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MTConnect-based Cyber-Physical Machine Tool: a case study

Chao Liu, Xun Xu*, Qijia Peng, Zhengyi Zhou

Department of Mechanical Engineering, University of Auckland, 20 Symonds Street, Auckland 1010, New Zealand

* Corresponding author. Tel.: +64 9 373 7599; Fax: +64 9 373 7479. *E-mail address:* xun.xu@auckland.ac.nz

Abstract

Recent advancements in Information and Communication Technology have shown immense potential of advancing current CNC machine tools to Cyber-Physical Machine Tools (CPMT). CPMT deeply integrates machine tool and machining processes with computation and networking, thus becoming more intelligent, interconnected and autonomous. However, challenges of data communication and management remain. This is due to the diversity of manufacturing devices, sensors used and hence the delivery of data types. This paper presents an MTConnect-based CPMT that allows diverse types of real-time manufacturing data to be effectively and efficiently collected and managed, to enable advanced human-machine interactions and cloud-based decision-making supports in CPMT.

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Keywords: Machine Tool 4.0; Cyber-Physical Machine Tool; MTConnect

1. Introduction

Machine tool 4.0 introduces a new generation of machine tools that are smarter, well connected, widely accessible, more adaptive and more autonomous [1]. Cyber-Physical Machine Tools (CPMT), based on recent advancements of Information and Communication Technology such as Cyber-Physical Systems (CPS), Internet of Things (IoT) and cloud-based solutions, provides a promising solution for Machine Tool 4.0. CPMT is defined as 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 [2]. Compared with a typical Computer Numerical Control (CNC) machine tool, CPMT has distinct advantages in terms of connectivity, intelligence and autonomy. The most significant of all is the use of Machine Tool Cyber Twin (MTCT). MTCT refers to the digital twin of the physical machine tool. It represents the real-time status of the machine tool and machining processes, monitors and controls the machine tool with built-in computation and intelligence, and provides the field-level machining data to the cloud for further analytics and decision-making supports.

In order to build a MTCT, various types of real-time machining data must be collected from the shop floor and transferred to the cyber space. In the cyber space, an information model of the machine tool needs to be developed to manipulate the machining data and correlate them with their associated components in a logical structure. While some real-time feedback such as power status and axes positions can be directly retrieved from some modern CNC controllers, diverse types of sensors and data acquisition devices also need to be deployed to collect real-time machining data such as cutting forces and vibrations. However, the diversity of CNC controllers, sensors and data acquisition systems results in various proprietary data formats and communication standards. Consequently, data communication, integration and management become challenging tasks in the development of CPMT. Recently, MTConnect and OPC Unified Architecture (OPC UA) have shown great potential for addressing these issues. 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 [3]. OPC UA is a set of open, royalty-

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free standards designed as a universal factory floor communication protocol developed by the OPC Foundation [4]. Despite their differences in data encoding, transmission method, information modelling method and so forth, both two standards are open, royalty-free, platform-independent and extensible. Hence both can be implemented in CPMT.

This paper introduces an MTConnect-based CPMT prototype developed in our laboratory. The prototype was developed based on a Sherline 3-axis milling machine. Various real-time machining data were collected from the CNC controller and different sensors such as radio frequency identification (RFID) tags, dynamometer, accelerometer and RPM sensor. MTConnect was implemented as the communication standard as well as the information modelling technique to realize unified and efficient data communication, integration and management in the MTCT. Experimental results have validated the feasibility and advantages of the proposed MTConnect-based CPMT.

The rest of this paper is organized as follows: Section 2 gives a brief review of MTConnect related work. Section 3 introduces the system architecture of MTConnect-based CPMT. Section 4 presents the developed MTConnect-based CPMT prototype. Section 5 concludes the paper.

