A systematic development method for cyber-physical machine tools

Article *in* Journal of Manufacturing Systems · February 2018

DOI: 10.1016/j.jmsy.2018.02.001

4 authors, including:

Chao Liu
University of Auckland
11 PUBLICATIONS **81** CITATIONS
SEE PROFILE

Ray Y. Zhong
The University of Hong Kong
117 PUBLICATIONS **1,558** CITATIONS
SEE PROFILE

Xun Xu
University of Auckland
326 PUBLICATIONS **5,384** CITATIONS
SEE PROFILE

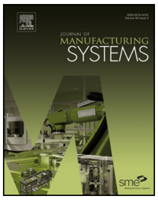
G Model
JMSY-638; No. of Pages 12
ARTICLE IN PRESS

Journal of Manufacturing Systems xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Journal of Manufacturing Systems

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



A systematic development method for cyber-physical machine tools

Chao Liu, Hrishikesh Vengayil, Ray Y. Zhong, Xun Xu*

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

ARTICLE INFO

Article history:
Received 30 November 2017
Received in revised form 21 January 2018
Accepted 2 February 2018
Available online xxx

Keywords:
Machine tools
Machine tool 4.0
Cyber-physical systems
Cyber twin
MTConnect

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

---

* Corresponding author.
E-mail address: xun.xu@auckland.ac.nz (X. Xu).

https://doi.org/10.1016/j.jmsy.2018.02.001
0278-6125/© 2018 Published by Elsevier Ltd on behalf of The Society of Manufacturing Engineers.

Please cite this article in press as: Liu C, et al. A systematic development method for cyber-physical machine tools. J Manuf Syst (2018), https://doi.org/10.1016/j.jmsy.2018.02.001

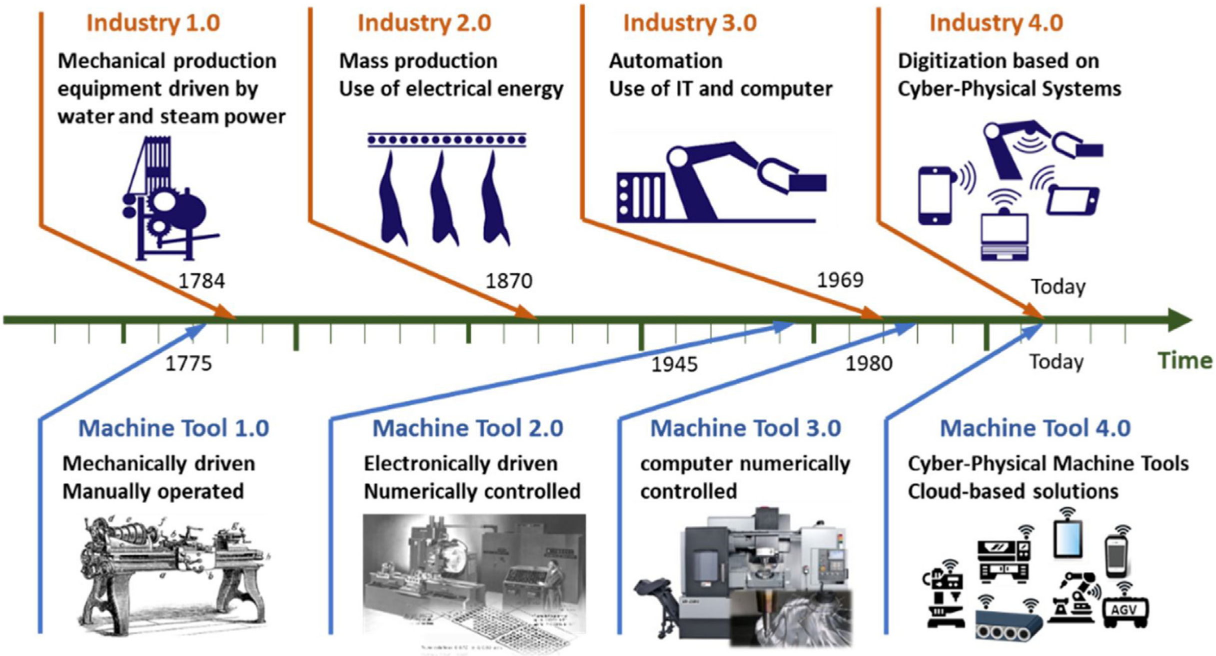


Fig. 1. Evolutionary history of industrialization and machine tools.

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

Please cite this article in press as: Liu C, et al. A systematic development method for cyber-physical machine tools. J Manuf Syst (2018), https://doi.org/10.1016/j.jmsy.2018.02.001

MTConnect protocol. The decision-making mechanism of the system was demonstrated through a LabView application which integrates process planning, health monitoring and tool condition monitoring. Focused on data-sharing capabilities, Li et al. [22] developed an intelligent CNC machining system consisted of a shared machining parameters database, an open and high-performance CNC system, an online monitoring module, a parameters optimization module, an energy efficiency analysis module and a machine tool health diagnosis platform.

Practitioners from industry are also making significant efforts to improve the connectivity, the digitization and the intelligence of machine tools. Recently, STEP Tools, Inc. is developing a digital thread solution for CNC machining processes to keep the design, manufacturing, and inspection of a product connected around a digital twin [23]. A 3D model-based machining simulator which fuses STEP (ISO 10303) models of the product, MTConnect status of the machine tool and Quality Information Framework (QIF) metrology feedback was developed to build the digital twin of the product with integrated machining and measurement while a part is being cut. Mazak Cooperation launched a Mazak SmartBox [24] as a scalable, end-to-end Industrial Internet of Things platform that connects manufacturing equipment, including machines, software and other devices, to a factory's network and allows the free flow of information to management systems via MTConnect. The Mazak SmartBox provides intelligent data analytics and monitoring of CNC machine tools while considering security issues. Aiming at facilitating the digitization of machine tools, DMG MORI provides a series of software solutions for machine tools such as Virtual Machine, Service Agent and Messenger, to offer high-fidelity simulation and estimation of machining processes, web-based real-time machine monitoring through mobile devices and intelligent maintenance services based on real machining data [25]. Shenyang Machine Tool Company developed an i5 smart numerical control system as an Internet-based intelligent terminal comprising intelligent control, intelligent operation, intelligent programming, intelligent maintenance and intelligent management [26]. Based on real-time data collection and cloud-based big data analytics, i5 enables remote machine monitoring and workshop management services through mobile devices.

The state-of-art work in this area shows that both researchers and industrial practitioners are striving to implement the CPS technology in machine tools. However, from the perspective of academia, most of the previous research focuses on the development of specific intelligent functions for a machine tool, such as CPS-based condition monitoring and prognostics, process planning, adaptive control and machining parameter optimization. These functions are usually developed as standalone CPS, and hence are difficult to integrate or cooperate with other functions of the machine tool. Few studies have been attempted to develop a machine tool as a complete CPS (or CPMT) in a systematic way. From the perspective of industry, machine tool manufacturers are making efforts to integrate CPS-based intelligent functions in their products. Nonetheless, most of the industrial solutions are vendor-dependent and require huge investments, presenting great integration and interoperability challenges for modern manufacturing systems which usually contain machine tools from different vendors.

To address these issues, this paper proposes a systematic development method for CPMT. A generic, extensible and standard-based system architecture is developed to provide guidelines for advancing existing a CNC machine tool to a CPMT. The proposed method enables the machine tool, machining processes, real-time machining data and intelligent algorithms to be deeply integrated through standardized communication protocols. Machine Tool Cyber Twin, as a digital model of the machine tool, is proposed to improve the intelligence, connectivity, accessibility, adaptability and autonomy of CPMT.

3. Generic system architecture for CPMT

This section provides generic system architecture for CPMT (Fig. 2). CPMT is a CPS-based machine tool featuring ubiquitous connectivity, advanced intelligence and autonomy. Real-time manufacturing data from the physical devices are collected by diverse types of sensors and transferred into the cyber space via different networks. In the cyber space, a Machine Tool Cyber Twin (MTCT) is modelled by integrating the manufacturing data with an information model, a database and different intelligent algorithms. MTCT is a digital abstraction of the machine tool which represents the characteristics and real-time status of the machine tool, monitors and controls the machine tool with built-in computation and intelligence, and sends the shop-floor manufacturing data to different Human-Machine Interfaces (HMIs) as well as the cloud to provide efficient decision-making support for different users. In this way, various types of feedback loops among the physical world, the cyber space and humans are established (indicated by colored arrows in Fig. 2). Consequently, the performance and the efficiency of the machine tools can be significantly improved. The detailed functions and the features of the proposed CPMT are explained in the following subsections.

3.1. Components and functions

A CPMT comprises three main components, i.e. Physical devices, Networks and MTCT.

