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Cyber-Physical Machine Tool – the Era of Machine Tool 4.0

Chao Liu, Xun Xu*

Department of Mechanical Engineering, University of Auckland, Auckland, 1010, New Zealand

* Corresponding author. Tel.: +64 9 373 7599; fax: +64 9 373 7599. *E-mail address:* xun.xu@auckland.ac.nz

Abstract

In the past five years, several industrial initiatives such as “Industry 4.0”, “Industrial Internet of Things”, “Factories of the Future” and “Made in China 2025”, have been announced by different governments and industrial leaders. These initiatives lead to an urgent need to advance current manufacturing systems into a high level of intelligence and autonomy. As the main component of any manufacturing system, machine tools have evolved from manually operated machines into the current computer numerically controlled (CNC) machine tools. It is predicted that current CNC machine tools are not intelligent and autonomous enough to support the smart manufacturing systems envisioned by the aforementioned initiatives. Inspired by recent advances in ICT such as Cyber-Physical Systems (CPS) and Internet of Things (IoT), this paper proposes a new generation of machine tools, i.e. Machine Tool 4.0, as a future development trend of machine tools. Machine Tool 4.0, otherwise known as Cyber-Physical Machine Tool (CPMT), is the integration of machine tool, machining processes, computation and networking, where embedded computers and networks can monitor and control the machining processes, with feedback loops in which machining processes can affect computations and vice versa. The main components and functions of a CPMT are presented. The key research issues related to the development of CPMT are identified and discussed. A three-layer CPMT-centered Cyber Physical Production System (CPPS) is proposed to illustrate both the vertical integration of various smart systems at different hierarchical levels and the horizontal integration of field-level manufacturing facilities and resources.

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Keywords: Machine tool 4.0; Cyber-Physical Machine Tool; Cyber Physical Production System;

1. Introduction

In the past five years, several industrial initiatives such as “Industry 4.0”, “Industrial Internet of Things”, “Factories of the Future” and “Made in China 2025”, have been announced by different governments and industrial leaders. Although the technological focus and implementation strategy of these initiatives may differ from one another, they have indicated that a new industrial revolution is currently happening. While previous industrial revolutions were triggered by the invention of mechanical manufacturing facilities (end of 18th century), the introduction of electrically-powered mass production (start of 20th century) and the intensive utilization of electronics and Information Technology (IT) (start of 1970s), respectively, the new industrial revolution that we are experiencing is predicted to be based on the advances of Information and Communication Technology (ICT) such as Cyber-Physical Systems (CPS), Internet of Things (IoT) and cloud computing [1].

Recently, Reference Architectural Model Industry 4.0 (RAMI 4.0) [2] was developed to provide a guideline for the interdisciplinary Industry 4.0 technologies. RAMI 4.0 illustrates the connection between IT, manufacturers/plants and product life cycle through a three-dimensional space. A new concept named “Industry 4.0 component” [3] was also proposed to complement RAMI 4.0 in connecting products, equipment and processes. Industry 4.0 component comprises physical objects and the Administration Shell (a virtual representation of the physical object and describes its functionalities). The integration of RAMI 4.0 and Industry 4.0 component bridges the gap between standards and Industry 4.0 technologies at the production level, giving rise to Cyber-Physical Production Systems (CPPS). CPPS are envisioned as the next generation production systems in which CPS monitor

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the physical processes, create virtual counterparts of the physical objects, make decentralized decisions with embedded intelligence and autonomously communicate and cooperate with each other as well as with humans in real time [4].

Machine tools have a hand in virtually everything that is manufactured and they no doubt play a unique and essential role in any CPPS. The development of machine tool technologies from the late 19th century up to the present time has, to a large extent, mirrored that of industrial revolution. The significance of such development affirms the claim that machine tools are the ubiquitous instruments of modern manufacturing. They have long occupied an iconic position in debates about industrial modernization. In light of the new era of industrialization and the important role that machine tools play, the need to advance machine tools to a new level that accords to the concept of Industry 4.0 has to be recognized and addressed urgently. In fact, like the industrializations as described above, machine tools have also gone through three stages of technological advancements. As we step into the era of Industry 4.0, so do we to the age of Machine Tool 4.0 (or MT 4.0).

