Available online at www.sciencedirect.com
ScienceDirect
Procedia CIRP 52 (2016) 12 – 17
www.elsevier.com/locate/procedia

Changeable, Agile, Reconfigurable & Virtual Production

Software-Defined Cloud Manufacturing for Industry 4.0

Lane Thames[a], Dirk Schaefer[b]*

[a]Tripwire, Inc., Alpharetta, GA 30009, USA
[b]University of Bath, Bath, BA2 7AY, UK

* Corresponding author. Tel.: +44 (0)1225 386 163; *E-mail address:* d.schaefer@bath.ac.uk

Abstract

Many of the world's leading industrial nations have invested in national initiatives to foster advanced manufacturing, innovation, and design for the globalized world. Much of this investment has been driven by visions such as Industry 4.0, striving to achieve a future where intelligent factories and smart manufacturing are the norm. Within this realm, innovations such as the Industrial Internet of Things, Cloud-based Design and Manufacturing (CBDM), and Social Product Development (SPD) have emerged with a focus on capitalizing on the benefits and economies of scale provided by Internet Protocol (IP) communication technologies. Another emerging idea is the notion of software-defined systems such as software-defined networks, which exploit abstraction and inexpensive hardware advancements in an effort to build more flexible systems. Recently, the authors have begun considering how the notion of software-defined systems might be harnessed to achieve flexible cloud manufacturing systems. As a result, this paper introduces the notion of Software-Defined Cloud Manufacturing (SDCM). We describe a basic SDCM architecture based on leveraging abstraction between manufacturing hardware and cloud-based applications, services, and platforms. The goal of SDCM is to advance Cloud-Based Manufacturing and other Industry 4.0 pillars by providing agility, flexibility, and adaptability while also reducing various complexity challenges.

Peer-review under responsibility of the scientific committee of the Changeable, Agile, Reconfigurable & Virtual Production Conference 2016

Keywords: Industry 4.0; Software-Defined Manufacturing; Cloud Manufacturing, Operationan Technology, Industrial Internet, Internet of Things

1. Introduction

Many of the world's leading industrial nations have invested in national initiatives to foster advanced manufacturing, innovation, and design for the globalized world. Much of this investment has been driven by visions such as Industry 4.0, striving to achieve a future where intelligent factories and smart manufacturing are the norm. Within this realm, innovations such as the Industrial Internet of Things, Cloud-based Design, Cloud-based Design & Manufacturing, and Social Product Development have emerged with a focus on capitalizing on the benefits and economies of scale provided by Internet Protocol (IP) communication technologies.

Over the past five years, we have investigated ways of integrating cloud-based systems and social networking into the design and manufacturing space [1-5]. Recently, we have been investigating the idea of Software-Defined Cloud Manufacturing (SDCM). SDCM seeks to advance cloud-based manufacturing by introducing a hardware-software abstraction layer between manufacturing hardware and cloud-based applications, services, and platforms. The ideas underlying SDCM are inspired by other software-defined systems such as software-defined networks [6]. The overarching objective is to provide more generic and reconfigurable hardware systems that are open and easily modified at the software level.

In this paper, we set the stage by providing a very brief overview of the Industry 4.0 vision and some of its associated pillars. The paper then introduces the ideas underlying software-defined systems along with a basic architecture of software-defined cloud manufacturing. The paper concludes

Peer-review under responsibility of the scientific committee of the Changeable, Agile, Reconfigurable & Virtual Production Conference 2016
doi:10.1016/j.procir.2016.07.041

with a discussion of future work and long-term research objectives along with an outline of potential opportunities and challenges associated with software-defined manufacturing.

2. Industry 4.0 and Smart Manufacturing

Industry 4.0 is sometimes referred to as the 4th industrial revolution, and it is a vision of smart factories built with intelligent cyber-physical systems. It will enable manufacturing ecosystems driven by smart systems that have autonomic self-properties, for examples self-configuration, self-monitoring, and self-healing. Industry 4.0 will allow us to achieve unprecedented levels of operational efficiencies and accelerated growth in productivity. New types of advanced manufacturing and industrial processes revolving around machine-to-human collaboration and symbiotic product realization will emerge.