1) *Physical devices:* It can be divided into two categories: machining devices and data acquisition devices. Machining devices include each component of the CNC machine tool, the cutting tools and the workpieces; while data acquisition devices contain various types of sensors and measurement devices such as radio frequency identification (RFID) tags and readers, power meters, dynamometers, accelerometers, Acoustic Emission (AE) sensors, and Coordinate Measuring Machines (CMM). During machining processes, the CNC controller and the data acquisition devices capture real-time machining data generated by the machining devices and send them to the cyber space for further analysis. Real-time machining data acquisition is the prerequisite for all the subsequent functions in a CPMT.
2) *Networks:* one of the distinct advantages of CPMT is the advanced connectivity. In CPMT, various types of networks can be implemented to achieve reliable, efficient and ubiquitous communications among the physical world, the cyber space and humans. Real-time feedback from the CNC controllers can be retrieved through various industrial Ethernet, fieldbus and serial communication protocols such as Profinet, EtherCAT, Powerlink, RS-232 and RS-485. Data collected by various sensors can be transmitted to the cyber space through different communication protocols such as Ethernet, WiFi, ZigBee and Bluetooth, with the implementation of low-cost microcontrollers such as Arduino and Raspberry Pi. Open communication standards such as MTConnect and OPC Unified Architecture (OPC UA) allow the data to be uniformly transferred across the data acquisition devices, data analysis applications and HMIs through the Internet. Consequently, various types of feedback loops among the CPMT, the cloud and humans can be realized.
3) *Machine Tool Cyber Twin:* The most significant difference between a CPMT and a traditional CNC machine tool lies in the MTCT. The MTCT comprises four main modules, including Data fusion, Information model, Intelligent algorithms and Database.

Please cite this article in press as: Liu C, et al. A systematic development method for cyber-physical machine tools. J Manuf Syst (2018), https://doi.org/10.1016/j.jmsy.2018.02.001

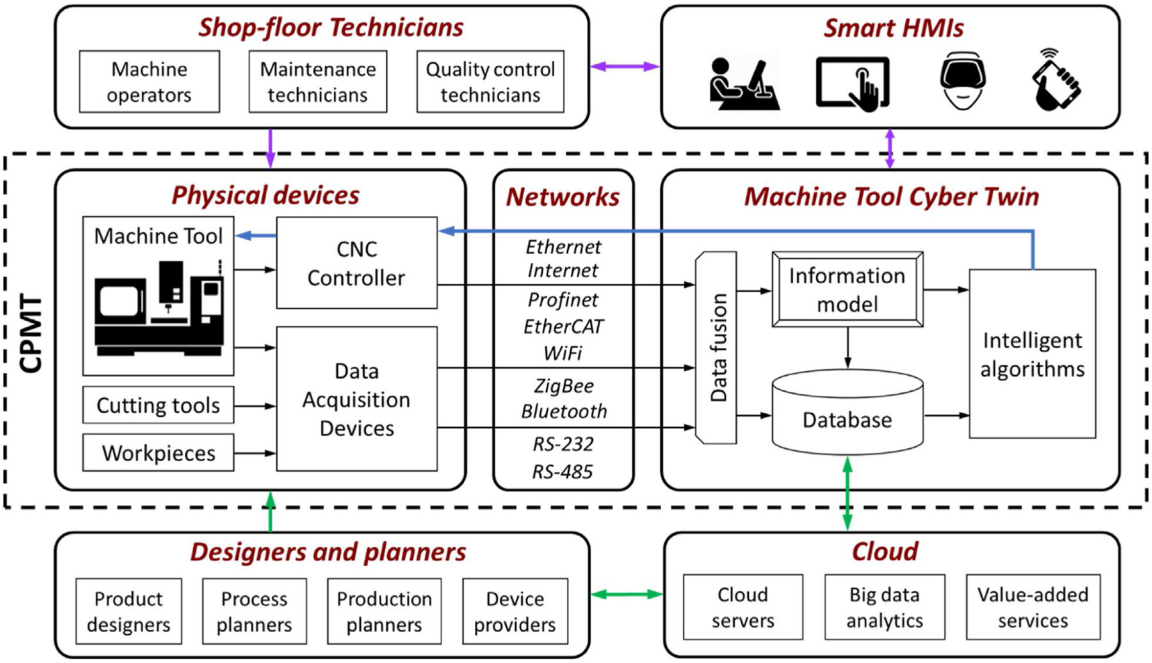


Fig. 2. Generic system architecture for CPMT.

- *Data fusion:* data fusion is a preliminary step to build the MTCT. Firstly, raw data generated by different sensors are cleansed and preprocessed so that meaningful information can be extracted. Secondly, real-time machining data generated by CNC controller and data acquisition devices are converted into a common format, such that the data can be efficiently manipulated in the following processes. Thirdly, data from different data sources (e.g. CNC controller, RFID tags and various sensors) are grouped to their correlated component, in preparation for the following information modelling. As a result, the data fusion module provides unified, accurate and reliable data as the basis for modelling the MTCT.
- *Information model:* The information model provides a comprehensive understanding of the machine tool. It clearly presents the logical structure of the machine tool including the relationships between each sub-system and critical component on one hand. On the other hand, it groups all the available data items related to a specific component together such that the real-time manufacturing data can be effectively manipulated and utilized in further analysis. Since the information model is digitally developed, it is easy to be modified or extended when existing physical components and data acquisition devices are replaced, or additional devices are implemented.
- *Intelligent algorithms:* various data visualization, process optimization and Prognostics and Health Management (PHM) algorithms can be embedded in the MTCT. These algorithms retrieve specific real-time machining data directly from the information model, endow the machine tool with intelligent and autonomous functions and provide efficient decision-making supports for shop-floor technicians. The output of these embedded algorithms can be directly sent to the CNC controller as control commands to realize autonomous in-process optimization, or fed back to machine operators to improve machine utilization and machining performances.
- *Database:* since the CNC controller and the data acquisition devices generate enormous amounts of real-time manufacturing data during machining processes, it is necessary for the MTCT to have a database that is able to safely, reliably and effectively store and manage all the big industrial data. On one hand, the database categorizes the real-time data into different groups and feeds them into the embedded intelligent algorithms in the MTCT based on specific data requirements. On the other hand, the database stores the timestamped real-time manufacturing data as historical data and provides them to the cloud for further data analytics and value-added services.

3.2. Feedback loops

Feedback loops are an indispensable part of any CPS since they complete the integration of the physical world, the cyber space and humans. The proposed CPMT enables three types of feedback loops as indicated by the colored arrows in Fig. 2, i.e. autonomous feedback control loop (blue arrows), shop-floor decision-making support loop (purple arrows) and cloud-based decision-making support loop (green arrows).

1) *Autonomous feedback control loop:* in the autonomous feedback control loop, the MTCT analyzes the real-time manufacturing data with embedded intelligent algorithms and sends control commands directly to the CNC controller, such that the machine tool can autonomously adjust machining parameters during machining processes to adapt to the changing machining conditions, while meeting specific requirements such as surface quality, cutting tool wear and processing time. It is worth mentioning that open CNC controllers such as STEP-NC based controllers [27,28] play an important role in this context. With the implementation of STEP-NC technology, data related to machine capability, process planning and various machining parameters can be optimized in STEP-NC files and directly feedback to the STEP-NC controllers as control commands [29–31]. Consequently, autonomous feedback control loop can be efficiently realized without developing additional interfaces between MTCT and CNC controllers.
2) *Shop-floor decision-making support loop:* The integration of the real-time analytical information generated by the embedded intelligent algorithms and the advancements of data visualization technologies such as AR give rise to various types of smart HMIs (e.g. smart phones, tablets and wearable devices) that

Please cite this article in press as: Liu C, et al. A systematic development method for cyber-physical machine tools. J Manuf Syst (2018), https://doi.org/10.1016/j.jmsy.2018.02.001

allow the shop-floor technicians (e.g. machine operators, maintenance technicians and quality control technicians) to have an instant, comprehensive and intuitive perception of the machining processes, thus enabling them to make efficient decisions to improve the machining performance as well as the equipment effectiveness.

3) *Cloud-based decision-making support loop:* during machining processes, enormous amounts of field-level historical manufacturing data generated from each component and machining process are transmitted to the MTCT. These big data will be further transferred to the cloud database for long-term archiving. Various big data analytics algorithms and computational resources can be utilized to provide cloud-based decision-making supports for the designers and planners. For example, product designers and process planners can optimize the product designs and the process plans based on the data related to the machining performance; production planners can improve the Overall Equipment Effectiveness based on the statistical data related to the machine utilization rate; device providers can also take advantage of the data provided by their customers to improve the design of their devices and provide value-added services. From another point of view, the MTCT can also be treated as a composite manufacturing service [32] that can be provided, managed and consumed in the cloud manufacturing platform.

3.3. Extensibility

Machine tools are usually not reconfigurable or extensible once they have been assembled in the shop floor. However, the proposed CPMT architecture allows the machine tool to be extensible in terms of the available real-time data, the information model, the autonomous functions, and the decision-making supports.

Firstly, different types of data acquisition devices can be deployed on the machine tool to extend the available real-time data based on specific needs of the users. Other than the feedback from the CNC controller, additional RFID tags and readers, cameras, accelerometers, dynamometers, AE sensors and so forth can be implemented to collect real-time machining data related to specific components and machining processes. Based on the unified communication standards and different types of networks, these extended data can be transferred to the cyber space and appended to their associated components as additional data items in the information model. Secondly, the autonomous functions can be extended by embedding customized intelligent algorithms in the MTCT. Various intelligent algorithms such as ANN [33,34], Fuzzy Logic [35,36], Random Forests [37] and Support Vector Machine (SVM) [38] can be embedded in the MTCT to retrieve multiple real-time data items directly from the information model, and endows the machine tool with autonomous in-process optimization, tool wear prediction, surface roughness prediction, and so forth. Furthermore, the advanced connectivity of CPMT allows diverse forms of decision-making supports and value-added services to be further developed. For example, cutting tool providers can access the machining data to help the users optimize the tool path and cutting parameters based on their knowledge. Maintenance service providers can access the prognosis data and provide remote maintenance guidance using AR technology.

