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Cyber-physical manufacturing cloud: Architecture, virtualization, communication, and testbed

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ABSTRACT

Cyber-physical systems are integrations of computation, networking, and physical processes and they are increasingly finding applications in manufacturing. Cloud manufacturing integrates cloud computing and service-oriented technologies with manufacturing processes and provides manufacturing services in manufacturing clouds. A cyber physical system for manufacturing is not a manufacturing cloud if it does not use virtualization technique in cloud computing and service oriented architecture in service computing. On the other hand, a manufacturing cloud is not cyber physical system if it does not have components for direct interactions with machine tools and other physical devices. In this paper, a new paradigm of Cyber-Physical Manufacturing Cloud (CPMC) is introduced to bridge gaps among cloud computing, cyber physical systems, and manufacturing. A CPMC allows direct operations and monitoring of machine tools in a manufacturing cloud over the Internet. A scalable and service-oriented layered architecture of CPMC is developed. It allows publication and subscription of manufacturing web services and cross-platform applications in CPMC. A virtualization method of manufacturing resources in CPMC is presented. In addition, communication mechanisms between the layers of the CPMC using communication protocols such as MTConnect, TCP/IP, and REST are discussed. A CPMC testbed is developed and implemented based on the proposed architecture. The testbed is fully operational in two geographically distributed sites. The developed testbed is evaluated using several manufacturing scenarios. Its testing results demonstrate that it can monitor and execute manufacturing operations remotely over the Internet efficiently in a manufacturing cloud.

1. Introduction

Cloud manufacturing (CMfg) is an integration of cloud and service computing with manufacturing processes [1,2]. The number of cloud manufacturing systems is increased due to the rapid research and development of CMfg. Cyber Physical Systems (CPS) are another paradigm, which integrates computation, networking, and physical processes and allows directly operating and monitoring physical devices over the Internet and finds applications in manufacturing too [3,4]. Hence, it is necessary to integrate cloud manufacturing and cyber physical systems for providing manufacturing services, which can directly operate and monitor machine tools in a manufacturing cloud. As a result, a new paradigm of Cyber Physical Manufacturing Clouds (CPMC) is introduced. A CPMC is a type of manufacturing clouds where machining tools can be directly monitored and operated over the Internet from clouds. Many existing manufacturing clouds provide manufacturing services and but do not allow their machining tools to be monitored and operated directly from the clouds. For example, Shapeways provide human-in-the-loop cloud manufacturing services [5]. They allow customers to order 3D printing services from a cloud, human operators manually operate 3D machines to perform manufacturing processes. It would be desirable to further automate manufacturing processes in manufacturing clouds by directly operating machining tools and monitoring their manufacturing processes with less human interventions. On the other hand, several cyber physical systems have been developed for manufacturing [6,7]. They allow direct operation and monitoring of machine tools over the Internet. But they are not manufacturing clouds with any virtualization methods and are not based on service-oriented architecture.

Several interesting research issues in CPMC need to be addressed. Firstly, a scalable service oriented architecture needs to be developed for CPMC. Secondly, virtualization of manufacturing resources needs to be investigated. Thirdly, communication mechanisms are needed to enable network communications among

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components of CPMC. There are many network enabled manufacturing tools in the existing manufacturing environments, but very few tools are utilized due to the lack of cyber-physical manufacturing clouds. Application scope of CPMC is widened by the recent developments of Industry 4.0 [8,9]. Therefore, the potential use of CPMC in manufacturing processes can significantly improve the use of underutilized network enabled manufacturing machines.

This paper presents a scalable service-oriented architecture of CPMC. It allows manufacturers to publish and subscribe web services for manufacturing operations and manufacturing applications to monitor and execute manufacturing operations remotely over the Internet. It also creates an open platform for the manufacturers and customers to develop rich Internet applications. Virtualization of manufacturing resources in CPMC is important due to the diversity and complexity of the manufacturing resources. The presented CPMC system virtualizes manufacturing tools by representing functionalities of machining tools using web services and other machining tool characteristics. Communications between layers of the layered architecture are critical due to the diversity of the technical characteristics of each layer. The communication mechanisms are developed using MTConnect, Transmission Control Protocol/Internet Protocol (TCP/IP), and REpresentational State Transfer (REST) protocol.