Industry 4.0 will encompass numerous technologies and associated paradigms. A few of these emerging paradigms include the Industrial Internet of Things, cloud-based manufacturing, and social product development. A brief overview of these paradigms is provided in the following sections.

2.1. Industrial Internet of Things

One of the most significant collections of technology that will contribute to Industry 4.0 and smart manufacturing is the Industrial Internet of Things (IIoT). The IIoT is a new revolution resulting from the convergence of industrial systems with advanced computing, sensors, and ubiquitous communication systems. It is a transformative event where countless industrial devices, both old and new, are beginning to use Internet Protocol (IP) communication technologies.

The Industrial Internet of Things is a subset of what we have come to know as the Internet of Things (IoT). The IoT is an abstract idea that captures a movement that started when we began integrating computing and communication technology into many of the “things” that we use at home and work. It started with the idea of tagging and tracking “things” with low cost sensor technologies such as radio frequency identification (RFID) devices. However, the paradigm shifted as the market began delivering low-cost computing and Internet-based communication technologies, simultaneously with the rise of the ubiquitous smartphone. This perfect storm of low cost computing and pervasive broadband networking has allowed the IoT to evolve. Now, the IoT includes all types of devices ranging from home appliances, light bulbs, automation systems, watches, to even our cars and trucks. Technically speaking, the IoT is a collection of physical artifacts that contain embedded systems of electrical, mechanical, computing, and communication mechanisms that enable Internet-based communication and data exchange.

The Industrial IoT follows the same core definition of the IoT, but the things and goals of the Industrial IoT are usually different. Fig. 1 illustrates the Industrial IoT at a simplified level. Some examples of the ‘things’ of the Industrial IoT include devices such as sensors, actuators, robots, manufacturing devices such as milling machines, 3D-printers, and assembly line components, chemical mixing tanks, engines, healthcare devices such as insulin and infusion pumps, and even planes, trains, and automobiles. Indeed, it is a vast spectrum of devices.

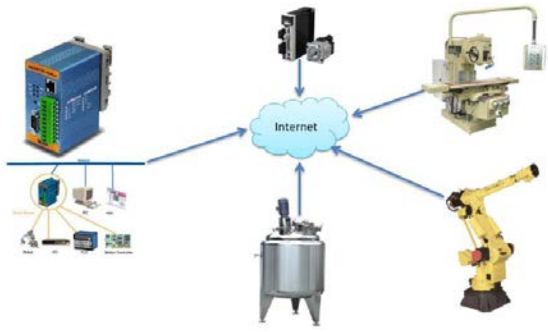

Fig. 1. Abstract idea of the Industrial Internet of Things.

Another term commonly used when discussing the Industrial IoT is operational technology. Operational technology (OT) refers to the traditional hardware and software systems found within industrial environments. Some examples include programmable logic controllers (PLC), distributed control systems (DCS), and human-machine interfaces (HMI). These systems are also known as Industrial Control Systems (ICS) because they “control” the various processes that occur within an industrial environment. These traditional control systems are rapidly beginning to use Internet-based communication technologies so that they can be integrated into manufacturing organizations’ information technology (IT) systems and infrastructures. This OT/IT integration movement is currently happening in large scale across numerous industries, and it provides a technological alignment with the needs of future smart manufacturing systems and Industry 4.0 [12,13].

2.2. Cloud-based Manufacturing

Cloud-based manufacturing (CBM) is another rising paradigm that will contribute significantly to the success of Industry 4.0. CBM can be described as a networked manufacturing model that exploits on-demand access to a shared collection of diversified and distributed manufacturing resources to form temporary, reconfigurable cyber-physical production lines which enhance efficiency, reduce product lifecycle costs, and allow for optimal resource allocation in response to variable-demand customer generated tasking [7-9]. Characteristics of CBM include networked manufacturing, scalability, agility, ubiquitous access, multi-tenancy and virtualization, big data and the IoT, everything-as-a-service (e.g., infrastructure-as-a-service, platform-as-a-service, hardware-as-a-service, and software-as-a-service), scalability, and resource pooling.

