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Cyber-physical manufacturing in the light of Professor Kanji Ueda's legacy

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Abstract

Cyber-physical manufacturing, i.e., the formerly never seen integration of the physical and virtual worlds in the manufacturing domain is considered the substance of the 4th industrial revolution. Much of the changes deemed now revolutionary are originated in a long and converging progress of manufacturing science and technology, as well as of computer science, information and communication technologies. One of the pioneers and influential thinkers of production engineering who paved the way towards cyber-physical manufacturing was unquestionably Professor Kanji Ueda (1946-2015). With this paper the authors would like to pay a tribute to his achievements, by highlighting his main contributions not only to the advancement of production engineering and industrial technology but also to the sustainability of our society.

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1. Introduction

Converging and mutually interacting research of manufacturing science and technology, computer science, as well as information and communication technologies resulted in what is termed now *Cyber-Physical Production Systems* (CPPS) [1][2][29]. There is general consensus that these developments established not only the key cyber-physical enabling technologies for tomorrow's production, but have also initiated fundamental, revolutionary changes affecting science, industry, education and society alike [27].

Professor Kanji Ueda (1946–2015) took part and even shaped this evolutionary process well before the concept of CPPS was coined at all. Having focused his research from grave technical issues of production engineering up to policy and broad industrial and societal agendas involving manufacturing, he was always apt to push research frontiers, challenge well proven methodologies, open dialog with other disciplines, assume their aspects and adopt their solutions. Along his overall trajectory of research all what he investigated and proposed was challenging and thought-provoking, and had spoken of a formidable craft, disciple as well as responsibility. He left behind an oeuvre of international acclaim which is still open and inspiring for the future generations, too.

Starting his professional career in the 1970s as a *manufacturing engineer*, he dealt with *cutting* processes with special emphasis on fracture mechanisms. He invented a micro-machining equipment for use inside a scanning electron microscope [14]. He investigated both the brittle fracture of cutting tools [34], and the cutting of brittle materials [44][45]. Later on, he developed finite element methods for the analysis of micro-cutting of amorphous or single crystal metals [46][48], and analyzed the 3D burr formation process in oblique cutting [9].

While these ingenious engineering solutions established Ueda in the field of manufacturing science and technology, his real *legacy* with respect to the cyber-physical manufacturing of our days is mainly related to his following research topics:

- biological and physical analogies for controlling manufacturing systems, biomimicry, artificial life and self-organization;
- emergent synthesis and complex adaptive systems;

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- manufacturing in the context of society: artifact axiology, innovation and value co-creation;
- service science, institutional design for sustainability.

In this memorial paper we attempt to outline and summarize his main achievements in the above four–each of them by itself broad–research areas, with the aim of highlighting his contribution to those developments which led to the paradigm of cyber-physical manufacturing of today. Hence, after a brief recapitulation of CPPS we discuss the challenges he realized together with his problem statements, the key solution ideas along with their evolution and applications, as well as their impact.

2. Cyber-physical production: industry, environment and society

Looking back at the progress of computer science, information and communication technologies (ICT), as well as manufacturing science and technology in the past decades, convergent and mutually interacting developments can be observed [4][27][28]. The achievements of the former contributed undoubtedly to the advancement of manufacturing, having though not a unilateral impact: the novel opportunities came along with innovative requirements, and the highly complex nature of production created in turn time and again intriguing problems for the other disciplines.

2.1. Cyber-physical production systems

Cyber-physical systems are assembled 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, networked data-accessing and data-processing services available typically on the Internet [1][2][29]. Cyber-Physical Production Systems, may lead to the 4th industrial revolution, frequently noted as *Industrie 4.0* [18]. CPPSs 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. Three main characteristics of CPPS are to be highlighted here [28]:

- *Intelligence and smartness:* the elements are able to acquire information from their surroundings and act autonomously, by doing the right or possibly even the best thing given the available information and limited computational resources. At the same time, they provide easy-to-use intuitive smart interfaces towards human users.
- *Connectedness*: the ability to set up and use connections to the other elements of the system–including humans–for collaboration and cooperation, and to harnessing the knowledge and services available in local networks or the Internet.
- *Responsiveness*: a continuously ongoing interplay and mapping between the status of physical system components and their virtual counterparts, which warrants that solutions work in reality, even under changing conditions. It is also a repeated effort of mapping projections—i.e., plans—to actual developments and actions in a real production environment [72].

Modelling the operation of a CPPS and also forecasting its emergent behavior raise a series of basic and application-oriented research issues, not to mention the control of any level of such a system. The fundamental questions are to explore the relations of *autonomy*, *cooperation*, *optimization* and *responsiveness*.

2.2. CPPS and sustainability

The potential of cyber-physical systems already permeated and changed almost every aspect of our lives. Achievements such as autonomous cars, intelligent buildings, smart electric grid, manufacturing and transportation, robotic surgery and implanted medical devices are just some of the practical examples that have already established themselves and are getting found broad application [29].

In manufacturing, the biggest changes happen where cyber-physical systems drive *disruptive innovation*. This requires strong interdisciplinary partnerships between information, communication and manufacturing companies, which will strengthen their links in existing ecosystems. Enterprises, consumers, products and services are getting massively interconnected, which opens now avenues for business, like value co-creation. There is also the potential of new players entering the market where ICT meets manufacturing competencies by offering the customer a direct benefit in form of service instead of products [69][71].

Furthermore, enterprises have to take a *socially responsible* and *sustainable* approach and be conscious of the parsimonious use of material, energy and human resources [17][72]. They have to learn to take ecological systems as fundamental life-supporting services of human civilization. A *sustainable* world is economically feasible, ecologically sound and socially just. The crux of sustainability is whether one violates the limits of what can be referred to as the *human condition*. In the context of production engineering, a poor design is unsustainable, just like a factory operating with large ecological footprint, or a supply network where parts are on a world tour before getting into a final assembly. The incentive to such a cooperative attitude between producers along the value chain—including consumers—can but come from a new ecosystem of production [37]. Solutions require multidisciplinary research over a broad range of contemporary information and communication technologies, organizational and management sciences, cooperation theory, production informatics and engineering.

3. The legacy and its impact

3.1. Biologically inspired design and control of manufacturing systems

One of the big challenges manufacturing faced in the past decades–and faces even now–is how to deal with the *growing complexity and dynamics* which arise within the production structures and in their surroundings. Nonlinear phenomena, uncertainty, combinatorial explosion of possible states make the problem hardly manageable with the traditional hierarchical approaches of production management and control. Already