2. Review of MTConnect related work

Owing to its open, lightweight, interoperable, extensible and easy implementation characteristics, MTConnect has attracted more and more attention in both academia and industry. Edrington et al. [5] introduced a web-based machine monitoring system that provides data collection, analysis, and machine event notification for any MTConnect compatible machines. The monitoring system provides shop floor managers with various production information to improve process efficiency and overall equipment effectiveness (OEE). Vijayaraghavan et al. [6] presented a case study using MTConnect data from a machine tool for process planning verification. The actual cutting parameters were compared with the programmed cutting parameters (including tool position and feed-rate) to prove the potential of MTConnect for improving the accuracy and impact of process planning. Shin et al. [7] developed a virtual machining model that uses STEP-NC files as process planning data to generate MTConnect-based machine-monitoring data. The virtual machining model enabled machining performance prediction during process planning stage. Lei et al. [8] proposed an MTConnect compliant method to implement a web-based monitoring system. Extended MTConnect data models were developed to represent a finishing system including on-machine touch-trigger probe and sensor-based intelligent fixturing related information.

Recognizing the potential of MTConnect, Boeing worked with NIST and other members of the Open Modular Architecture Controllers User Group, to test the performance of MTConnect on a distributed “Dual Ethernet” factory testbed [9]. By measuring the computational load under different working conditions, they proved that MTConnect satisfies the communication requirement in shop floors. In the next year, the same group investigated the feasibility of MTConnect-based Kaizen on the plant floor [10]. Using real-time MTConnect data, the Kaizen transformation of machine data into production knowledge was performed to understand energy consumption, asset operation and process performance. Mazak Cooperation launched a Mazak SmartBox [11] as a scalable, end-to-end Industrial Internet of Things platform. MTConnect is used as the underlying protocol to connect machines, software and other devices to a factory’s network and management systems. 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 [12]. A 3D model-based machining simulator which fuses STEP models of the product, MTConnect status of the machine tool and Quality Information Framework (QIF) metrology feedback was developed to build the digital twin.

Previous work has shown great potential and advantages of implementing MTConnect in manufacturing systems. In effect, MTConnect is not only a communication protocol; it also provides an information modelling method specially designed for CNC machine tools. Therefore, this paper investigates the feasibility of developing a CPMT based on MTConnect.

3. System architecture of MTConnect-based CPMT

The system architecture of the proposed MTConnect-based CPMT is shown in Figure 1. It is comprised of four layers, including Physical devices, Networks, MTCT and Cloud.

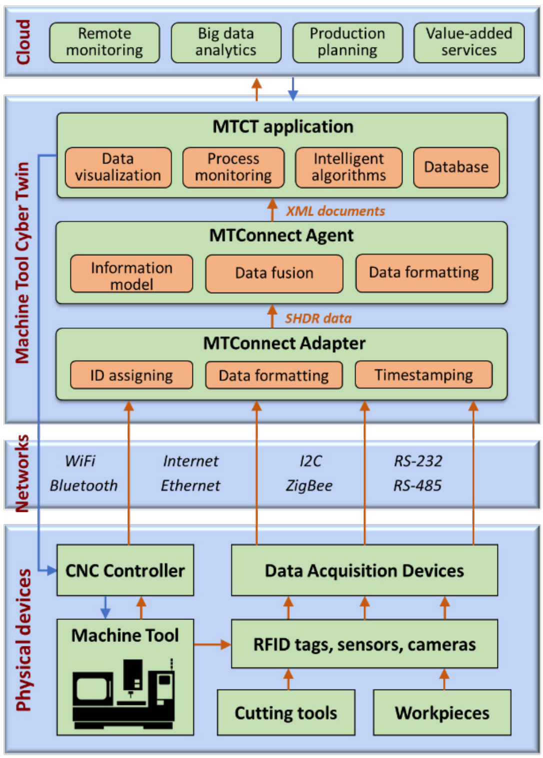


Fig. 1. System architecture of MTConnect-based CPMT

In the Physical devices layer, real-time machining data of the machine tool, the critical components and the machining processes are collected from the CNC controller and various sensors. Modern CNC controllers can provide some real-time feedback such as power status, operation mode and axes positions of the machine tool. However, additional sensors such as RFID tags, accelerometers and dynamometers also need to be deployed to obtain the critical data that significantly affect the machining performance. These critical data include the static attributes of the machine tool, the cutting tools and the workpieces as well as the real-time machining data such as cutting forces, vibrations, acoustic emissions, and so forth.