A similar paradigm to CBM has become known as cloud-based design and manufacture (CBDM) [4]. CBDM refers to a more comprehensive view of the product realization process whereby the eligible components of the overall system of design and manufacturing resources are integrated into cloud-computing model. CBDM was originally defined by Schaefer, Thames, et al. [4] as follows: “Cloud-Based Design and Manufacturing refers to a product development model that enables collective open innovation and rapid product development with minimum costs through social networking and crowd-sourcing platforms coupled with shared service pools of design and manufacturing resources and components.” Essentially, CBDM seeks to enhance cloud-based manufacturing by integrating it with cloud-based design along with the idea of social product development.

2.3. Social Product Development

The old model of the lone inventor is being replaced by a new model where different players in a network interact to bring new products to market. It has been established that innovation projects which are largely based on external developments have shorter development times and need less investment than similar projects based solely on internal research. All of these concepts point toward developing products through the use of a network of people, internal and/or external to a firm developing a product. This notion is referred to as Social Product Development (SPD) [10].

SPD is a relatively new concept in the world of product development. While the word means different things to different people, it can generally be described as the use of social computing technologies, tools, and media, influencing the product life cycle at any stage through the use of a defined and qualified crowd with the goal of enhancing the value of communication. Some of the tenants of Social Product Development are crowdsourcing, mass collaboration, open innovation, and cloud-based design and manufacturing. Social Product Development can be categorized into Web 2.0 and Enterprise 2.0 technologies, the distinction being whether the technologies are used to interface with internal (Web 2.0) or external (Enterprise 2.0) entities from the product development enterprise.

3. Software Defined Cloud Manufacturing

Industry 4.0 and smart manufacturing of the future will, indeed, take advantage of numerous Internet-based technologies and associated paradigms. Three such paradigms were described in the previous section. However, practitioners in the field are facing complexity challenges. For example, one interesting aspect of Industrial IoT devices is system complexity. In particular, Industrial IoT devices can contain systems of IoT systems. For example, an industrial robot as a whole might contain multiple sensors working both independently and as a group, and one or more of these sensors could control one or more actuators that, in turn, control the robot’s movement. Further, the sensors, actuators, and other parts of the robot can connect independently to an IP network with some centralized server that governs the overall control of the robot.

System complexity is not the only challenge. A few other challenges include management complexity associated with networked systems, software, configuration, compliance, and security.

On the other hand, if complexity can be controlled, Industry 4.0 systems such as the IIoT, CBM, and SPD can be harnessed to provide flexible, adaptive, and scalable manufacturing systems of systems, at least for certain domains of manufacturing. In order to achieve this, architectures, design principles, and system models must be introduced that address the complexities and system management challenges that will be faced by Industry 4.0 stakeholders. One possible research domain that can lead us to addressing this problem is that of Software-Defined Systems.

3.1. Software-Defined Systems

Recently, the information technology field has begun to utilize software defined systems. It is a new paradigm of thinking about hardware and software, largely enabled by inexpensive, highly-functional hardware and virtualization technologies. Technologies that have emerged within this domain include software-defined networking, software-defined storage, software-defined computing, software-defined data center, and software-defined radio.

Software-defined networking (SDN) is defined as the physical separation of the network control plane from the forwarding plane where a control plane controls several devices [6]. To understand the ramifications of this design, one must consider the paradigm it is replacing. Particularly, non-SDN networking devices are based on a design whereby each network device is totally isolated from the other devices in its network. Although it might coordinate and work with other devices, its so-called control plane is isolated to itself and its control plane functionality cannot be modified (outside of traditional patching, upgrades, etc.). With SDN, the control plane is managed centrally, it is defined by software, and it can apply to multiple devices. The idea is that network devices have “generic” hardware that does not require vendor-specific software, and the control plane functionality can be molded to fit a given design goal and can apply to multiple devices. SDN is known to be flexible, manageable, adaptive, and very cost-effective. It allows the control plane to be directly “programmable” instead of fixed software that is only “configurable”.

The software-defined supply chain is yet another emerging software-defined system recently described by Paul Brody [11]. Brody suggests that product design and manufacturing are changing, and the change is due to “emerging, maturing, and converging” technologies. Namely, Brody suggests that three particular technologies will reshape manufacturing. These technologies include 3D printing, next generation intelligent assembly robots, and open source hardware. Brody goes on to say that “Success in the future will require developing and adopting a new set of mental models, business processes, and enterprise technologies” [11].