This paper proposes a new generation of machine tools as a future development trend. MT 4.0 gives rise to Cyber-Physical Machine Tool (CPMT), which serves as a key enabler for CPPS. The rest of this paper is organized as follows: Section 2 gives a review of the historical evolution of machine tools from MT 1.0 to MT 4.0; Section 3 introduces the proposed CPMT, including the definition, main components and characteristics; In Section 4, the key research issues related to the development of CPMT are identified and discussed; A three-layer CPMT-centered CPPS is proposed in Section 5; Section 6 concludes the paper.

2. From Machine Tool 1.0 to Machine Tool 4.0

Machine tools came into being when the tool-path first became guided by the machine itself, in replacement of direct and freehand human guidance of the tool-path. Figure 1 shows the evolution of machine tools from MT 1.0 to MT 4.0.

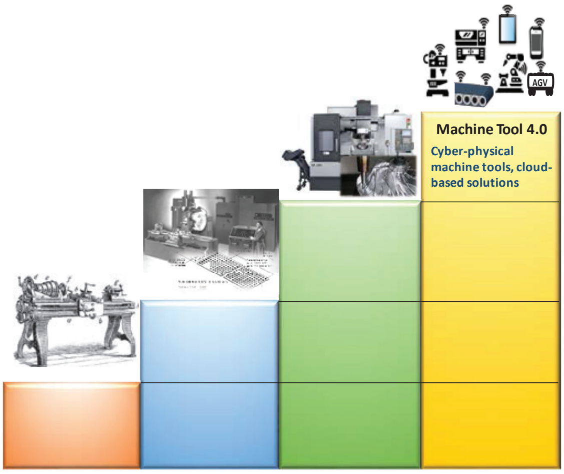

Fig. 1. From Machine Tool 1.0 to Machine Tool 4.0

2.1. Machine Tool 1.0 (1775-1945)

While it is true that certain machine tools existed long before the Industrial Revolution, there is no doubt that the development of machine tools as we know them today is closely linked to the first several decades of the Industrial Revolution, namely from the late 1700s to early 1800s. The first machine tools offered for sale (i.e. commercially available) were constructed in England around 1800. During this time, both Maudslay and Whitworth were responsible for dramatically advancing the accuracy of the machine tools [5]. With these new machine tools, the decades-old objective of producing interchangeable parts was finally realized. In the early 20th century, automobile manufacture dominated machine tool development in that the automotive industry pushed for a rapid progress of standardization and the advances of machine tool design and construction. Machine tools up till this time were mostly manually operated with some form of mechanical assistance for high precision machining. These tools still required a great deal of skill and experience from the operator.

2.2. Machine Tool 2.0 (1945-1980)

Since the late 1940s, machine tools had experienced a significant advancement in motion actuation and control, i.e. the development and deployment of numerical control (NC), and the gradual shift from mechanical to electronic actuations in general. The first NC machines were designed for manual or fixed cycle operations at the Massachusetts Institute of Technology in the late 1940s [6]. These machines had numerical control systems added, but only for numerical control on positioning the workpiece relative to the tool. Considerable time was saved, yet the operator had to select the tools, speeds and feeds. Later, the enhanced NC machines enabled material removal to occur at the same time as control of the workpiece/tool movements. These NC machines were also termed tape-controlled machines, because the information was stored on either punched card/tape or magnetic tape [7]. It was cumbersome to edit the programs at the machine; the machines had only very limited memory capacity. Nevertheless, in comparison with the conventional manually-operated machine tools, the advantages of NC machine tools are multiple. Savings were made in manpower, machining time, cutting tools and some accessories. NC machine tools also helped improve product quality and cut down rejects.

2.3. Machine Tool 3.0 (1980-)

The advancement of computers, in particular around the 1970s, eventually resulted them being used in assisting NC machines, hence the birth of Computer Numerical Control (CNC) machine tools [8]. In a CNC machine, a microcomputer stores machining programs that are prepared beforehand and controls the operation of the machine. Typically, a CNC system contains a machine-control unit (MCU) and the machine tool itself. MCU is further divided into two elements: the data-processing unit (DPU) and the control-loop unit (CLU). The DPU processes the coded data and passes information on position in each axis, direction of motion, feed, and auxiliary function control signals to the CLU. The CLU operates the drive mechanisms of the machine, and receives feedback signals about the actual position and velocity on each axis.