The Networks layer endows the CPMT with advanced connectivity. It connects the physical machine tool with its MTCT by transmitting all the real-time machining data from the CNC controllers and data acquisition devices to the MTConnect Adapter. Based on different communication requirements, various types of networks such as Ethernet, WiFi, Bluetooth, I2C (Inter-Integrated Circuit) and RS-232 need to be implemented to realize reliable and efficient data communication between the physical world and the MTCT.

MTCT is the core of CPMT. It comprises three main components: (1) MTConnect Adapter, (2) MTConnect Agent and (3) MTCT application.

(1) MTConnect Adapter: it receives all the real-time data from the Networks layer and assigns each data item with a unique ID. It converts all these data into SHDR (Simple Hierarchical Data Representation) format and timestamps each piece of data. These data will then be associated to MTConnect data items. MTConnect adapter filters the duplicated data and continuously sends the changed data to the MTConnect Agent.

(2) MTConnect Agent: an MTConnect-based machine tool information model resides in the MTConnect Agent. The information model is an XML file which represents the logical structure of the machine tool, including all the critical components and their related data items. MTConnect Agent receives the SHDR data from MTConnect Adapter, and correlates each data item with its associated component in the information model using their unique IDs. In this way, data from different sources can be grouped together to comprehensively represent the status of certain components. MTConnect Agent works as a web server. It formats all the real-time data into XML files based on the schemas defined by MTConnect standard, and sends these XML files to other applications based on specific HTTP requests through TCP/IP protocol.

(3) MTCT application: it requests real-time machining data from the MTConnect Agent and uses these data to model the MTCT. Firstly, it provides intuitive data visualization by displaying the logical structure of the machine tool as well as all the available real-time data of each critical component. Secondly, it provides process monitoring functions based on real-time analysis of the machining data. Thirdly, various intelligent algorithms can be embedded in the application to improve the intelligence of the machine tool. Moreover, the application has a database which manages and stores the timestamped real-time machining data. These historical data can then be accessed by other applications to realize big data analytics and value-added services.

The cloud layer contains various cloud-based applications which access the MTCT through the Internet and provide cloud-based services. Firstly, remote process monitoring on mobile devices (e.g. smart phones, tablets and wearable devices) can be easily achieved by requesting the XML files directly from the MTConnect Agent, and processing and displaying them on the mobile devices. Secondly, various big data analytics tools and resource management systems can access the historical manufacturing data in the MTCT. Thus cloud-based decision-makings for product designers, production planners and enterprise managers can be realized. Furthermore, MTCT can be mapped to the cloud, such that it becomes a manufacturing service that can be provided, managed and consumed in the context of cloud manufacturing [13].

Feedback control is an indispensable part of CPMT. Since MTConnect is a one-way protocol, feedback control directly through MTConnect is not possible. Moreover, CNC controllers are usually proprietary and closed, raising more challenges of feedback control in the MTConnect-based CPMT. To address these issues, three different types of feedback control in MTConnect-based CPMT are proposed, including 1) manual feedback control, 2) autonomous feedback control, and 3) cloud-based feedback control.

Firstly, MTCT provides various advanced real-time data visualization and Prognostics and Health Management (PHM) functions [14], such that shop floor technicians (machine operators, maintenance technicians, etc.) can make more efficient decisions such as proactive maintenance during machining processes. Secondly, various embedded process optimization algorithms retrieve specific real-time machining data, analyze them in real time and send the results as control commands to the CNC controller to realize autonomous in-process machining optimization. For open CNC controllers such as LinuxCNC used in our case study, control commands can be directly sent to the controller through Application Programming Interfaces (APIs) of the control software. However, for proprietary and closed CNC controllers, control commands have to be sent to the controllers through proprietary interfaces or adapters provided by the CNC manufacturers. Thirdly, various cloud-based data analytics such as deep learning algorithms [15] take advantage of the historical machining data and provide value-added services as feedback to the physical world. Examples of the results of cloud-based feedback include optimized production plans, process plans, maintenance schedules, and so forth.

