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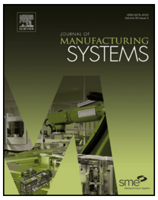

A systematic development method for cyber-physical machine tools

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ABSTRACT

Machine Tool 4.0 introduces a new generation of machine tools that are smarter, well connected, widely accessible, more adaptive and more autonomous. Cyber-Physical Machine Tools (CPMT), based on recent advancements of the Information and Communication Technology, provides a promising solution for Machine Tool 4.0. This paper proposes a systematic development method for CPMT. Generic system architecture is developed to provide guidelines for advancing existing Computer Numerical Control (CNC) machine tools to CPMT. The proposed architecture allows machine tool, machining processes, real-time machining data and intelligent algorithms to be deeply integrated through various types of networks. The development methodologies for the core of the CPMT, the Machine Tool Cyber Twin (MTCT), are studied and discussed in detail. MTCT enables different types of feedback loops among the physical world, the cyber space and humans to be realized. An MTConnect-based CPMT prototype is developed to validate the proposed CPMT. Experimental results have proved great interoperability, connectivity and extensibility of the proposed CPMT. The potential of implementing artificial intelligence in CPMT is also discussed.

1. Introduction

Machine tools are machines that are powered to cut, shape or finish metal or other rigid materials [1,2]. They are known as the "mother machines" since they enable the manufacture of other machines which produce virtually everything used in daily life. In the realm of manufacturing, machine tools have always been playing a crucial role in boosting productivity ever since their advent. Their performances directly affect the product quality as well as the production efficiency. The evolutionary history of machine tools has significantly affected the history of industrialization. As shown in Fig. 1, while industrialization can be briefly divided into four industrial revolutions, i.e. Industry 1.0 (mechanization, end of 18th century), Industry 2.0 (mass production, start of 20th century), Industry 3.0 (automation and IT, start of 1970s) and Industry 4.0 (Cyber-Physical Systems-based digitization, present time) [3]; the technological evolution of machine tools up to now can be correspondingly summarized as four stages, namely Machine Tool 1.0 (mechanically driven but manually operated, end of 18th century), Machine Tool 2.0 (electronically driven and numerically controlled, middle of 20th century), Machine Tool 3.0 (computer numerically controlled, late 20th century) and Machine Tool 4.0 (Cyber-Physical Machine Tools and cloud-based solutions, present time) [4]. The term "Machine Tool 4.0" stands for a new technological evolution of machine tools which is currently in progress triggered by the recent advancements in Cyber-Physical Systems (CPS), Internet of Things (IoT) and cloud-based solutions. In general, Machine Tool 4.0 defines a new generation of machine tools that are smarter, well connected, widely accessible, more adaptive and more autonomous [5].

Recent advancements in Information and Communication Technology have attracted more and more attention in the domain of manufacturing. As a result, research on Cyber-Physical Production Systems (CPPS) [6], IoT-enabled manufacturing systems [7,8] and Cloud Manufacturing [9,10] have been extensively studied in recent years. Although these topics differ from one another in terms of technological focus, implementation strategy, system framework and so forth, a common trend in the development strategy for manufacturing systems has been clearly indicated – the deep integration of the cyber/virtual world and the physical manufacturing devices. Previous research in this area mainly focused on the development of CPS-based manufacturing systems in terms of the design principles [6,11], system frameworks [12] and implementation strategies [13,14], few studies on the development of CPS-based machine tools have been done. Owing to the unique and essential role that machine tools are playing in any manufacturing system, as we step into the new era of Industry 4.0, current machine tools must be advanced to a higher level of intelligence, autonomy and connectivity, i.e. Machine Tool 4.0. Due to the lack of a systematic development method for CPS-based machine tools in the new era of Machine Tool 4.0, Cyber-Physical Machine Tools (CPMT) is proposed to bridge the research gap [5]. CPMT refers to the