Due to the generic and extensible characteristics, the proposed CPMT system architecture provides strategic guidelines for advancing traditional CNC machine tools to CPMT. From the perspective of machine tool design, the proposed architecture also provides guidelines for the design of the next generation of machine tools that thoroughly integrate machine tool, data acquisition devices, MTCT and networks from the initial design stage right down to the shop floor deployment.

Table 1
Static property data of manufacturing devices in CPMT.

Devices	Static property data (examples)
Machine tool	Manufacturer; Date of manufacture; Machine type; CNC controller model; Dimension; Weight; Number of axes; Working area; Axes travel distance; Clamping area; Maximum table load; Rapid motion speed; Maximum spindle speed; Maximum torque; Tool turret capacity
Cutting tools	Manufacturer; Date of manufacture; Serial number; Tool type; Material; Various geometries
Workpieces	Material; Dimensions; CAD file; Process plan; Machining program

4. Development methodologies for machine tool cyber twin

MTCT is the essential reason that distinguishes CPMT from a traditional CNC machine tool. Modelling of MTCT is the process of digitizing the physical machine tool and machining processes in the cyber space. This section reports on the development methodologies of the core modules in the MTCT, including manufacturing data acquisition, data fusion, information modelling, database and intelligent algorithms.

4.1. Manufacturing data acquisition

In order to provide comprehensive, reliable and accurate data of the manufacturing devices and the machining processes, the useful data as well as their related data acquisition techniques must be recognized. In general, the field-level manufacturing data in a CPMT can be divided into three categories, i.e. static property data, real-time machining data and measurement data.

4.1.1. Static property data

Static property data represent the basic properties of the related physical devices. Table 1 lists some static property data of the machine tool, the cutting tools and the workpieces. These data are usually collected from the manuals of the devices. To efficiently transmit these data to the information model in the cyber space, RFID technology can be utilized given the various advantages of RFID including the remote accessibility, durability, reusability, data capacity, security, and so forth. Ideally, each machine tool, cutting tool and workpiece should be equipped with an RFID tag containing its static property data listed in Table 1. RFID readers can then read and transmit these data to the information model in the cyber space.

4.1.2. Real-time machining data

Real-time machining data represent the status of the machining processes from various aspects. Some of the real-time machining data have significant influences on the machining performance and are commonly used as the input data for various data analytics and process optimization algorithms, thus need to be collected and transmitted to the cyber space for further analysis. In the proposed CPMT, real-time machining data can be obtained from the CNC controller as well as various sensors that embedded in or attached to the machine tools. Table 2 lists the commonly used real-time machining data and the related data acquisition devices.

CNC controllers can usually provide some real-time feedback as listed in Table 2. However, owing to the diversity of existing CNC controllers, retrieving real-time data from CNC controllers becomes a challenging task. For the open source CNC controllers such as LinuxCNC, it is easy to access the CNC data through pre-defined Application Programming Interfaces (APIs). However, for the proprietary CNC controllers (e.g. FANUC, Siemens, Haas) that predominate the CNC control market, specific adapters (specially designed hardware or software) have to be implemented for

Please cite this article in press as: Liu C, et al. A systematic development method for cyber-physical machine tools. J Manuf Syst (2018), https://doi.org/10.1016/j.jmsy.2018.02.001

Table 2
Real-time machining data and data acquisition devices in CPMT.

Data acquisition device	Real-time machining data (examples)
CNC controller	Operation status; Alarms; Programs; Tool turret position; Spindle speed; Spindle rotating direction; Feed-rate; Positions, speeds, accelerations of axes
Power meter; Wattmeter	Motor power and current
Dynamometer; Strain gauge	Cutting forces and torques
AE sensor	Acoustic emission
Piezoelectric accelerometer; Vibrometer	Vibration, chatter
Thermocouple; Infrared thermometer	Cutting zone temperature
Cameras	Machining process visualization

Table 3
Measurement data and data acquisition devices in CPMT.

Measurement device	Measurement data (examples)
CMM; Laser scanner	Dimensional and geometric accuracy of workpieces
Profilometer; CCD camera	Surface roughness, texture, and finish of workpieces
Optical sensor; Camera	Cutting tool wear

specific CNC controllers such that the internal real-time data can be accessed. It is worth mentioning that more and more recently developed CNC controllers have been embedded with their own adapters that support open communication standards such as MTConnect and OPC UA.

The implementation strategies of different sensors and signal processing techniques for machining processes have been extensively studied and they are not the focus of this research, thus the detailed sensing techniques are not discussed in this paper. Some comprehensive reviews of the related techniques can be found in [39–41].

4.1.3. Measurement data

Measurement data refer to the measurement results obtained from various measurement devices that reflect the actual machining performance. Table 3 lists the commonly used measurement data in CPMT. The accuracy and surface integrity of workpieces provide the basic requirements for various optimization processes such as product design optimization, process planning optimization and machining parameter optimization. The cutting tool wear data have significant influence on the cutting tool condition and the machining performance. These measurement data can be obtained during or after the machining processes, based on different user requirements. In addition, these measurement data should also be stored in the RFID tags attached to the workpieces and cutting tools, such that they can be utilized by different algorithms in the cyber space.

4.2. Data fusion

The data fusion module contains four main functions, i.e. data cleansing, data pre-processing, data formatting and data grouping. Fig. 3 shows the functions and the data flows in the data fusion module.

Data cleansing and pre-processing ensure the raw data obtained by various sensors are reliable, accurate and meaningful. These two functions can be achieved using various low-cost microcontroller boards such as Arduino and Raspberry Pi. Specific signal processing algorithms need to be implemented for specific sensor data. An example of the implementation of data cleansing algorithm in CPMT was introduced in one of our previous research [42].

Data formatting is responsible for translating all the manufacturing data obtained from the aforementioned data acquisition devices into a unified data format, such that they can be efficiently managed and analyzed in the cyber space. Recently, MTConnect and OPC UA have shown great potential for addressing this issue. MTConnect is a set of open, royalty-free standards designed for the exchange of data between shop floor equipment and software applications, developed by the MTConnect Institution [43]. MTConnect transforms the data from various data acquisition devices into a common XML (Extensible Markup Language) format defined by the standard and uses HTTP (Hypertext Transfer Protocol) as the underlying transport protocol. OPC UA is a set of open, royalty-free standards designed as a universal factory floor communication protocol developed by the OPC Foundation [44]. OPC UA is able to encode the field-level manufacturing data as the pre-defined OPC UA Binary messages or XML messages and deliver them over TCP/IP connections. Both two standards are open, royalty-free, platform-independent and extensible. In addition, an MTConnect-OPC UA Companion Specification has been released to ensure interoperability and consistency between them. Therefore, both of these two standards can be implemented as the data communication standard in the proposed CPMT.

With various data acquisition devices implemented in the CPMT, the data generated by each data source may be related to multiple components. On the other hand, data generated by different data acquisition devices may be related to a same component. This complexity makes the data manipulation a challenging task. Data grouping addresses this issue by assigning each data item with a unique ID, and grouping the data from different data sources to the certain component that they are related to. Consequently, the status of each component can be comprehensively expressed in the information model.

4.3. Information modelling

Information model is one of the cores in MTCT. The information model of CPMT should have three fundamental capabilities. First, it should represent the structure of the machine tool and all the critical components in a logical manner. Second, it should contain both the static properties and the dynamic status of each critical component. Third, the information model must be extensible such that additional components and data can be easily integrated. Both MTConnect and OPC UA provide a feasible information modelling method that meets the requirements.

4.3.1. MTConnect-based machine tool information model

MTConnect defines a hierarchical XML data model for machine tools. It has two primary types of XML elements, i.e. structural elements and data elements [45]. A structural element represents a physical or logical component. The static properties of that component are expressed by the attributes of the structural element. Each structural element may have some sub-elements based on their relationships. The data elements refer to all the real-time data items that can be collected from that component. MTConnect defines a comprehensive dictionary of the important components and data items especially for CNC machine tools, thus users only need to choose the appropriate attributes (data types, units, etc.) for their specific information model. The XML schema that defines the data model can also be extended to add custom components and data based on specific needs [46]. Fig. 4 shows the structure of an MTConnect-based information model of a simple turning lathe. As shown in the figure, the Machine tool has three sub-components including Controller, Axes and Cutting tool. Axes is an abstract component that comprises three sub-components including Linear X, Linear Y and Spindle. Each component has its own attributes and data items, representing its static properties and real-time data

Please cite this article in press as: Liu C, et al. A systematic development method for cyber-physical machine tools. J Manuf Syst (2018), https://doi.org/10.1016/j.jmsy.2018.02.001

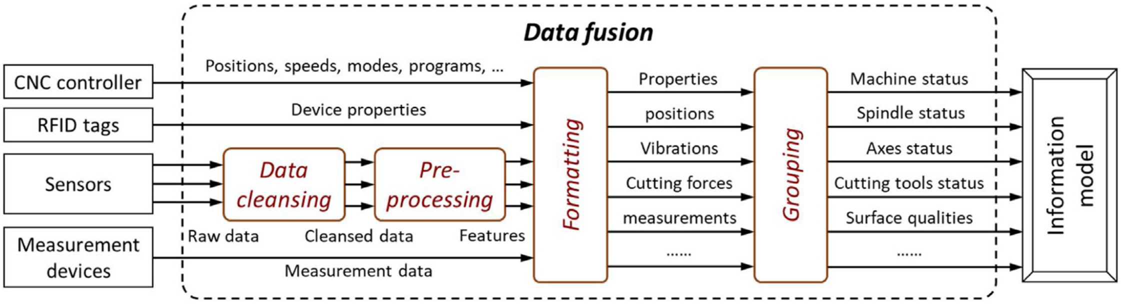


Fig. 3. Functions and data flows in the data fusion module.