4. MTConnect-based CPMT prototype

This section introduces the MTConnect-based CPMT prototype developed in our laboratory. The prototype validates the feasibility of implementing MTConnect in CPMT as the communication standard as well as the information modelling technique.

4.1. Experimental setup

To investigate the data integration capability of MTConnect, different data acquisition devices and networks were implemented on the prototype to collect real-time machining data. The experimental setup of the MTConnect-based CPMT prototype is shown in Figure 2. The prototype was developed on a Sherline 3-Axis Milling machine. Two 13.56MHz RFID tags were assigned to the machine tool and a cutting tool to store their attributes data. An NFC shield was installed on an Arduino Uno development board to read the data in the RFID tags. An RPM sensor was mounted above the spindle to detect the actual spindle speed. A Kistler type 9273 3-axis dynamometer was mounted on the work table to measure the cutting forces in X, Y and Z direction. A PCB model 352C65 Piezoelectric accelerometer was used to measure the vibration of the spindle.

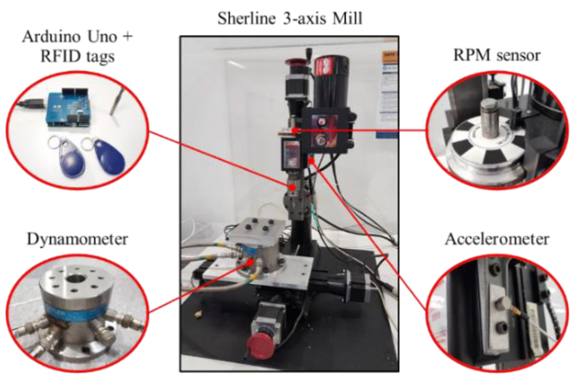


Fig. 2. Experimental setup of MTConnect-based CPMT prototype

4.2. MTConnect implementation

The overall system architecture of the MTConnect-based CPMT prototype is described in Figure 3. The machine tool is controlled by LinuxCNC software installed in a Linux based computer. The NFC shield on the Arduino microcontroller reads the RFID tags and sends the attributes data of the machine tool and cutting tool 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. The signals are filtered and processed using LabView software. A TCP server created in LabView sends the pre-processed sensor data (i.e. cutting forces, vibration and spindle speed) to the MTConnect Adapter

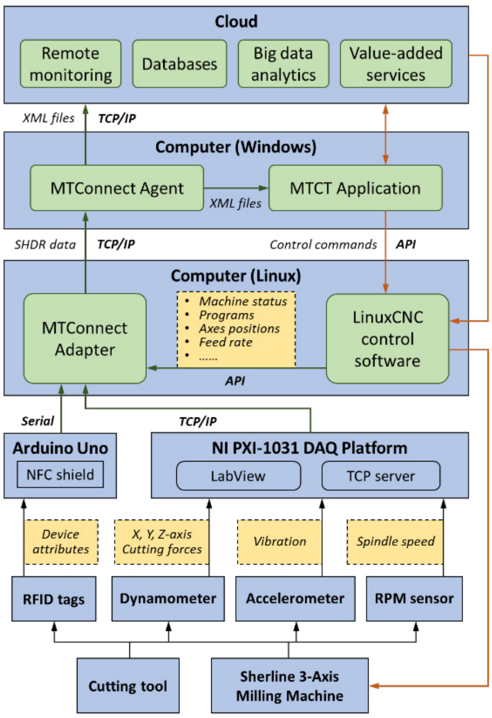


Fig. 3. Overall system architecture of MTConnect-based CPMT prototype

through TCP/IP connection. Real-time machining data from the CNC controller, including machine status, machining programs, axes positions, feed rate and so on, 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 is written in C++. It receives all the real-time data through the aforementioned connections and converts them into SHDR format with timestamps attached. Then the MTConnect Adapter keeps sending these data to the MTConnect Agent through TCP/IP connection once they are connected. To reduce data redundancy, only changed values of each data item will be sent. Figure 4 shows a screenshot of the SHDR data sent by the adapter during machining process. The data refresh interval for this MTConnect Adapter is set to 100ms due to the large amount of real-time data need to be transmitted. As shown in Figure 4, axes positions, spindle speed, vibration and cutting forces were continuously sent since they were changing. The power status, controller mode, feed rate and so forth will only be sent when they changed.