Introduction of CNC machines radically changed the landscape of manufacturing. Curves are as easy to cut as straight lines; complex 3-D structures are relatively easy to produce; and the number of machining steps that require human action is dramatically reduced. CNC automation also allows for more flexibility in the way that part programs for different components can be quickly produced and executed on a single machine tool. The significance of CNC machines in fact goes much further beyond machines themselves. Several CNC machines can be tied together and/or controlled via a central computer to perform coordinated machining processes. This gives rise to Direct Numerical Control (DNC) [9]. CNC machines also brought manufacturing much closer to the component design processes (i.e. CAD) by tools such as computer-aided process planning (CAPP) and computer-aided manufacturing (CAM). For the first time, integration of design and manufacturing became a possibility [10].

2.4. Machine Tool 4.0

Throughout the evolution process of machine tools from MT 1.0 to MT 3.0, efforts to make machine tools faster, more accurate, reliable, flexible and safer have never stopped. Today's machine tools have also become more economical and resource-efficient [11]. Machining centers continue to offer more functions [12]. Technologies for machine tool components (e.g. bearing, spindle unit, control unit and drivers) have also contributed to the continued technological enhancement of machine tools [13,14]. Nevertheless, as we step into the era of Industry 4.0, an urgent need to advance current CNC machine tools to a higher level of connectivity, intelligence and autonomy, has also been raised.

Machine Tool 4.0 defines a new generation of machine tools that are smarter, well connected, widely accessible, more adaptive and more autonomous. MT 4.0 features an extensive implementation of CPS, IoT and cloud computing technologies in CNC machine tools. With MT 4.0, vertical and horizontal integration in production systems becomes possible. Machine tools will no longer exist as a piece of isolated manufacturing equipment; they are service and solution providers. MT 4.0 gives rise to the Cyber-Physical Machine Tool, which serves as a key enabler for the envisioned CPPS.

3. Cyber-Physical Machine Tool

Inspired by recent advances in ICT such as CPS, IoT and cloud computing, we propose a new generation of machine tools – Cyber-Physical Machine Tools – as a promising development trend of machine tools in the era of MT 4.0.

3.1. Definition

CPMT is the 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.

CPMT is an application of CPS in the manufacturing environment. It shares the common features with typical CPS, including network connectivity, adaptability, predictability, intelligence, with real-time feedback loops and with humans in the loop. More specifically, real-time data generated by machine tool and machining processes are captured using various sensors, data acquisition devices and cameras. Together with the feedback from the CNC controller, these real-time data from the physical world are transferred into the cyber space through various networks to build a Cyber Twin of the machine tool. The Machine Tool Cyber Twin (MTCT), as a digital abstraction of the machine tool, has built-in computation and decision-making which monitor and control the physical components and processes and provide the data to the cloud for further analysis.

3.2. Components and functions

As shown in Figure 2, the proposed CPMT consists of four main components: (1) CNC Machine Tool, (2) Data Acquisition Devices, (3) MTCT, and (4) Smart Human-Machine Interfaces (HMIs).

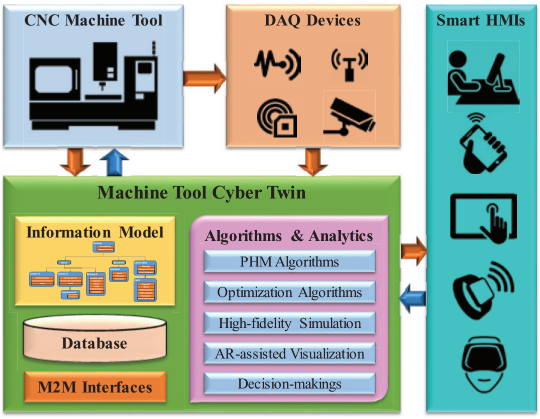

Fig. 2. Components and functions of Cyber-Physical Machine Tool

(1) CNC Machine Tool: The CNC machine tool refers to the physical CNC machine tool including all components and subsystems, as well as the machining processes. The machine tool receives machining tasks from the CNC controller and performs machining operations.