An operational testbed is implemented based on the layered architecture of CPMC. The testbed consists of two groups of manufacturing machines located in geographically distributed sites – the University of Arkansas (UARK), and the Missouri Institute of Science and Technology (MST). The testbed cloud is hosted in the network of UARK. These manufacturing machines are virtualized as REpresentational State Transfer based (or RESTful) web services and published using the service-publishing center in the cloud. Multiple manufacturing applications are developed using the published web services over platforms such as Web, iOS, and Android. An application center is developed to publish manufacturing applications. These published applications are ready to be subscribed and used for manufacturing. MTConnect protocol is used in the testbed to monitor manufacturing machines remotely over the Internet. MTConnect is a popular RESTful Internet communication protocol for collecting status information of the machine tools. By design, it supports read-only communication of the machines. Consequently, Transmission Control Protocol/Internet Protocol (TCP/IP) is used in order to operate the manufacturing machines.

This paper has four contributions: (1) design of a scalable and service-oriented layered architecture of CPMC; (2) development of a virtualization method of manufacturing resources for CPMC; (3) development of communication mechanisms for components of CPMC; and (4) implementation of a fully operational testbed of CPMC based on the architecture.

The next section in this paper presents related works. Section 3 discusses a scalable service-oriented architecture of the CPMC system. In addition, a virtualization method of the manufacturing resources and the communication mechanisms of the CPMC system are described in Section 3. Section 4 demonstrates the open platform for publishing applications and web services for manufacturing operations. This section also illustrates different workflows based on the roles of the participants in a CPMC system. In Section 5, a testbed of CPMC is presented and its efficiency is evaluated by multiple application scenarios. Section 6 and 7 discusses the results and concludes the research.

2. Literature survey

Cloud manufacturing is an emerging manufacturing paradigm. The concept of cloud manufacturing initially was introduced by Li Bo-hu and his team in 2010 [1]. Several researches have been conducted by them on the architecture of cloud manufacturing [10–13]. According to Esmaeilian et al., research in cloud manufacturing can be classified into three categories: studies focused on designing platform and data-sharing architecture, studies concentrated on resource allocation and management, and studies aimed at describing new business models and cloud manufacturing applications. The first group of studies describes the Information Technology (IT) systems requirement and data integration platforms [14]. Huang et al. [15] discussed an architecture of cloud manufacturing service platforms in small and medium-sized enterprises. Suo and Gao [16] illustrated how simulation software packages can be used to find the optimal configuration for cloud manufacturing service platforms. Zhang et al. [17] demonstrated an application of fiber optic sensing in improving the efficiency of cloud manufacturing service platforms. The paradigm of cloud manufacturing enables companies to expand their capabilities and have flexibility in scale depending on market demand. Helo et al. [18] described a limitation of current IT solutions in distributed manufacturing in a multi-layer supply chain and proposed a new cloud-based centralized software application, where a proper information-sharing infrastructure is provided between suppliers and other supply chain entities. Tao et al. [10] proposed a computing and service-oriented manufacturing model describing a ten-layer cloud-manufacturing architecture incorporating the regular manufacturing processes and applications. The architecture also provided important insights on the manufacturing machine virtualization. However, method of virtualizing the manufacturing machines were not discussed elaborately. In addition, the context of communication between layers were not described in the architecture description. Several other studies on cloud manufacturing were conducted. A high-level four-layer architecture of cloud manufacturing was proposed by Xu [2]. Numerous researchers provided surveys of cloud manufacturing [19–22]. A number of prototypes of cloud manufacturing were developed [23,24]. The above research efforts projects some progresses on scalable architecture of cloud manufacturing. However, the aforementioned researches do not address the unique needs of cyber-physical manufacturing clouds where manufacturing machines are operated and monitored directly from clouds based on an integration of the internet technologies, deeply embedded computing, automatic control and monitoring, and networked manufacturing.

The paradigm of cyber-physical systems has gained momentum in research and development [3,25–27]. Recently cyber-physical systems are finding applications in manufacturing [4,21,28]. A cyber-physical production system was introduced [28]. Wang et al. [29] presented a synopsis of the status of cyber-physical systems in manufacturing systems. In another study, Wang et al. [30] described what the system architecture and data-sharing infrastructure should be for controllability of cyber-physical systems on the cloud. Lee et al. [31] discussed an application of cyber-physical systems and smart algorithms in equipment maintenance. Cooper and Wachter [32] studied the application of cyber-physical systems for thermal modeling in the additive manufacturing processes. Seitz and Nyhuis [33] presented a learning factory idea and discussed the importance of cyber-physical systems for not only monitoring production, but also educating and training the employees in manufacturing. While the overall influence of cyber-physical systems as technological changeovers already has been discussed in the literature, current studies are still in the conceptual level stage [14].

Wang et al. [6] presented an integrated cyber-physical system for cloud manufacturing. It introduced an architecture of cyber physical system for cloud manufacturing with three tiers: control tier, view tier with a web interface, and model tier. Three case studies are provided: the first one is about remote monitoring and control in a mini robotic cell with one serial robot, the second one