Computers in Industry 81 (2016) 128–137

Contents lists available at ScienceDirect

Computers in Industry

journal homepage: www.elsevier.com/locate/compind

Big Data and virtualization for manufacturing cyber-physical systems: A survey of the current status and future outlook

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A R T I C L E I N F O

Article history:
Received 16 April 2015
Received in revised form 22 December 2015
Accepted 29 February 2016
Available online 8 March 2016

Keywords:
Sensor-based real-time monitoring
Big Data
Internet of things
Cloud computing
Manufacturing cyber-physical systems

A B S T R A C T

The recent advances in sensor and communication technologies can provide the foundations for linking the physical manufacturing facility and machine world to the cyber world of Internet applications. The coupled manufacturing cyber-physical system is envisioned to handle the actual operations in the physical world while simultaneously monitor them in the cyber world with the help of advanced data processing and simulation models at both the manufacturing process and system operational levels. Moreover, a sensor-packed manufacturing system in which each process or piece of equipment makes available event and status information, coupled with market research for true advanced Big Data analytics, seem to be the right ingredients for event response selection and operation virtualization. As a drawback, the resulting manufacturing cyber-physical system will be vulnerable to the inevitable cyber-attacks, unfortunately, so common for the software and Internet-based systems. This reality makes cybersecurity penetration within the manufacturing domain a need that goes uncontested across researchers and practitioners. This work provides a review of the current status of virtualization and cloud-based services for manufacturing systems and of the use of Big Data analytics for planning and control of manufacturing operations. Building on already developed cloud business solutions, cloud manufacturing is expected to offer improved enterprise manufacturing and business decision support. Based on the current state-of-the-art cloud manufacturing solutions and Big Data applications, this work also proposes a framework for the development of predictive manufacturing cyber-physical systems that include capabilities for attaching to the Internet of Things, and capabilities for complex event processing and Big Data algorithmic analytics.

1. Introduction

The current manufacturing global operations asks for more and stringent requirements than ever before, such as strict deadlines, low inventories, uncertain demand, standardization of manufacturing processes, product diversity, and security aspects [1]. Enhancing the manufacturing environment for more visibility and better control of the production processes becomes essential. Advances in sensor and communication technologies can provide the foundations for linking the physical facility and machine world to the cyber world of Internet applications and the software world. The coupled Manufacturing Cyber-Physical System (M-CPS) is envisioned to handle the actual operations in the physical world while simultaneously monitor them in the cyber world with the help of advanced data processing and simulation models at both the manufacturing process and system operational levels [2]. Moreover, a sensor-packed manufacturing system in which each process or piece of equipment makes available event and status information, coupled with market research for true advanced Big Data analytics, seem to be the right ingredients for event response selection and operation virtualization, and thus moving manufacturing operations closer to the cloud manufacturing paradigm [3]. As a drawback, the resulting M-CPS will be vulnerable to the inevitable cyber-attacks, unfortunately, so common for the software and Internet-based systems. This reality makes cybersecurity penetration within the manufacturing

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http://dx.doi.org/10.1016/j.compind.2016.02.004
0166-3615/

domain a need that goes uncontested across researchers and practitioners.

The globalization trend, exhibited by the world economy for a while now, comes with significant challenges for the manufacturing industries of both developed and under development countries. The new predictive manufacturing paradigm, which is referred to more and more in recent peer-reviewed publications and proposal solicitations for funding competitions, is transformative in name. But more so, this new paradigm will be transformative in its implementation [4]. While the tools seem to be already available, what is needed is their customization for the manufacturing domain, new integration architectures and control algorithms, and mostly the willingness of the manufacturing actors. Tools such as cyber-physical devices, Big Data, IT infrastructures are now ubiquitous available. Manufacturing domain needs to take a hard look at them and perform the necessary customized integration.

This work provides a comprehensive literature review of the current status of virtualization and cloud-based services for manufacturing systems and of the use of Big Data analytics for planning and control of manufacturing operations. In the enterprise context, cloud solutions usually consider the business layer and address the needed tighter interaction with the customer and the integration with suppliers, competition, and regulatory bodies [2]. Building on already developed cloud business solutions, cloud manufacturing is expected to offer improved enterprise manufacturing and business decision support. Based on the current state-of-the-art of cloud manufacturing solutions and Big Data manufacturing applications, this work also proposes a framework for the development of predictive M-CPS that include capabilities for attaching to the Internet of Things, and capabilities for complex event processing and Big Data algorithmic analytics [3]. The development challenges for the M-CPS as identified in the literature as well as uncovered by outlining and detailing the proposed framework are also discussed.