(2) Data Acquisition Devices: Data acquisition devices include various types of sensors (e.g. power meters, dynamometers, accelerometers, AE sensors, temperature sensors, etc.), cameras, RFID tags and readers, signal processing devices, and so forth. Data acquisition devices are responsible for collecting real-time field-level manufacturing data from the critical components and machining processes

such that important real-time manufacturing data generated during machining processes can be recorded and analyzed in the next stages.

(3) Machine Tool Cyber Twin: The most significant difference between a CPMT and a traditional CNC machine tool lies in the Machine Tool Cyber Twin. MTCT is a digital model of the physical machine tool with embedded computational capabilities. It functions as the brain of the machine tool, takes full advantage of the real-time data collected from the physical world and endows the physical machine tool with intelligent and autonomous functionalities. MTCT comprises four main components: a) Information Model, b) Database, c) Intelligent Algorithms and Analytics, and d) Machine-to-Machine (M2M) Interfaces.

- The Information Model comprehensively represents both the structure of the machine tool and the real-time status of each critical component by taking full advantage of the real-time data coming from the Data Acquisition Devices.
- The Database records all the important historical information of the machine tool, making it available for further analysis both locally and in the cloud.
- Intelligent algorithms and analytics transform the data coming from Data Acquisition Devices into meaningful information and offer various intelligent and autonomous functions, such as Prognostics and Health Management (PHM), machining optimization and Augmented Reality (AR)-assisted process visualization. Intelligent algorithms and analytics make the machine tool more adaptive to the changing machining conditions.
- M2M Interfaces allow the MTCT to semantically communicate with the Cyber Twins of other field-level devices (robots, AGVs, workpieces, etc.). Embedded algorithms enable the physical objects in the manufacturing system to monitor and control each other, leading towards an autonomous-cooperative manufacturing environment.

(4) Smart Human-Machine Interfaces: With extensive real-time data and computations deeply integrated with machining processes, CPMT requires Smart HMIs that allow users to intuitively interact with the system and make efficient decisions. Smart HMIs should provide users with ubiquitous access to the data and functions offered by MTCT. PCs, tablets, smart phones and wearable devices are all able to become smart HMIs with the implementations of various network and interaction technologies.

4. Key research issues

The key research issues related to the development of CPMT are identified and discussed in this section, intending to provide future research directions in this area.

4.1. Real-time manufacturing data acquisition

During machining processes, each component and subsystem of the machine tool generates large amounts of real-time data. Some of the data have significant influence on the product quality, productivity and cost efficiency. Collecting these data is the prerequisite for all the subsequent functionalities of the CPMT.

Although modern CNC controllers could directly provide some useful feedback data (e.g. spindle speed, axes position, etc.), some critical data that severely affect the manufacturing processes such as tool/workpiece/machine vibration, temperature, cutting force, etc. can only be acquired by deploying additional sensors [15]. With the rapid development of sensing technology, various sensors (e.g. force/torque, accelerometers, acoustic emission, motor power and current sensors, etc.) are available for extracting different data from the machine tool. However, identification of appropriate data sources and implementation of reliable, accurate and efficient sensing technologies in the real manufacturing environment still remains a great challenge. A summary of real-time data acquisition technologies regarding process monitoring can be found in [16].

4.2. Data integration and communication

Although different data acquisition technologies could be implemented to acquire data from various data sources, the meaning, wording, units and values of those data usually vary from machine to machine and device to device. This complexity makes the data integration, management and exchange in the CPMT a challenging task. There is an urgent need for a unified data exchange standard for the field-level manufacturing devices.