3.2. A Software Defined Cloud Manufacturing Architecture

In general, software-defined systems are characterized by properties such as being agile, programmable, manageable, configurable, interoperable, adaptable, and protectable. Indeed, Industry 4.0 technologies and smart manufacturing systems can benefit from these characteristics. Consequently, in this section we propose a new Software-Defined Cloud Manufacturing (SDCM) architecture to achieve these characteristics for various Industry 4.0 systems. Our simplified SDCM architecture is illustrated in Fig. 2. In this architecture, we assume a large network of hardware and software elements that have Internet-based communication frameworks, i.e. a TCP/IP stack. The goal is to utilize elements that constitute an Industry 4.0 system such as an IIoT, CBM, or SPD or combination thereof.

An important aspect of the SDCM architecture is separation of concerns (SoC). SoC is a design principle that allows one to break extremely large and complex systems into manageable parts. For example, the world-wide Internet is based on the SoC design principle. Our proposed SDCM architecture is first broken into two planes: the Software Plane and the Hardware Plane. In the architecture's current state, we seek to distinguish the hardware elements from software elements. In particular, hardware does the final work whereas software will define how the work is orchestrated through to completion. The hardware plane includes a Distributed Hardware Layer (DHL). The DHL is further comprised of Distributed Hardware (DH) elements. For example, a DH could be a generic 3-D printer built on generic hardware from some particular maker community.

The software plane contains two layers, the virtual and control layers. The control layer is comprised of control elements (CE) and the virtual layer contains final user applications. Information flows are indicated by the arrows. The DHL communicates with the control layer and vice versa using an appropriate communication interface. Likewise, the virtual layer interfaces with the control layer.

Within each layer, multiple elements can be composed to create higher-level elements. As such, we define a software defined cloud manufacturing entity as a three-tuple $M = (V,C,D)$, where M is an SDCM entity, $V = \{a\}$, $C=\{ce\}$, $D=\{dh\}$. We say that V is a set representing an application composition, C is a set representing a control element composition, and D is a set representing a hardware composition. Particularly, our software defined cloud manufacturing model represents per-level element composition services that provide, in general, the capability to produce complex manufacturing services.

3.3. SDCM Workflow Scenarios

In this section, we will provide a short overview of how the proposed SDCM architecture will work in practice. A key functionality of SDCM is composition. At "runtime" applications, control elements, and distributed hardware elements are dynamically composed, and the composition depends on the overall SDCM service being provided.

Control elements are responsible for composition. Composition is initiated via an application's invocation (residing at the virtual layer). Controller elements are the core masterminds of a given SDCM service and contain the controller logic for composing the elements of the given service.

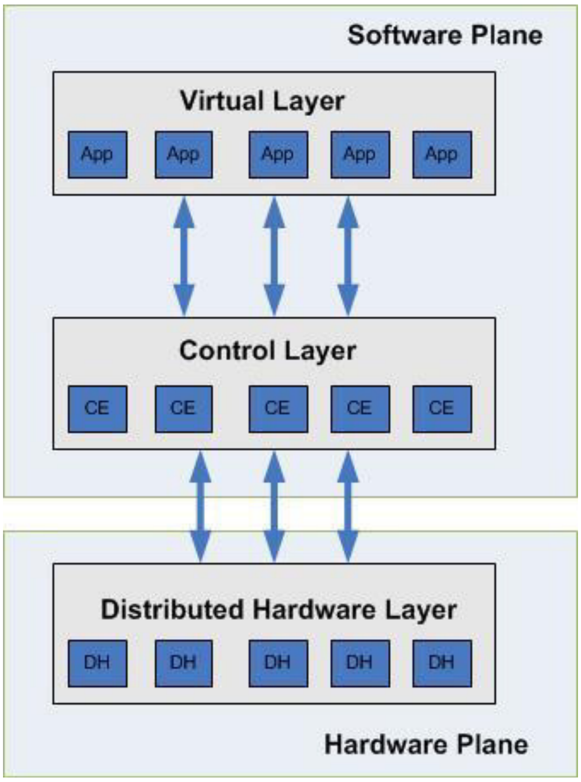

Fig. 2. A simplified software-defined cloud manufacturing architecture.