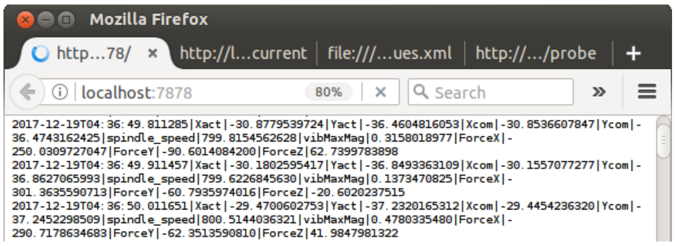


Fig. 4. SHDR data sent by MTConnect Adapter

MTConnect provides an information modelling method for machine tools. It defines a hierarchical XML data model comprised of two primary types of XML elements, i.e. structural elements and data elements [16]. Structural elements represent the physical or logical components of the machine tool; while data elements represent the data items related to each component. MTConnect also defines a comprehensive dictionary of the components and data items for typical CNC machine tools. An MTConnect-based information model for the Sherline 3-Axis mill was developed as a XML file. Figure 5 shows the structure of the information model.

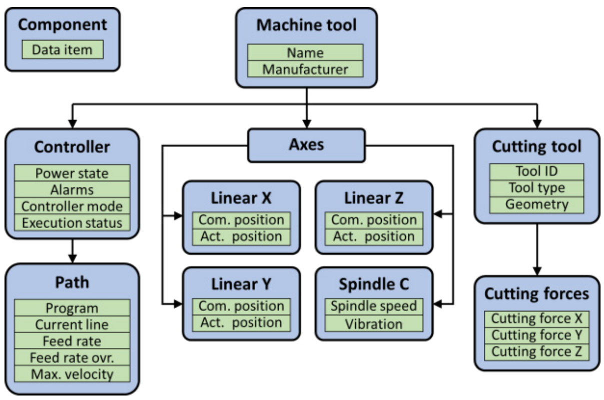


Fig. 5. Structure of MTConnect-based information model for Sherline mill

The information model groups all the data items from different sources into their related components to represent comprehensive status of each component. For example, the data items of Controller and Spindle are shown in Figure 6(a) and 6(b). Data items including power state, alarm, controller mode and execution status retrieved from the LinuxCNC software are grouped under Controller component. The spindle speed measured by the RPM sensor and the vibration magnitude measured by the accelerometer are grouped under Spindle component.

The MTConnect Agent used in this prototype is an open sourced C++ agent developed by the MTConnect Institute. It ran on a Window computer which was connected to the Linux computer in local network. The MTConnect Agent receives the SHDR data from the Adapter through TCP/IP connection and correlates them to the data items in the information model. Then it formats all the data into MTConnect-based XML files and sends them to other applications based on HTTP requests.

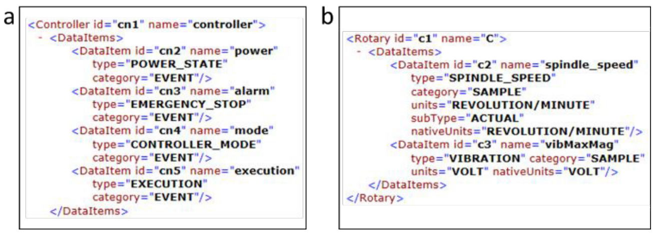


Fig. 6. (a) data items of Controller; (b) data items of Spindle

4.3. MTCT application

An MTCT application was developed in C# to demonstrate basic functions of the MTCT. It requests all the real-time data as XML files from the MTConnect Agent by sending HTTP requests. The current MTCT application has four main functions. First, it parses the information model and displays the logical structure of the machine tool in a tree structure as shown in Figure 7. The relations of the critical components and their associated data items are clearly presented, including the names and types of the data.