Currently, MTConnect and OPC-UA are both striving to address this issue. MTConnect is a lightweight, open, and extensible protocol designed for the exchange of data between shop floor equipment and software applications [17]. OPC-UA is an open and royalty free set of standards designed as a universal factory floor communication protocol developed by the OPC Foundation [18]. MTConnect and OPC-UA both have their pros and cons. MTConnect provides a bottom-up strategy which makes it easy to be implemented. However, it is currently a read-only standard, which means it is only able to be used in reading data from the devices, but not writing to them. On the other hand, OPC-UA is a bidirectional standard which is able to be used for both monitoring and controlling. However, a lot of effort has to be spent on building the application-specific information models, which usually makes the implementation of OPC-UA complex and inefficient. Extensive efforts from both academia and industry still need to be made to address this issue.

4.3. Intelligent algorithms and analytics

Even with extensive data gathered from field-level devices, intelligent algorithms and data analytics methods have to be developed to take full advantage of these data. These intelligent algorithms and analytics need to be embedded into the MTCT to endow the physical devices with advanced autonomous functionalities and decision-making capabilities.

Research in this area has always been active. To shorten machining time and increase product quality, Ridwan et al. [19] developed a Fuzzy logic algorithm that allows in-process feed-rate optimization. Kadir et al. [20] developed a System Manager algorithm to achieve high-fidelity machining simulation by the utilization of STEP, STEP-NC and real-time monitoring data. A comprehensive review of PHM methodologies and techniques can be found in [21]. Although a lot of work has been done in this area, the industrial big data generated by field-level devices still require a major research effort in developing effective, accurate and reliable algorithms and data analytics methods in order to provide the machine tool with real intelligence.

4.4. M2M communication

Generally, M2M refers to the communications among computers, embedded processors, sensors, actuators, and mobile terminal devices without or with limited human intervention [22]. In the proposed CPMT, M2M communications include the communications between the machine tool and other field-level devices, for example robots, AGVs, workpieces, and so forth. M2M interfaces should allow the machine tool to exchange information with other devices so that they can actively monitor and control each other.

Research on M2M communication is still at the preliminary stage. Developing M2M interfaces for the proposed CPMT is a crucial and challenging task.

4.5. Advanced Human-Machine Interactions

Although it is important to endow the physical devices with intelligence and autonomy, CPMT is not gravitating towards an unmanned system. In effect, with extensive real-time data and computations deeply integrated with machining processes, CPMT allows advanced human-machine interactions. Smart, mobile, networked and context-sensitive HMIs need to be developed to provide users with: (1) comprehensive and intuitive perception of the CPMT, (2) ubiquitous access to the real-time information and applications, as well as (3) instant and distributed decision-making support. PCs, Smart phones, tablets and wearable devices can play an important role in this situation.

Recently, AR, as a novel human-computer interaction technology that overlays computer-generated virtual information on the real world environment [23], is attracting more and more attention in manufacturing. AR-enabled process monitoring [24] and AR-assisted machining simulation [25] have shown great advantages and potentials in improving human-machine interactions. AR will be a key enabling technology for human-machine interactions in the proposed CPMT.

5. CPMT-centered CPPS

5.1. System architecture

The aim of developing CPMT is to promote the realization of CPPS. To illustrate the feasibility and functionalities of the proposed CPMT, a CPMT-centered CPPS is proposed as shown in Figure 3. The CPPS comprises three layers: Physical Level, Cyber Space and Service Cloud.

(1) Physical level: The Physical Level contains all the physical elements involved in the manufacturing system including the machine tools and its components, the cutting tools, the workpieces, the industrial robots, the AGVs, and various data acquisition devices. Critical objects which may generate valuable data during the manufacturing processes (such as the spindle of the machine tool, the cutting tools, the workpieces, etc.) are equipped with sensors and actuators so that real-time data from the Physical Level can be collected and the assigned tasks can be executed.

(2) Cyber space: The Cyber Space is a networked space comprised of interconnected Cyber Twins of the critical objects. Similar to the MTCT, each Cyber Twin in the Cyber Space represents a digital abstraction of its physical counterpart. On the one hand, embedded algorithms and analytics take advantage of the real-time data collected from the Physical Level such that the Cyber Twins can monitor and control its physical counterpart with intelligent and autonomous functions. On the other hand, M2M interfaces allow the Cyber Twins to communicate with each other, thus enabling autonomous cooperation between field-level manufacturing devices. In addition, the Cyber Twins record the historical information of their physical counterparts and provide them to the cloud through various networks so that further analysis and value-added services can get direct access to the field-level manufacturing data.