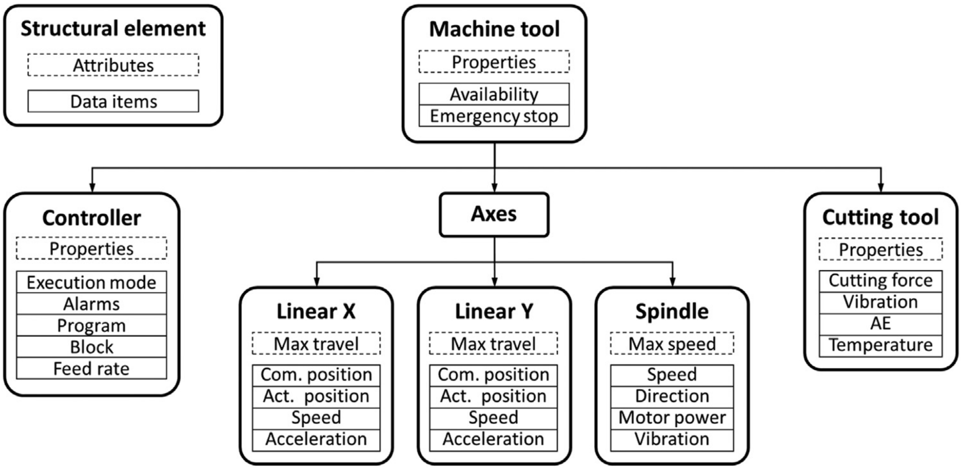


Fig. 4. Structure of an MTConnect-based information model of a simple turning lathe.

respectively. Take the sub-component Spindle as an example; it represents the spindle of the turning lathe. The static property of the spindle is indicated by its maximum speed, which is obtained from the specification of the machine tool and manually input to the information model. The real-time status of the spindle is represented by the speed and rotating direction obtained from the CNC controller, the motor power obtained from the power meter, and the vibration obtained from the accelerometer. In this way, the MTConnect-based information model comprehensively represents the status of the entire machine tool.

4.3.2. *OPC UA-based machine tool information model*

OPC UA, compared with MTConnect, provides a more generic information modelling method. OPC UA defines an object-based address space model as a Meta model, based on which various domain-specific information models can be developed. The objects, similar to the concept of Object-Oriented Programming, are placeholders of variables, events and methods. Objects and their components are represented in the address space as a set of nodes described by attributes and interconnected by references [47]. Consequently, in order to develop a machine tool information model using OPC UA, the developer needs to build the structure of the information model and define all the objects, attributes and references within it according to the actual structure, components and available data of the machine tool. Fig. 5 shows the structure of an OPC UA-based information model of a simple turning lathe. Each component is modelled as an object and may have sub-components and property as its child nodes. Each object may have some data items modelled as its attributes with different data types. It is obvious that OPC UA provides developers with more flexibilities to build the machine tool information model, but in the meantime, relatively more effort and time are required.

4.4. *Database and intelligent algorithms*

Having all the static property data and real-time machining data represented by the information model, a database must be developed in the MTCT such that the big data can be safely, reliably and effectively stored, managed, as well as retrieved by external intelligent algorithms and data analytics tools. Since the information model has already assigned each data item with a unique ID and a timestamp, an efficient strategy for developing the database is to divide the database into different categories in accordance with the structure of the information model. Each category represents a component in the information model, containing the static properties and all the real-time data. Based on the open and royalty-free data communication standards applied in the MTCT, various database developing tools such as MySQL, PostgreSQL and SQLite can be utilized to develop the database. Fig. 6 shows a generic structure of the proposed database. Based on this structure, a comprehensive performance history of each component and machining process of the CPMT can be archived. Consequently, various data analytics applications in the cloud can retrieve specific historical data items in specific time periods.

Intelligent algorithms embedded in the MTCT make the CPMT intelligent and autonomous. The proposed MTCT builds a solid foundation for the implementation of artificial intelligence in machine tools. In the MTCT, various types of embedded intelligent algorithms can access the real-time data directly from the information model and extract specific data items to provide real-time monitor and control functions, such as in-process machining optimization, high-fidelity simulation, data visualization and PHM. For example, Augmented Reality (AR)-based algorithms can be embedded to retrieve the real-time machining video, axes positions and speeds, and perform AR-assisted monitoring and simulation [48].

Please cite this article in press as: Liu C, et al. A systematic development method for cyber-physical machine tools. J Manuf Syst (2018), https://doi.org/10.1016/j.jmsy.2018.02.001

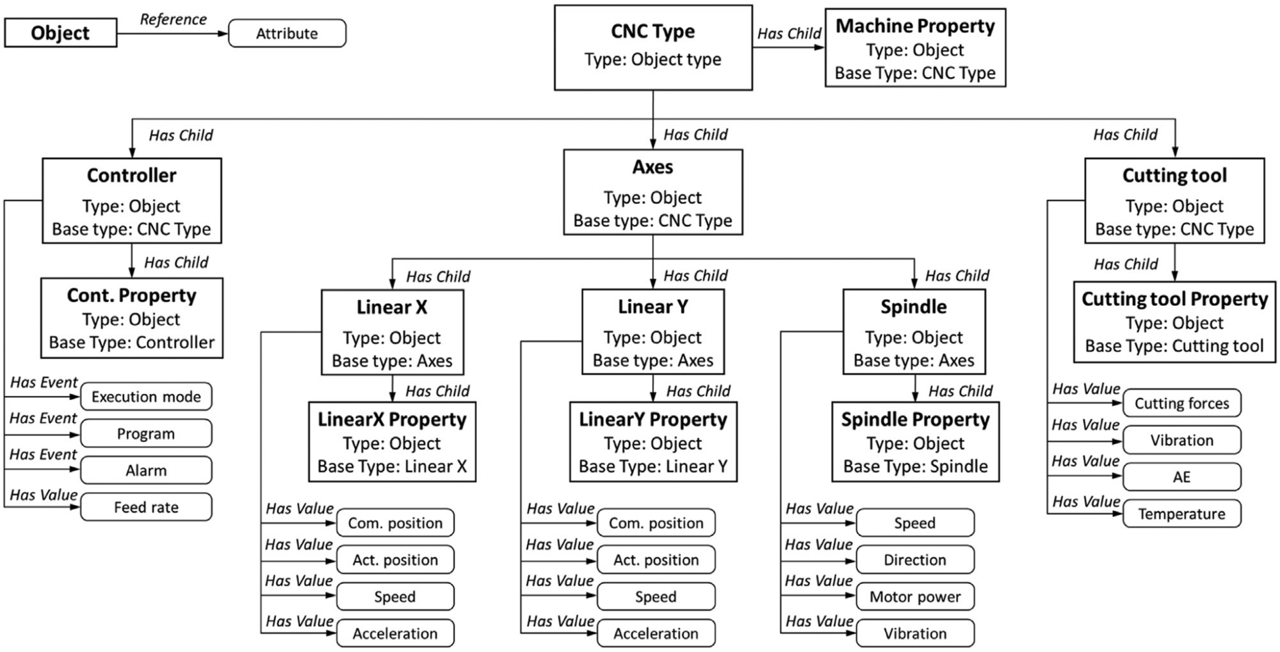


Fig. 5. Structure of an OPC UA-based information model of a simple turning lathe.

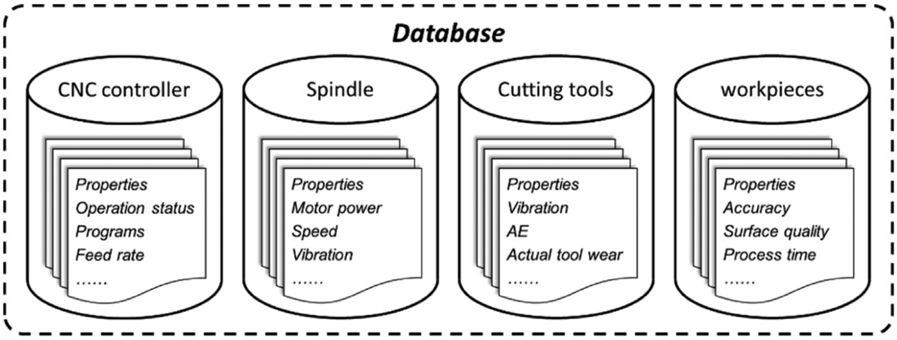


Fig. 6. Structure of the database in MTCT.

Artificial Neural Network (ANN) algorithms can be embedded to retrieve the cutting speed, feed and depth of cut, and perform tool wear prediction [33]. Fuzzy inference systems can be embedded to retrieve the spindle speed, feed-rate and depth of cut, and perform surface roughness prediction [49]. The development methodologies of the intelligent algorithms will not be discussed in detail since it is beyond the scope of this paper.

5. MTConnect- based CPMT prototype

An MTConnect-based CPMT prototype was developed to validate the feasibility and performance of the proposed CPMT architecture and development methodologies. MTConnect was utilized as the communication standard and the information modelling technology.

5.1. Experimental setup

The experimental setup of the MTConnect-based CPMT prototype is shown in Fig. 7. The prototype was built based on a Sherline 3-Axis Milling machine. The machine tool and a test cutting tool were both assigned with a 13.56 MHz RFID tag containing their static property information. An Arduino Uno development board with an NFC shield connected was used to read the data from the RFID tags. A Kistler 3-axis dynamometer (type 9273) was mounted on the work table to measure the cutting forces in X, Y and Z direction. A PCB Piezoelectric accelerometer (model 352C65) was used to measure the vibration of the spindle. An RPM sensor was mounted above the spindle to measure the spindle speed.