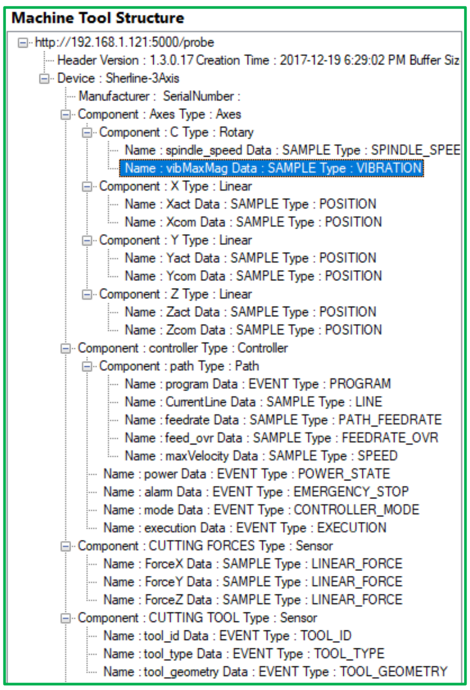


Fig. 7. Logical structure of the machine tool

Second, the values of all the available data items are displayed and updated (every 100ms) to present the real-time status of each component and machining process. Figure 8 shows a snapshot of the machine tool status during a random machining process. The Controller component indicates the power state of the machine tool, the execution status and mode of the controller, the program location, the current line of the program, the feed rate and the feed rate override. The actual and commanded positions of X, Y and Z axis and the speed and vibration of the spindle are displayed under Axes component. The basic information of the cutting tool being used and the cutting forces in X, Y and Z axis are presented at the bottom.

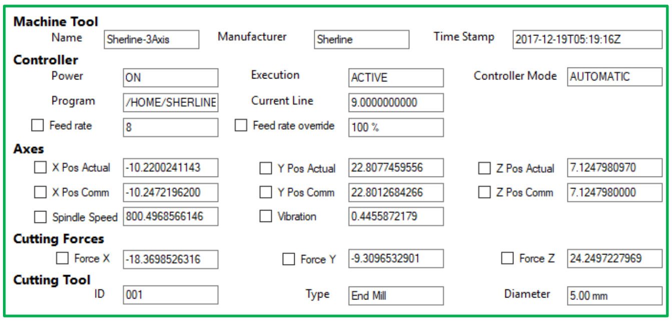
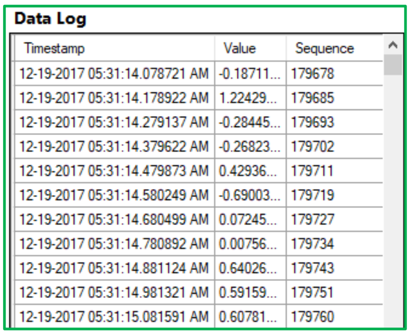


Fig. 8. Snapshot of real-time machine tool status

Third, the historical data of each available data item can be stored and displayed as a spreadsheet in the Data log window. Figure 9 shows an example of the historical data of spindle vibration. The first column indicates the timestamps of each value. The second column contains the values of the data. The third column shows the MTConnect sequence number of each value. These historical data can be directly saved as spreadsheets locally or transferred to the cloud database through the Internet. Consequently, various cloud-based data analytics and decision-makings can be realized.



Data Log

Timestamp	Value	Sequence
12-19-2017 05:31:14.078721 AM	-0.18711...	179678
12-19-2017 05:31:14.178922 AM	1.22429...	179685
12-19-2017 05:31:14.279137 AM	-0.28445...	179693
12-19-2017 05:31:14.379622 AM	-0.26823...	179702
12-19-2017 05:31:14.479873 AM	0.42936...	179711
12-19-2017 05:31:14.580249 AM	-0.69003...	179719
12-19-2017 05:31:14.680499 AM	0.07245...	179727
12-19-2017 05:31:14.780892 AM	0.00756...	179734
12-19-2017 05:31:14.881124 AM	0.64026...	179743
12-19-2017 05:31:14.981321 AM	0.59159...	179751
12-19-2017 05:31:15.081591 AM	0.60781...	179760