From this point forward the paper is structured as follows: Section 2 provides a review of the most important aspects of complex event processing, cloud computing and virtualization in manufacturing, Internet of Things, Big Data analytics, and cybersecurity within the manufacturing domain. Then, Section 3 presents modeling framework guidelines for the manufacturing cyber-physical system, detailing certain critical modeling aspects and instantiates the predictive manufacturing systems paradigm. Finally, the future outlook for manufacturing cyber-physical systems is sketched and needed research is outlined.

2. Manufacturing cyber-physical systems component technologies and processes review

The technologies and processes that make possible the creation of M-CPS are already in use in other domains, some of them also reaching a certain degree of maturity. However, the penetration of these technologies and/or processes into the manufacturing domain is slower compared to other domains. This is due to the nature of manufacturing operations, which need to deal with large pieces of hardware equipment, many of them being legacy systems, the high cost of manufacturing equipment, which makes it unlikely to be replaced before the end of its useful life, and the resistance of senior management to the introduction of new technologies in already well-adjusted processes and systems. Still, the march of technology is an unstoppable one-way direction road, and manufacturing domain cannot and will not go against the technology wave. Ubiquitous computing in general is a reality and the first steps towards ubiquitous manufacturing, defined as the use of IT available tools as part of the manufacturing domain, are already reported in the literature. Ferreira et al. [5] propose a manufacturing architecture where ubiquity and effectiveness are enabled by cloud platforms and layers of new services directed to communication between users. Kiirikki and Haag [6] apply the ubiquitous computing concepts to manufacturing assembly cells, Lee et al. [7] apply them to decision support systems, while Horvath and Vroom [8] study their application to computer-aided design (CAD). Nevertheless, there are remaining challenges that need to be addressed not only for ubiquitous manufacturing, but also in the area of general ubiquitous computing. Botta et al. [9] attempt to identify the most pressing ubiquitous computing challenges within the cloud computing-Internet of Things workspace, as follows: standardization, power and energy efficiency, Big Data, security and privacy, network integration, and network communications, and others related to management operations. Several of these identified challenges are also part of the proposed M-CPS model.

2.1. Complex event processing in the manufacturing domain

Manufacturing domain is driven by events, and many times those events are collected through sensors and/or executed by actuators. Any action, activity, or monitored parameter change, which influences the operational status of a manufacturing process or system, is viewed as an event. When simultaneous or a series of time-ordered simple events occur, the resulting set of events is viewed as a complex event. The objective of complex event processing is described by Luckham [10] as the identification of game-changing events, in the form of opportunities and/or threats, and the generation of a reasonable answer within certain timing constraints. As an example, Nagorny et al. [11] consider the deployment of sensor/actuator cyber-physical devices and implements their collected events in Petri Nets models that support reasoning-based control, monitoring, and management functionalities. The implemented virtualization transfers all the data processing in the cloud and makes it available for all registered users. Attempts to formalize the process and make it available in the cloud have also been made. For example, Prabhu [12] proposes that a cyber-physical device data collection event be modeled as a set (device ID, event ID, time), which is initialized and changed at any times when the sensors or actuators collect or receive data.

At the shop-floor level, traditionally, manufacturing operations are event-based operations controlled using programmable logic controllers (PLC) and computer numerical controlled (CNC) resources. The forward step to operations virtualization and cloud-shared manufacturing files needs also consider the shop-floor aspects for legacy reasons, as many manufacturers will still use the traditional technology for a while. Chaplin et al. [13] propose a solution for the integration of legacy PLC and CNC controllers into a decentralized, context-aware, data distribution service, which can be used as a model for linking legacy systems to IT-cloud based systems. Other literature models related to integration of legacy systems into Internet-based systems are reported by Bodenheim et al. [14] for PLC controllers and by Hentz et al. [15] for CNC controllers.

Besides the expected events that drive manufacturing operations, at unknown points during manufacturing cycles, unexpected detrimental simple events, or aggregation of events, may also occur. The capability of manufacturing operations to cope with complex events and respond in acceptable time is called resilience. A more formal definition of resilience is found in literature [16] and addresses the ability to prepare for, absorb, and recover from actual or potential adverse events. Francis and Bekera [17] conducted an ample study on resilience, which includes the following characteristics: system identification, resilience objective, vulnerability analysis, and stakeholder engagement. A resilient manufacturing system model designed to sustain