Composition of hardware elements can be achieved across a vast spectrum of scenarios. Here, we provide an overview of the ideas of this composition process at two opposite ends of the spectrum. On one end of this spectrum, we consider the idea of design and manufacturing hardware that might be found in domains such as open source hardware, DIY hardware, and maker spaces [14]. As Brody [11] suggests, 3D printing, next generation intelligent assembly robots, and open source hardware will have significant impact on future manufacturing processes. Open source hardware (and its associated open source software) will lead to fast and incremental updates to hardware platforms. This could be utilized by various manufacturing entities. One aspect of this scenario is the ability to reconfigure these hardware platforms based on a desired set of functionality; this is where SDCM comes in to the picture. Fig. 3 will be used to illustrate the ideas.

From Fig. 3, there is an open source hardware platform (OSHP) that contains 3 high-level components (C1, C2, and C3). This OSHP is considered to be a single hardware element (DHE). It has manufacturing capabilities that can be initiated via the composition of component C1 with component C2 or with component C2 and component C3. In this example, a controller element is in charge of uploading and installing firmware that configures the device based on the desired composition. After the firmware has been installed and initialized, a second control element loads a design file into the system and begins its particular manufacturing service.

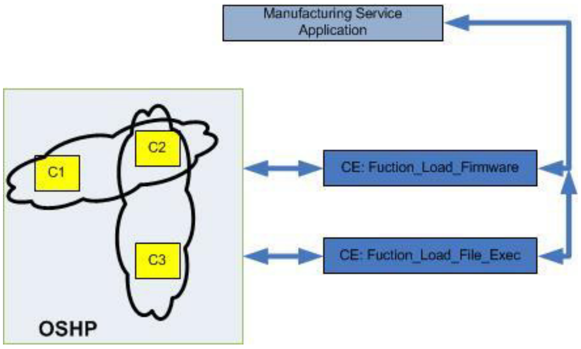

Fig. 3. An illustrated view of the SDCM workflow.

The previous example exploited the ideas of open source hardware of the near future where resources included within a given hardware platform can be composed to produce a certain type of manufacturing service. Further, it assumes that the platform could be reconfigured for different types of manufacturing services. Obviously, this will depend on the hardware platform and its internal resources. The workflow that is described, however, can be utilized at a different level of abstraction. This workflow provided by SDCM can be applied to multiple, independent hardware platforms. This abstraction is indeed a powerful aspect of SDCM. An equivalent workflow, for example, could be the composition of a manufacturing robot (i.e.,C1 is the robot) along with a 3D printer and CNC milling machine (C2 and C3, respectively). An SDCM manufacturing entity could be the composition of the robot and the CNC machine or the robot and the 3D printer. Controller elements and user interfaces (virtual applications) can be developed to implement a manufacturing service that utilizes these compositions to create some artifact. The artifact could in turn be designed by some cloud-based CAD program that is also brought in as a higher-order composition. For example, the CAD program can be yet another component in the total composition.

3.4. SDCM Summary

Smart manufacturing systems of the future, such as those envisioned by Industry 4.0, have the potential to reshape our design and manufacturing processes. To achieve its success, these future systems need to be agile, programmable, manageable, configurable, interoperable, adaptable, and protectable. In order to achieve these characteristics, new architectures, frameworks, and models will need to be investigated for this domain. In this section, we have proposed a simplified software-defined cloud manufacturing architecture inspired by the well-known characteristics of other existing software defined systems, and we have illustrated two potential SDCM workflow scenarios. These scenarios were given in order for the reader to better grasp the compositional aspects of the proposed SDCM architecture.

4. Conclusion and Future Work

Industry 4.0 will allow us to achieve unprecedented levels of operational efficiencies and accelerated growth in productivity. New types of advanced manufacturing and industrial processes revolving around machine-to-human collaboration and symbiotic product realization will emerge. However, complexity and management challenges need to be addressed in order to take full advantage of the many potential opportunities that Industry 4.0 and smart manufacturing can provide. In particular, architectures, frameworks, and models designed to tackle these complexity and management challenges need to be introduced and investigated. In this paper, we have introduced a simplified software-defined cloud manufacturing architecture. We believe the architecture, which was inspired by software-defined systems, can be utilized and expanded upon to address complexity challenges faced by various Industry 4.0 systems.