(3) Service cloud: The Service Cloud contains various software applications provided by different equipment manufacturers and third-party service providers. For example, machine tool manufacturers may provide machining optimization service for their machine tool users; cutting tool manufacturers may offer tool wear prediction service for their cutting tool users; third-party software developers may provide Enterprise Resource Planning applications for enterprise managers. These applications reside in the Service Cloud. They are able to access the information in the Cyber Space through the networks. Smart HMIs enable these services to be accessed through various types of interactions from anywhere. Users can request specific services based on their requirements and pay based on usage.

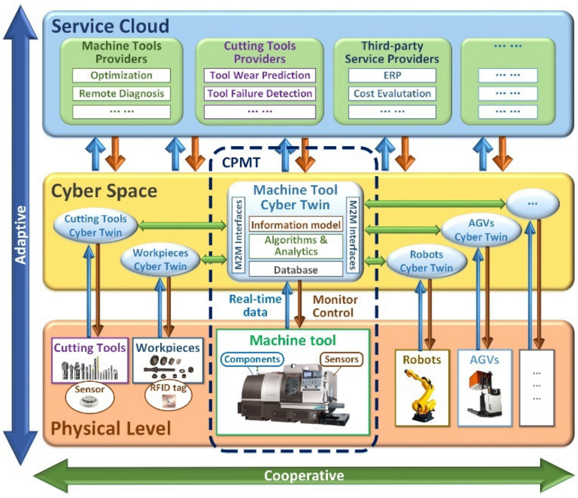

Fig. 3. System architecture of CPMT-centered CPPS

5.2. Vertical integration and horizontal integration

The proposed system architecture allows the CPMT-centered CPPS to realize two dimensional integrations of a manufacturing system, i.e. vertical integration and horizontal integration. Vertical integration refers to the integration of the various smart systems at different hierarchical levels of a manufacturing system (e.g. components, actuators and sensors in the device level, controllers and PLCs in the control level, and data analytics and production planning applications in the ERP level). Horizontal integration refers to the integration of machine tools with other field-level manufacturing facilities and resources (e.g. robots, AGVs and other machine tools).

The vertical integration endows the CPPS with adaptiveness. The Cyber Twins acquire real-time data of their physical counterparts, monitor and control them with the aid of various algorithms and data analytics tools, making the field-level devices semi-autonomous. In the meantime, real-time data from the shop floors can be effectively accessed by the applications in the service cloud so that high-level business planning activities can be integrated with field-level production activities. The horizontal integration, on the other hand, endows the CPPS with autonomous cooperation capabilities. The Cyber Twins communicate with each other through M2M interfaces, monitor and control each other based on specific algorithms and the real-time data they obtained from the real world. In this way, the field-level devices autonomously cooperate with each other, thus a significant reduction of the required human effort can be realized.

The combination of vertical integration and horizontal integration in the CPPS leads to improved product quality, increased productivity and reduced production cost.

6. Conclusions

At the dawn of the new industrial revolution, several industrial initiatives have clearly indicated an urgent need to advance current manufacturing systems into a high level of intelligence and autonomy, i.e. CPPS. As the key element of any production system, machine tools are expected to make step-changes to the so-called Machine Tool 4.0. MT 4.0 defines a new generation of machine tools that are smarter, well connected, widely accessible, more adaptive and more autonomous. Inspired by recent advances in ICT such as CPS, IoT and cloud computing, a new generation of machine tools, i.e. Cyber-Physical Machine Tools, is proposed as a promising development trend of machine tools in the era of MT 4.0. A three-layer CPMT-centered CPPS is proposed to illustrate both the vertical integration of various smart systems at different hierarchical levels and the horizontal integration of field-level manufacturing facilities and resources.

Machine Tool 4.0 is set to transform a machine tool from a physical production commodity to a product service system and cloud resource. This new generation of machine tools requires a collective effort from the machine tool manufacturers, users and researchers to define a roadmap for technology development and a strategy for industry implementation.

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