The overall system architecture of the CPMT prototype is described in Fig. 8. The machine tool is controlled by LinuxCNC software installed in a Linux based computer. The static property data of the machine tool and cutting tool in the RFID tags are read by the Arduino microcontroller, and transferred to the MTConnect Adapter through serial connection. The sensor signals from the dynamometer, the accelerometer and the RPM sensor are transferred to a NI PXI-1031 data acquisition platform and processed using LabView software. The processed data are then sent to the MTConnect Adapter through TCP/IP connection. Real-time machining data from the CNC controller are retrieved from the LinuxCNC software to the MTConnect Adapter directly through APIs since LinuxCNC is open sourced and they were installed in the same Linux computer. The MTConnect Adapter transforms all the received data into SHDR (Simple Hierarchical Data Representation) format with timestamps attached in front of each changed data, and keeps sending these data to the MTConnect Agent through TCP/IP connection. The MTConnect Agent, running on a Windows computer, will then group all the data into the information model, format the data into

Please cite this article in press as: Liu C, et al. A systematic development method for cyber-physical machine tools. J Manuf Syst (2018), https://doi.org/10.1016/j.jmsy.2018.02.001

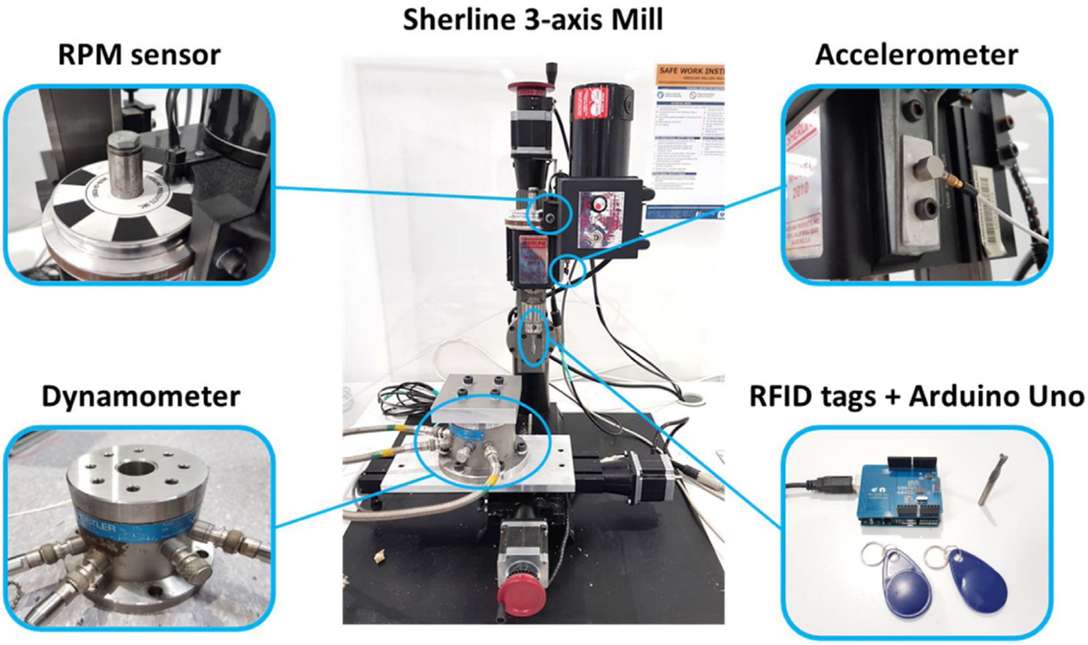


Fig. 7. Experimental setup of the MTConnect-based CPMT prototype.

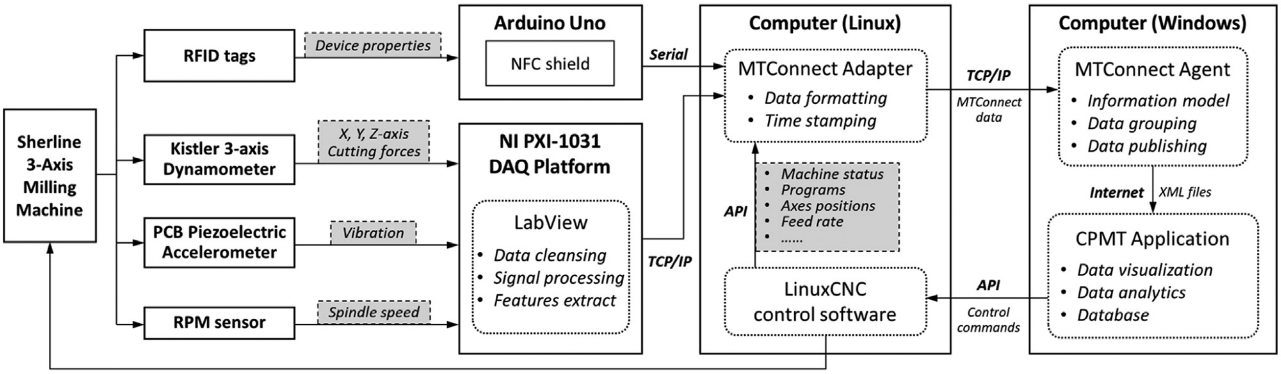


Fig. 8. System architecture of the MTConnect-based CPMT prototype.

XML format and publish them to various applications through the Internet.

5.2. Information modelling

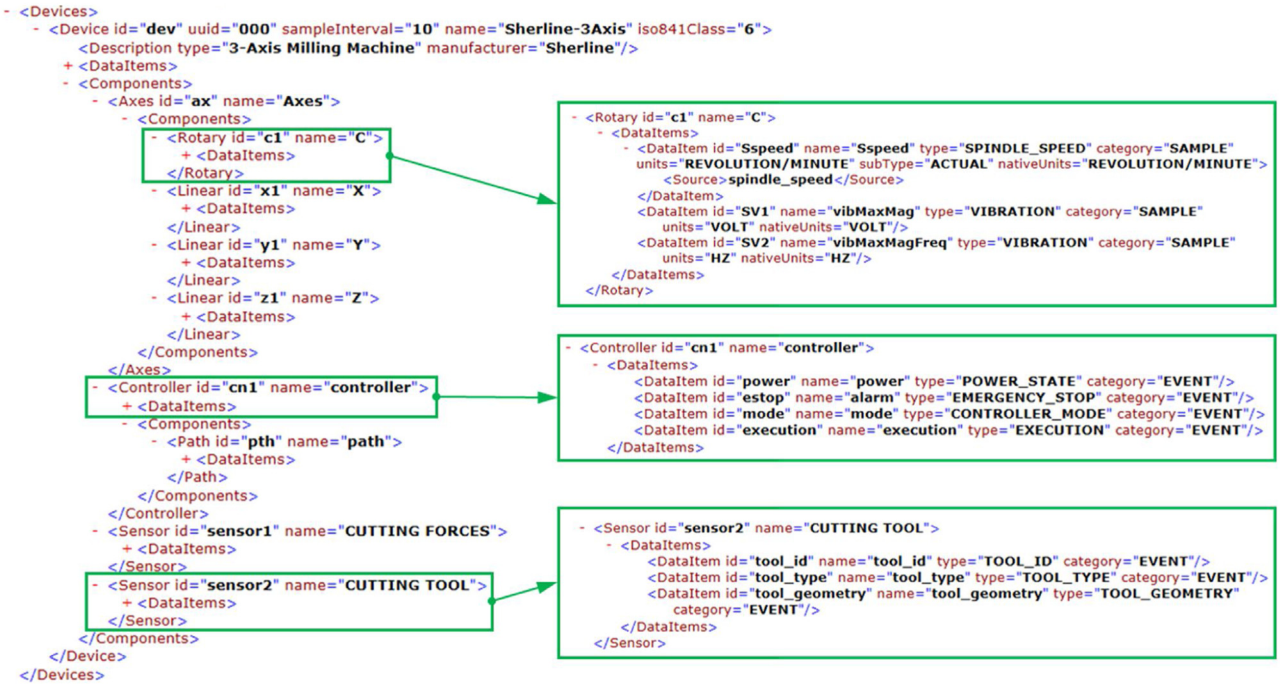
The MTConnect-based information model for this machine tool was developed as a Device.xml file based on the XML schema provided by MTConnect standard. Fig. 9 shows the structure and all the components involved in the information model. All the data items are collapsed due to space limitation. The detailed data items of the spindle, the CNC controller and the cutting tool are expanded on the right to illustrate how the data from different sources were grouped. As shown in Fig. 9, the spindle speed and vibration data collected from different sensors, the execution status information retrieved from the LinuxCNC software, and the static property data of the cutting tool obtained from the RFID tags were grouped as data items under the spindle component, controller component and cutting tool component respectively. Each component and data item were assigned with a unique ID such that each component and data item can be retrieved and manipulated separately.

5.3. CPMT-Cyber twin application

A CPMT-Cyber Twin application was developed as the MTCT of the MTConnect-based CPMT prototype. Fig. 10 shows the User Interface of the application. It comprises four main modules as marked in Fig. 10. The application connects to the MTConnect Agent through the Internet by specifying the IP address and port number of the Agent. Once connected, the application reads the Device.xml file and displays the logical structure of the machine tool as a tree structure in module 1. The tree structure clearly shows the logical relationships between each component. All the available data items are shown under the component to which they are associated. The name and data type of each data item are also displayed in the tree structure. Consequently, this structure provides a comprehensive understanding of the static attributes of the machine tool.

