including human-robot) symbiosis*. The development of a geometric data framework to fusion assembly features and sensor measurements and fast search algorithms to adapt and compensate dynamic changes in the real environment is required.

6. Conclusions

In this paper the parallel development of computer science and information and communication technologies on one hand, and of manufacturing on the other, was highlighted, pointing out their mutual influence. The concept of cyber-physical production systems was introduced in short, together with the high expectations towards them. The roots of CPPSs were also enumerated, mainly based on contributions by members of the International Academy for Production Engineering (CIRP). Some of the numerous R&D challenges in realizing CPPS were also highlighted. As to more concrete and recent developments, we refer to the literature [28]-[44].

Without any questions, CPPS can be considered as an important step in the development of manufacturing systems. Whether this step would be regarded as the fourth industrial revolution will be decided by the coming generations, but certainly, this will happen with no zero probability.

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