Fig. 9. Historical data of spindle vibration in the Data log window

Last, some basic real-time data visualization and analysis functions were embedded in the MTCT application to provide more intuitive perception of the machining processes. Figure 10 shows some examples. Figure 10(a) displays the execution status of the machine tool (Active, Interrupted or Ready) in the time domain. The machine utilization rate was calculated accordingly and shown as a pie chart on the right. Figure 10(b) presents the actual position of X-axis in the time domain as a line graph. This function can be used on any data item which has a tick box in Figure 8. The cutting forces in X, Y and Z axis are simultaneously displayed in Figure 10(c). Figure 10(d) shows the maximum vibration magnitude of the spindle in the time domain. This data was previously filtered and pre-processed by LabView. These functions proved that various intelligent algorithms can be easily embedded in the MTCT application, such that advanced artificial intelligence and human-machine interactions can be achieved. An example of Augmented Reality-assisted human-machine interaction in CPMT can be found in our previous research [17].

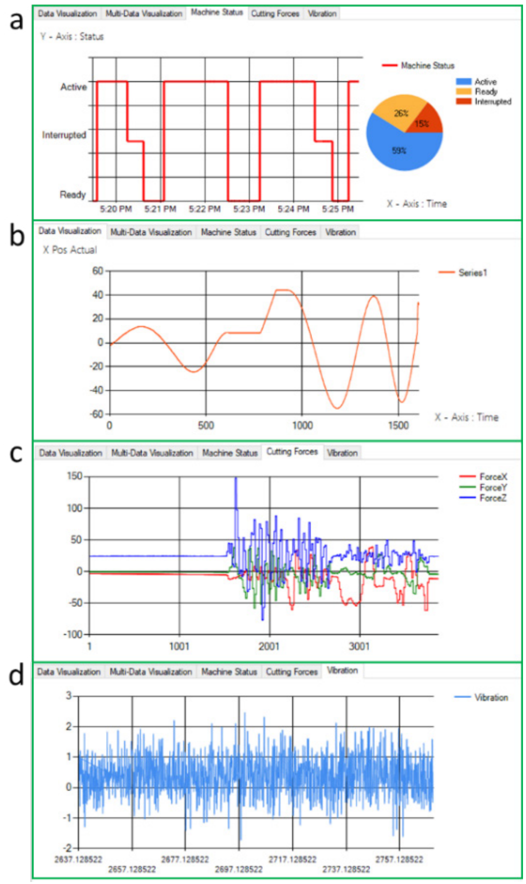


Fig. 10. (a) machine tool execution status; (b) X-axis position; (b) cutting forces in X, Y, Z axis; (d) maximum vibration magnitude of spindle

5. 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. To address the data communication and information modelling issues in CPMT, this paper proposes an MTConnect-based CPMT.

A four-layer system architecture is proposed to integrate MTConnect with CPMT. An MTConnect-based CPMT prototype was developed to validate the feasibility of the proposed method. The prototype was developed based on a Sherline 3-Axis Milling machine. Various sensors such as RFID tags, accelerometer, dynamometer and RPM sensor were deployed to collect real-time machining data from the critical components and machining processes. Experimental results proved that MTConnect allows unified and efficient data communication across different networks and operation systems. The MTConnect-based information model shows great advantages of data integration and management in CPMT. An MTCT application was developed to demonstrate the basic functions of the MTCT, including machine tool structure representation, real-time status monitoring, data visualization and analysis, and historical data archiving. The application shows great potential of the implementations of artificial intelligence, advanced human-machine interactions and cloud-based decision-making supports in MTConnect-based CPMT.

The focus of our future work will be the implementation of artificial intelligence and different types of feedback control in MTConnect-based CPMT. Advanced data visualization and analytics algorithms will be embedded in the MTCT. Autonomous in-process machining optimization such as feed-rate optimization will be realized by sending control commands from MTCT to LinuxCNC through APIs. Moreover, mobile applications for the prototype will be developed on smart phones and wearable devices to enable various cloud-based decision-making support and value-added services.

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