Module 2 shows the real-time status of each component and machining process. All the available real-time data items are displayed and continuously updated in the text boxes under their related component. The Machine Tool components show the basic attributes of the machine tool and the time stamp of all the real-time data. The Controller component shows the real-time status

Please cite this article in press as: Liu C, et al. A systematic development method for cyber-physical machine tools. J Manuf Syst (2018), https://doi.org/10.1016/j.jmsy.2018.02.001



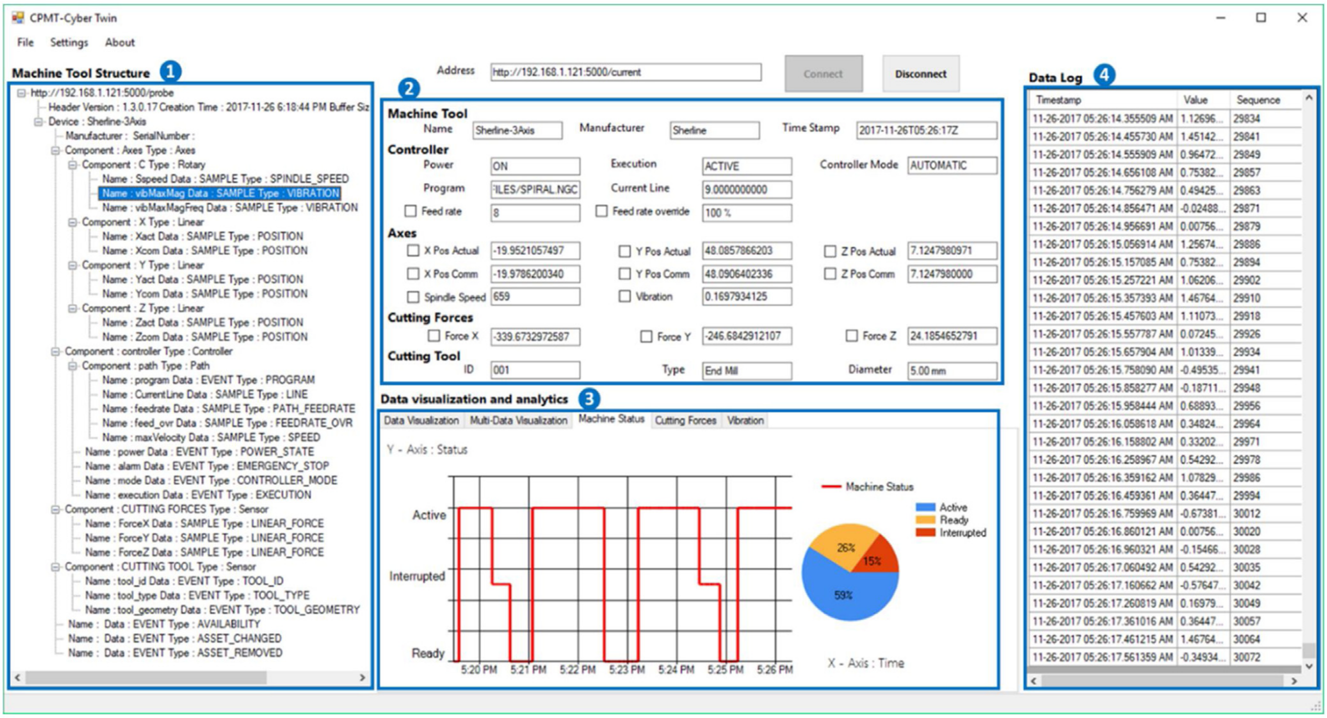
```
- <Devices>
  - <Device id="dev" uuid="000" sampleInterval="10" name="Sherline-3Axis" iso841Class="6">
      <Description type="3-Axis Milling Machine" manufacturer="Sherline"/>
    + <DataItems>
    - <Components>
      - <Axes id="ax" name="Axes">
        - <Components>
          - <Rotary id="c1" name="C">
            + <DataItems>
            </Rotary>
          - <Linear id="x1" name="X">
            + <DataItems>
            </Linear>
          - <Linear id="y1" name="Y">
            + <DataItems>
            </Linear>
          - <Linear id="z1" name="Z">
            + <DataItems>
            </Linear>
          </Components>
        </Axes>
      - <Controller id="cn1" name="controller">
        + <DataItems>
        - <Components>
          - <Path id="pth" name="path">
            + <DataItems>
            </Path>
          </Components>
        </Controller>
      - <Sensor id="sensor1" name="CUTTING FORCES">
        + <DataItems>
        </Sensor>
      - <Sensor id="sensor2" name="CUTTING TOOL">
        + <DataItems>
        </Sensor>
      </Components>
    </Device>
  </Devices>
```

```
- <Rotary id="c1" name="C">
  - <DataItems>
    - <DataItem id="Sspeed" name="Sspeed" type="SPINDLE_SPEED" category="SAMPLE"
      units="REVOLUTION/MINUTE" subType="ACTUAL" nativeUnits="REVOLUTION/MINUTE">
        <Source>spindle_speed</Source>
      </DataItem>
      <DataItem id="SV1" name="vibMaxMag" type="VIBRATION" category="SAMPLE"
        units="VOLT" nativeUnits="VOLT"/>
      <DataItem id="SV2" name="vibMaxMagFreq" type="VIBRATION" category="SAMPLE"
        units="HZ" nativeUnits="HZ"/>
    </DataItems>
  </Rotary>
```

```
- <Controller id="cn1" name="controller">
  - <DataItems>
      <DataItem id="power" name="power" type="POWER_STATE" category="EVENT"/>
      <DataItem id="estop" name="alarm" type="EMERGENCY_STOP" category="EVENT"/>
      <DataItem id="mode" name="mode" type="CONTROLLER_MODE" category="EVENT"/>
      <DataItem id="execution" name="execution" type="EXECUTION" category="EVENT"/>
    </DataItems>
```

```
- <Sensor id="sensor2" name="CUTTING TOOL">
  - <DataItems>
      <DataItem id="tool_id" name="tool_id" type="TOOL_ID" category="EVENT"/>
      <DataItem id="tool_type" name="tool_type" type="TOOL_TYPE" category="EVENT"/>
      <DataItem id="tool_geometry" name="tool_geometry" type="TOOL_GEOMETRY"
        category="EVENT"/>
    </DataItems>
  </Sensor>
```

Fig. 9. MTConnect-based XML Information model of Sherline 3-axis milling machine.



Machine Tool Structure ①

```
⊟ http://192.168.1.121:5000/probe
   Header Version : 1.3.0.17 Creation Time : 2017-11-26 6:18:44 PM Buffer Siz
   ⊟ Device : Sherline-3Axis
      Manufacturer :  SerialNumber :
      ⊟ Component : Axes Type : Axes
         ⊟ Component : C Type : Rotary
            Name : Sspeed Data : SAMPLE Type : SPINDLE_SPEED
            Name : vibMaxMag Data : SAMPLE Type : VIBRATION
            Name : vibMaxMagFreq Data : SAMPLE Type : VIBRATION
         ⊟ Component : X Type : Linear
            Name : Xact Data : SAMPLE Type : POSITION
            Name : Xcom Data : SAMPLE Type : POSITION
         ⊟ Component : Y Type : Linear
            Name : Yact Data : SAMPLE Type : POSITION
            Name : Ycom Data : SAMPLE Type : POSITION
         ⊟ Component : Z Type : Linear
            Name : Zact Data : SAMPLE Type : POSITION
            Name : Zcom Data : SAMPLE Type : POSITION
      ⊟ Component : controller Type : Controller
         ⊟ Component : path Type : Path
            Name : program Data : EVENT Type : PROGRAM
            Name : CurrentLine Data : SAMPLE Type : LINE
            Name : feedrate Data : SAMPLE Type : PATH_FEEDRATE
            Name : feed_ovr Data : SAMPLE Type : FEEDRATE_OVR
            Name : maxVelocity Data : SAMPLE Type : SPEED
         Name : power Data : EVENT Type : POWER_STATE
         Name : alarm Data : EVENT Type : EMERGENCY_STOP
         Name : mode Data : EVENT Type : CONTROLLER_MODE
         Name : execution Data : EVENT Type : EXECUTION
      ⊟ Component : CUTTING FORCES Type : Sensor
         Name : ForceX Data : SAMPLE Type : LINEAR_FORCE
         Name : ForceY Data : SAMPLE Type : LINEAR_FORCE
         Name : ForceZ Data : SAMPLE Type : LINEAR_FORCE
      ⊟ Component : CUTTING TOOL Type : Sensor
         Name : tool_id Data : EVENT Type : TOOL_ID
         Name : tool_type Data : EVENT Type : TOOL_TYPE
         Name : tool_geometry Data : EVENT Type : TOOL_GEOMETRY
      Name :  Data : EVENT Type : AVAILABILITY
      Name :  Data : EVENT Type : ASSET_CHANGED
      Name :  Data : EVENT Type : ASSET_REMOVED
```

Address http://192.168.1.121:5000/current

②

Machine Tool
Name Sherline-3Axis
Manufacturer Sherline
Time Stamp 2017-11-26T05:26:17Z

Controller
Power ON
Execution ACTIVE
Controller Mode AUTOMATIC
Program ILES/SPIRAL.NGC
Current Line 9.0000000000
☐ Feed rate 8
☐ Feed rate override 100 %