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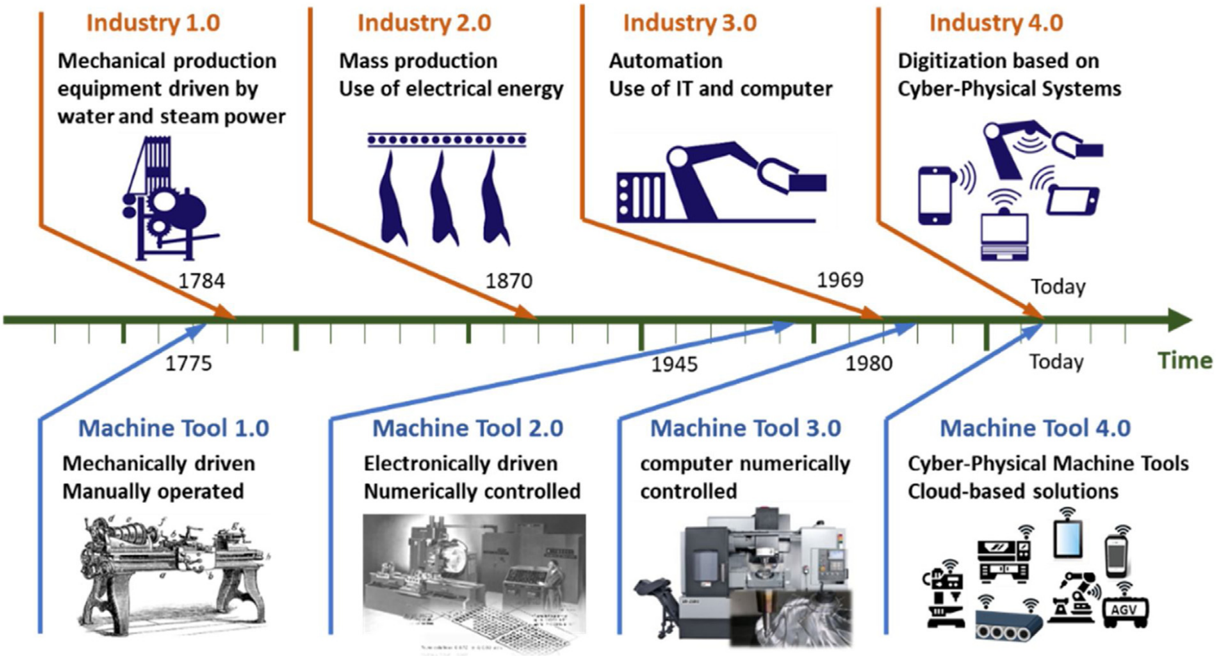

Fig. 1. Evolutionary history of industrialization and machine tools.

integration of the machine tool, machining processes, computation and networking, where embedded computations monitor and control the machining processes, with feedback loops in which machining processes can affect computations and vice versa [4]. With CPS technology deeply implemented, CPMT has distinct advantages in comparison with traditional machine tools. On one hand, embedded computations take full advantage of the real-time manufacturing data, providing efficient decision-making support for humans, meanwhile endowing CPMT with advanced intelligence and autonomy. Consequently, machining performance and efficiency can be significantly improved. On the other hand, ubiquitous networking and advanced connectivity enable the servitization of CPMT, hence CPMT becomes product-service systems [15] as well as cloud manufacturing resources [16] that provide significant benefits for both the machine tool manufacturers and the users.

This paper proposes a systematic development method for CPMT. Generic system architecture for CPMT is developed. The key components and functions included in a typical CPMT are proposed and explained. The proposed CPMT architecture provides guidelines for advancing existing CNC machine tools to CPMT. The development methodologies for the Machine Tool Cyber Twin, the core of a CPMT, are studied and discussed to provide directions for future research. An MTConnect-based CPMT prototype developed in our lab is introduced. The experimental results validated the feasibility and advantages of the proposed CPMT. The remainder of this paper is organized as follows. Section 2 provides an overview of the state-of-the-art work related to the development of CPMT in both academia and industry. Section 3 introduces the generic system architecture for CPMT. Section 4 studies and discusses the development methodologies of each key component of the Machine Tool Cyber Twin. Section 5 introduces an MTConnect-based CPMT prototype developed in our lab. Section 6 concludes the paper and provides directions for the future work.

2. State of the art

Although there have been few studies on the generic development methods for CPS-based machine tools, the effort to make machine tools more flexible, adaptable and intelligent has never stopped. The development and implementation strategies of intelligent CNC machining systems have been a topic if research for some time. Cheng et al. [17] developed an intelligent CNC system to improve the intelligence and communication ability of conventional NC machine tools under the distributed network manufacturing mode. The system comprised a tool monitoring module, a mechanical actuator error compensation module, an intelligent control module and a communication module. Aiming at improving the intelligence of machine tools, Kim et al. [18] proposed an agent-based knowledge evolution system in the machine-to-machine environment. A sensory agent, a dialogue agent and a decision support agent were developed to autonomously gather knowledge, produce knowledge and make decisions during machining processes. Work-offset compensation and recommendation of cutting condition based on thermal change were performed on a tapping machine to verify the proposed system. In order to achieve the intelligent control of production processes, Zhang et al. [14] proposed a data-driven add-on CPS architecture of a CNC machine tool. Three key issues of the configuration design of the add-on CPS system were studied, i.e., node configuration of the add-on cyber-physical system, interconnection technology of the heterogeneous nodes and data-driven adaptive configuration method of the sensor networks. Ridwan and Xu [19] developed an intelligent machine condition monitoring system that allows machining parameter optimization before, during and after machining to shorten machining time and increase product quality. Real-time cutting power, vibration and feed-rate data collected using different sensors were streamed in MTConnect format and fuzzy logic was utilized to realize autonomous in-process feed-rate optimization. Morgan and O'Donnell [20] presented the design and development of a reconfigurable, flexible and extensible CPS monitoring system for machine tools. An advanced signal processing chain was developed to realize the semi-autonomous process characterization of a CNC turning machine tool. Atluru et al. [21] proposed a system framework for a smart machine supervisory system which integrates individual process monitoring and control modules to realize a globally optimal machining solution. The communication mechanism of the system was based on

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