The notion of software-defined cloud manufacturing and our associated architecture are setting the stage for a new thread of research for the authors. Future work will be focused on further refining the operational aspects of the architecture's elements and measuring its effectiveness across characteristic parameters such as agility, interoperability, configurability, programmability, and protect ability. Future research will also investigate the architecture's ability to induce new types of cybersecurity for Industry 4.0 systems.

References

[1] Dazhong Wu, J. Lane Thames, David Rosen, Dirk Schaefer (2013): "Enhancing the Product Realization Process with Cloud-Based Design and Manufacturing Systems", ASME Journal of Computing & Information Science in Engineering (JCISE), Vol. 13, No. 4, 2013, Article #041004.

[2] J. Lane Thames (2014): "Distributed, Collaborative, and Automated Cybersecurity Infrastructures for Cloud-based Design and Manufacturing Systems", In: D. Schaefer (Ed.): Cloud-Based Design and Manufacturing (CBDM): A Service-Oriented Product Development Paradigm for the 21st Century, Springer International Publishing, pp. 207-229, ISBN 978-3-319-07398-9, DOI 10.1007/978-3-319-07398-9_8.

[3] J. Lane Thames, Randal Abler, Andrew Hyder, Robert Wellman, and Dirk Schaefer (2011): "Architectures and Design Methodologies for Scalable and Sustainable Remote Laboratory Infrastructures", In: Azad, Auer, and Judson (Eds.): Internet Accessible Remote Laboratories: Scalable E-learning Tools for Engineering and Science Disciplines, IGI Global Publishing, ISBN 978-1-61350-186-3, Chapter 13, pp. 254-275.

[4] Dirk Schaefer, J. Lane Thames, Robert Wellman, Dazhong Wu, Sungshik Yim, and David Rosen (2012): "Distributed Collaborative Design and Manufacture in the Cloud—Motivation, Infrastructure, and Education", ASEE 2012 Annual Conference & Exposition, San Antonio, Texas, June 10-13, 2012, Paper# AC2012-3017.

[5] Dazhong Wu, J. Lane Thames, David Rosen, and Dirk Schaefer (2012): "Towards a Cloud-Based Design and Manufacturing Paradigm: Looking Backward, Looking Forward", ASME 2012 International Design Engineering Technical Conference & Computers and Information in Engineering Conference (IDETC/CIE), Chicago, Illinois, August 12-15, 2012, Paper# DETC2012-70780.

[6] Open Networking Foundation (ONF), “Software-Defined Networking: The New Form for Networks”, April 2012.

[7] Wu D, Greer MJ, Rosen DW, Schaefer D. Cloud manufacturing: strategic vision and state-of-the-art. Journal of Manufacturing Systems, 2013.

[8] Li BH, Zhang L, Wang SL, Tao F, Cao JW, Jiang XD, et al. Cloud manufacturing: a new service-oriented networked manufacturing model. Computer Integrated Manufacturing Systems 2010;16(1):1–7.

[9] Xu X. From cloud computing to cloud manufacturing. Robot Computer-Integrated Manufacturing 2012;28(1):75–86.

[10] Anna Peterson, Dirk Schaefer: "Social Product Development: Introduction, Overview, and Current Status", In: D. Schaefer (Ed.): Product Development in the Socio-sphere: Game Changing Paradigms for 21st Century Breakthrough Product Development and Innovation, Springer International Publishing, pp. 63-98, ISBN 978-3-319-07403-0.

[11] Paul Brody (2013), “Get ready for software-defined supply chain”, Web: http://www.supplychainquarterly.com/topics/Manufacturing/20140110-get-ready-for-the-software-defined-supply-chain/

[12] Eric Knapp, Joel Langill (2015), Industrial Network Security: Securing Critical Infrastructure Networks for Smart Grid, SCADA, and Other Industriaal Control Systems, Second Edition, ISBN: 978-0-12-420114-9

[13] NIST Special Publication 800-82, (2011) “Guide to Industrial Control Systems (ICS) Security”, http://csrc.nist.gov/publications/nistpubs/800-82/SP800-82-final.pdf

[14] M. Hatch, (2014), “The Maker Movement Manifesto”, McGraw-Hill Education, ISBN-10: 0071821120