Axes
☐ X Pos Actual -19.9521057497
☐ Y Pos Actual 48.0857866203
☐ Z Pos Actual 7.1247980971
☐ X Pos Comm -19.9786200340
☐ Y Pos Comm 48.0906402336
☐ Z Pos Comm 7.1247980000
☐ Spindle Speed 659
☐ Vibration 0.1697934125

Cutting Forces
☐ Force X -339.6732972587
☐ Force Y -246.6842912107
☐ Force Z 24.1854652791

Cutting Tool
ID 001
Type End Mill
Diameter 5.00 mm

Data visualization and analytics ③

Data Log ④

Timestamp	Value	Sequence
11-26-2017 05:26:14.355509 AM	1.12696...	29834
11-26-2017 05:26:14.455730 AM	1.45142...	29841
11-26-2017 05:26:14.555909 AM	0.96472...	29849
11-26-2017 05:26:14.656108 AM	0.75382...	29857
11-26-2017 05:26:14.756279 AM	0.49425...	29863
11-26-2017 05:26:14.856471 AM	-0.02488...	29871
11-26-2017 05:26:14.956691 AM	0.00756...	29879
11-26-2017 05:26:15.056914 AM	1.25674...	29886
11-26-2017 05:26:15.157085 AM	0.75382...	29894
11-26-2017 05:26:15.257221 AM	1.06206...	29902
11-26-2017 05:26:15.357393 AM	1.46764...	29910
11-26-2017 05:26:15.457603 AM	1.11073...	29918
11-26-2017 05:26:15.557787 AM	0.07245...	29926
11-26-2017 05:26:15.657904 AM	1.01339...	29934
11-26-2017 05:26:15.758090 AM	-0.49535...	29941
11-26-2017 05:26:15.858277 AM	-0.18711...	29948
11-26-2017 05:26:15.958444 AM	0.68893...	29956
11-26-2017 05:26:16.058618 AM	0.34824...	29964
11-26-2017 05:26:16.158802 AM	0.33202...	29971
11-26-2017 05:26:16.258967 AM	0.54292...	29978
11-26-2017 05:26:16.359162 AM	1.07829...	29986
11-26-2017 05:26:16.459361 AM	0.36447...	29994
11-26-2017 05:26:16.759969 AM	-0.67381...	30012
11-26-2017 05:26:16.860121 AM	0.00756...	30020
11-26-2017 05:26:16.960321 AM	-0.15466...	30028
11-26-2017 05:26:17.060492 AM	0.54292...	30035
11-26-2017 05:26:17.160662 AM	-0.57647...	30042
11-26-2017 05:26:17.260819 AM	0.16979...	30049
11-26-2017 05:26:17.361016 AM	0.36447...	30057
11-26-2017 05:26:17.461215 AM	1.46764...	30064
11-26-2017 05:26:17.561359 AM	-0.34934...	30072

Fig. 10. User Interface of the CPMT-Cyber Twin application.

of the controller, including the current power status (ON or OFF), execution status (Active, Interrupted or Ready), controller mode (Automatic or Manual), NC program (file path and name), current line of the CN program, feed rate and feed rate override. The Axes component shows the commanded and actual positions of each linear axis and the speed and vibration of the spindle. The cutting forces and cutting tool information are also displayed. The tick-box before the data item indicates that it can be chosen and plotted as a line graph in module 3.

Module 3, at the bottom of the interface, provides data visualization and analytics functions based on the real-time data. As shown in Fig. 10, under the Machine Status tab, the historical execution status of the machine tool is displayed as a line graph, where the X-axis indicates the time and the Y-axis indicates the execution status, i.e. Active (machining), Interrupted (paused) or Ready (stopped). The machine utilization rate is calculated and shown as a pie chart accordingly. The current application allows all the real-time data to be directly visualized as line graphs in the time

Please cite this article in press as: Liu C, et al. A systematic development method for cyber-physical machine tools. J Manuf Syst (2018), https://doi.org/10.1016/j.jmsy.2018.02.001

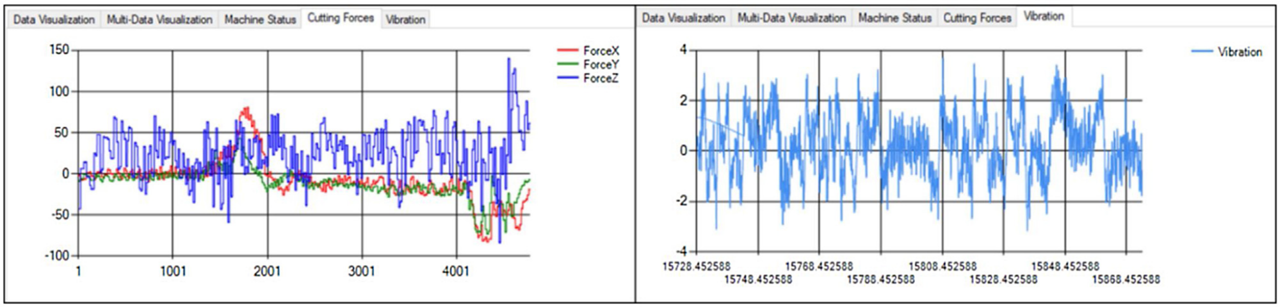


Fig. 11. Data visualization of cutting forces and spindle vibration.

domain. Fig. 11 shows another two examples of the visualization of cutting forces and spindle vibration. These data visualization functions help the machine operators to identify severe changes of machining conditions during machining processes and make quick decisions to prevent further damages. In effect, these data can be further analyzed in frequency and discrete time domain using wavelet transform and SVM, to predict and avoid chatter [50].

Module 4 displays the historical data of a specific data item selected in the machine tool structure. As shown in Fig. 10, the spindle vibration is selected in the machine tool structure, and the historical vibration data are displayed as a spreadsheet in module 4. The first column contains the timestamps of each value. The second column shows the values of the data. The third column indicates the sequence numbers of each value that are defined in MTConnect standard. These historical data can be directly saved as spreadsheets locally or transferred to the cloud database through the Internet. Various machine learning algorithms can directly use these data as training data or test data and provide the machine tool with self-learning capabilities.

This application represents the MTCT of the MTConnect-based CPMT prototype. It allows users to remotely monitor the real-time status of the machine tool, its critical components and the machining processes through the Internet. Based on this application, machine operators can make efficient decisions to improve the machining performance; maintenance technicians can perform proactive maintenance to improve the machine utilization rate; production planners and managers can remotely monitor the machine status in real time and optimize the production plans; various service providers can access the historical data in the cloud to provide value-added services using their own applications.

5.4. *Discussion*

The MTConnect-based CPMT prototype validated the feasibility of the proposed CPMT system architecture. Various real-time manufacturing data were collected from the CNC controller, RFID tags and different sensors. Different types of networks were utilized to transmit the data to the cyber space. Data fusion was realized based on the implementation of MTConnect standard across different operation systems. An MTConnect-based information model was developed to represent the logical structure of the machine tool as well as the real-time status of each component and machining process. The experimental results shown in the CPMT-Cyber Twin application have proved that the MTConnect-based CPMT prototype has great potential of improving machining performances and increasing machine tool utilization. It not only provides the basic requirements for implementing artificial intelligence in machine tools, but also enables various forms of feedback loops proposed in Section 3.2 to be realized. MTConnect has been proved to be capable of providing CPMT with great interoperability, connectivity and extensibility.

It is worth mentioning that there are several limitations of the current prototype. First, MTConnect is a read-only standard. The feedback loops cannot be realized directly through MTConnect. Additional interfaces need to be developed to control the machine tool. Second, since the amount of the real-time data is enormous, the data transmission rate from the MTConnect agent to the application in the current prototype is limited to 100 ms. This could be improved by optimizing the application program or utilizing higher bandwidth networks. Third, the cutting tool is modelled as a sensor component containing some basic data items in the information model. To realize a comprehensive cutting tool information model, the MTConnect Assets model which is compatible with ISO 13399 (Cutting tool data representation and exchange) can be implemented. Last, the current CPMT-Cyber Twin application only provides some basic data visualization and analytics functions. Advanced intelligent algorithms need to be embedded to improve the intelligence of the prototype.

6. Conclusions and future work

Machine Tool 4.0 introduces a new generation of machine tools that are smarter, well connected, widely accessible, more adaptive and more autonomous. CPMT, based on the advancements of CPS, IoT and cloud technology, provides a promising solution for Machine Tool 4.0. In this paper, a systematic development method for CPMT is proposed to provide guidelines for advancing current CNC machine tools to CPMT. Generic system architecture for CPMT is developed. Based on this architecture, machine tool, machining processes, real-time machining data and intelligent algorithms are integrated through diverse types of networks. MTCT is proposed as the digital model of the physical machine tool in the cyber space. It monitors and controls the machine tool with embedded intelligence, and enables various types of feedback loops among the physical world, the cyber space and humans. Development methodologies for the key modules in MTCT including manufacturing data acquisition, data fusion and information modelling of machine tools are proposed and discussed.

The feasibility and advantages of the proposed CPMT architecture and development methodologies are demonstrated through the development of an MTConnect-based CPMT prototype. Static property data and real-time machining data were collected from the CNC controller and different sensors such as RFID tags, accelerometer, dynamometer and RPM sensor. MTConnect was utilized to realize unified and efficient data communication across different networks and operation systems. A CPMT-Cyber Twin application was developed to demonstrate the advancements of the MTCT. Experimental results validated that MTCT represents a comprehensive digital model of the machine tool, including the structure of the machine tool and the real-time status of each component and machining process. Data visualization and analytics functions developed in the application have indicated the great potential of implementing artificial intelligence in CPMT by embedding various intelligent algorithms in the MTCT. Furthermore, the advanced connectivity of MTCT allows the real-time data and historical data to be accessed by different users through the Internet, thus enabling the servitization of the machine tool.

Future work is summarized as follows. Firstly, our main focus will be on the implementation of artificial intelligence in CPMT. Various data visualization and analytics algorithms will be embedded into MTCT to take full advantage of the real-time machining data. Secondly, mobile applications for the developed CPMT prototype will be developed on different HMIs such as smart phones and wearable devices, to enhance the human-machine interaction between different users and CPMT. Thirdly, an OPC UA-based CPMT prototype is under development in our lab. A universal CPMT platform that integrates these two CPMT prototypes will be introduced in our future work. Furthermore, the integration of CPMT and cloud manufacturing platform will be investigated in the future.

Although the development method proposed in this paper focuses on machine tools, the basic philosophy also applies to other manufacturing equipment such as industrial robots and 3D printers. In the era of Industry 4.0, manufacturing equipment is expected to become CPS-based systems, such that autonomy and Machine-to-Machine communications can be realized through their Cyber Twins, thus the envisioned CPPS and smart factories can be eventually realized.

References

[1] Rosenberg N. Technological change in the machine tool industry, 1840–1910. J Econ Hist 1963;23:414–43.
[2] Geoffrey B, Winston AK. Fundamentals of Machining and Machine Tools; 1989.
[3] Kagermann H, Wahlster W, Helbig J. Securing the future of German manufacturing industry: recommendations for implementing the strategic initiative INDUSTRIE 4.0. Final Rep Ind 2013;40:1–84. Work Gr.
[4] Xu X. Machine Tool 4.0 for the new era of manufacturing. Int J Adv Manuf Technol 2017;92:1893–900.
[5] Liu C, Xu X. Cyber-physical machine tool – the era of machine tool 4.0. Procedia CIRP 2017;63:70–5.
[6] Monostori L. Cyber-physical production systems: roots, expectations and R&D challenges. Procedia CIRP 2014;17:9–13.
[7] Zuehlke D. SmartFactory-towards a factory-of-things. Annu Rev Control 2010;34:129–38.
[8] Tao F, Cheng Y, Da Xu L, Zhang L, CCIoT-CMfg Li BH. Cloud computing and internet of things-based cloud manufacturing service system. IEEE Trans Ind Informatics 2014;10:1435–42.
[9] Xu X. From cloud computing to cloud manufacturing. Robot Comput Integr Manuf 2012;28:75–86.
[10] Wu D, Greer MJ, Rosen DW, Schaefer D. Cloud manufacturing: strategic vision and state-of-the-art. J Manuf Syst 2013;32:564–79.
[11] Monostori L, Kádár B, Bauernhansl T, Kondoh S, Kumara S, Reinhart G, et al. Cyber-physical systems in manufacturing. CIRP Ann – Manuf Technol 2016;65:621–41.
[12] Lee J, Bagheri B, Kao HA. A cyber-physical systems architecture for industry 4.0-based manufacturing systems. Manuf Lett 2015;3:18–23.
[13] Wang L, Torngren M, Onori M. Current status and advancement of cyber-physical systems in manufacturing. J Manuf Syst 2015;37:517–27.
[14] Zhang C, Jiang P, Cheng K, Xu XW, Ma Y. Configuration design of the add-on cyber-physical system with CNC machine tools and its application perspectives. Procedia CIRP 2016;56:360–5.
[15] Isaksson O, Larsson TC, Ronnback AO. Development of product-service systems: challenges and opportunities for the manufacturing firm. J Eng Des 2009;20:329–48.
[16] Lu Y, Xu X, Xu J. Development of a hybrid manufacturing cloud. J Manuf Syst 2014;33:551–66.
[17] Cheng T, Zhang J, Hu C, Wu B, Yang S. Intelligent machine tools in a distributed network manufacturing mode environment. Int J Adv Manuf Technol 2001;17:221–32.
[18] Kim DH, Song JY, Lee JH, Cha SK. DevelopMent and evaluation of intelligent Machine tools based on knowledge evolution in M2 M environMent. J Mech Sci Technol 2009;23:2807–13.
[19] Ridwan F, Xu X. Advanced CNC system with in-process feed-rate optimisation. Robot Comput Integr Manuf 2013;29:12–20.
[20] Morgan J, O'Donnell GE. Cyber physical process monitoring systems. J Intell Manuf 2015:1–12.
[21] Atluru S, Huang SH, Snyder JP. A smart machine supervisory system framework. Int J Adv Manuf Technol 2012;58:563–72.
[22] Li Y, Liu Q, Xiong J, Wang J. Research on data-sharing and intelligent CNC machining system, 2015. 2015. p. 625–30.
[23] STEP Tools Inc. Digital thread for manufacturing; 2017 https://www.steptools.com/sln/thread/.
[24] Mazak Corporation. Mazak SmartBox; 2017 https://www.mazakusa.com/machines/technology/digital-solutions/mazak-smartbox/.
[25] DMG MORI CO. LTD. DMG MORI software; 2017 https://us. dmgmori. com/products#Software.
[26] SHENYANG MACHINE TOOL CO. LTD. i5 smart numeric control; 2017 http://www.i5cnc.cn/pages/i5. html.
[27] Wang H, Xu X, Des Tedford J. An adaptable CNC system based on STEP-NC and function blocks. Int J Prod Res 2007;45:3809–29.
[28] Rauch M, Laguionie R, Hascoet JY, Suh SH. An advanced STEP-NC controller for intelligent machining processes. Robot Comput Integr Manuf 2012;28:375–84.
[29] Ridwan F, Xu X, Liu G. A framework for machining optimisation based on STEP-NC. J Intell Manuf 2012;23:423–41.
[30] Um J, Suh S-H, Stroud I. STEP-NC machine tool data model and its applications. Int J Comput Integr Manuf 2016;29:1058–74.
[31] Xu XW, Newman ST. Making CNC machine tools more open, interoperable and intelligent—a review of the technologies. Comput Ind 2006;57:141–52.
[32] b Li B-H, Zhang L, Wang S-L, Tao F, Cao J-W, Jiang X-D, et al. Cloud manufacturing: a new service-oriented networked manufacturing model. Jisuanji Jicheng Zhizao Xitong/Computer Integr Manuf Syst CIMS 2010;16, 1-7+16.
[33] Palanisamy P, Rajendran I, Shanmugasundaram S. Prediction of tool wear using regression and ANN models in end-milling operation. Int J Adv Manuf Technol 2008;37:29–41.
[34] Zain AM, Haron H, Sharif S. Prediction of surface roughness in the end milling machining using Artificial Neural Network. Expert Syst Appl 2010;37:1755–68.
[35] Aliustaoglu C, Ertunc HM, Ocak H. Tool wear condition monitoring using a sensor fusion model based on fuzzy inference system. Mech Syst Signal Process 2009;23:539–46.
[36] Lo S-P. An adaptive-network based fuzzy inference system for prediction of workpiece surface roughness in end milling. J Mater Process Technol 2003;142:665–75.
[37] Wu D, Jennings C, Terpenny J, Gao RX, Kumara S. A comparative study on machine learning algorithms for smart manufacturing: tool wear prediction using random forests. J Manuf Sci Eng 2017;139:71018.
[38] Widodo A, Yang B-S. Support vector machine in machine condition monitoring and fault diagnosis. Mech Syst Signal Process 2007;21:2560–74.
[39] Liang SY, Hecker RL, Landers RG. Machining process monitoring and control: the state-of-the-art. J Manuf Sci Eng 2004;126:297.
[40] Teti R, Jemielniak K, O'Donnell G, Dornfeld D. Advanced monitoring of machining operations. CIRP Ann – Manuf Technol 2010;59:717–39.
[41] Abellan-Nebot JV, Subirón FR. A review of machining monitoring systems based on artificial intelligence process models. Int J Adv Manuf Technol 2009;47:237–57.
[42] Deng C, Guo R, Liu C, Zhong RY, Xu X. Data cleansing for energy-saving: a case of cyber-physical machine tools health monitoring system. Int J Prod Res 2017;7543:1–16.
[43] MTConnect Institution. MTConnect; 2008 http://www.mtconnect.org/.
[44] Foundation OPC. OPC unified architecture; 2006 https://opcfoundation.org/about/opc-technologies/opc-ua/.
[45] Sobel W. MTConnect ® standard part 2–device information model; 2014.
[46] Lei P, Zheng L, Wang L, Wang Y, Li C, Li X. MTConnect compliant monitoring for finishing assembly interfaces of large-scale components: a vertical tail section application. J Manuf Syst 2017;45:121–34.
[47] Mahnke W, Leitner SH, Damm M. OPC unified architecture; 2009.
[48] Liu C, Cao S, Tse W, Xu X. Augmented reality-assisted intelligent window for cyber-physical machine tools. J Manuf Syst 2017;44:280–6.
[49] Ho W-H, Tsai J-T, Lin B-T, Chou J-H. Adaptive network-based fuzzy inference system for prediction of surface roughness in end milling process using hybrid Taguchi-genetic learning algorithm. Expert Syst Appl 2009;36:3216–22.
[50] Yao Z, Mei D, Chen Z. On-line chatter detection and identification based on wavelet and support vector machine. J Mater Process Technol 2010;210:713–9.

Please cite this article in press as: Liu C, et al. A systematic development method for cyber-physical machine tools. J Manuf Syst (2018), https://doi.org/10.1016/j.jmsy.2018.02.001