

A Cyber-Physical Machine Tools Platform using OPC UA and MTConnect

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ABSTRACT: Cyber-Physical Machine Tools (CPMT) represent a new generation of machine tools that are smarter, well connected, widely accessible, more adaptive and more autonomous. Development of CPMT requires standardized information modelling method and communication protocols for machine tools. This paper proposes a CPMT Platform based on OPC UA and MTConnect that enables standardized, interoperable and efficient data communication among machine tools and various types of software applications. First, a development method for OPC UA-based CPMT is proposed based on a generic OPC UA information model for CNC machine tools. Second, to address the issue of interoperability between OPC UA and MTConnect, an MTConnect to OPC UA interface is developed to transform MTConnect information model and its data to their OPC UA counterparts. An OPC UA-based CPMT prototype is developed and further integrated with a previously developed MTConnect-based CPMT to establish a common CPMT Platform. Third, different applications are developed to demonstrate the advantages of the proposed CPMT Platform, including an OPC UA Client, an advanced AR-assisted wearable Human-Machine Interface and a conceptual framework for CPMT powered cloud manufacturing environment. Experimental results have proven that the proposed CPMT Platform can significantly improve the overall production efficiency and effectiveness in the shop floor.

Key words: Cyber-Physical Machine Tools; Machine Tool 4.0; digital twin; OPC UA; MTConnect

1. INTRODUCTION

Machine tools play a vital role in the realm of manufacturing in that their performances significantly impact on production efficiency and effectiveness. In response to the requirements of Cyber-Physical Production Systems (CPPS) [1,2] and Smart Factory[3–6], there exists an urgent need to advance existing Computer Numeric Control (CNC) machine

tools to a higher level of connectivity, accessibility, intelligence and autonomy. In this context, Machine Tool 4.0 [7] was proposed as a new technological evolution of machine tools triggered by recent advancements of Information and Communication Technologies (ICT) such as Cyber-Physical Systems (CPS), Internet of Things (IoT) and cloud technology. 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 [8]. Xu [7] proposed three new types of machine tools as the possible solutions of Machine Tool 4.0, namely Cyber-Physical Machine Tools (CPMT), vertically-integrated machine tools, and horizontally-integrated machine tools.

- CPMT refers to 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.
- Vertically-integrated machine tools are those that can support end-to-end digital integration throughout the engineering process encompassing design, process planning, manufacturing, assembly, and so forth. Model-based manufacturing such as STEP-NC-enabled CAD/CAM/CNC integration [9,10] is one of the key enabling technologies;
- Horizontally-integrated machine tools refer to machine tools that are interconnected with other manufacturing facilities and resources (e.g. robots, conveyors, measurement devices, enterprise resource planning systems) through semantics-enabled machine-to-machine (M2M) communications, eventually leading towards a cooperative production system.

The focus of this research is on CPMT. In general, CPMT is a CPS-based machine tool which has the characteristics of a typical CPS, such as network connectivity, adaptability, predictability, intelligence, with real-time feedback loops and with humans in the loop [11]. With extensive real-time machining data and computations deeply integrated with machine tool and machining processes, CPMT provides various types of feedback loops such as autonomous feedback control, shop floor decision-making support and cloud-based analytics; all intend to improve the performance, efficiency and effectiveness of a machine tool. The core of a CPMT, as well as the most significant advancement of CPMT compared to traditional CNC machine tools, lies in its Machine Tool Digital Twin (MTDT). MTDT refers to the digital twin of the machine tool that is capable of: (1) representing the characteristics

and real-time status of the machine tool, (2) monitoring and controlling the machine tool with built-in computation and intelligence, and (3) sending 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.

Modelling of the MTDT is a challenging task. Firstly, CNC machine tools are complex systems comprising various types of components and peripheral devices. Different types and brands of machine tools may have different structures and components. In order to comprehensively and intuitively represent a physical machine tool in the cyber world, a generic information model for machine tools representing the logical structure as well as the real-time status of each critical component of the machine tool must be developed. Secondly, a large amount of different types of real-time machining data obtained from various types of data acquisition devices (e.g. CNC controller, RFID tags, power meters, accelerometers, dynamometers, acoustic emission sensors) presents a great challenge in data communication, management and analytics. Open, unified and cross-platform communication standards must be implemented to address these issues. Recently, MTConnect [12] and OPC UA [13] have both shown great capabilities in terms of information modelling and real-time data exchange for manufacturing systems. Both MTConnect and OPC UA are open and royalty free communication standards designed for industrial automation. MTConnect provides a concrete information modelling method specifically designed for CNC machine tools with some predefined data structures and rules, whereas OPC UA offers a more generic information modelling method in order to cover a broader range of industrial equipment and systems.

In our previous work presented in [14], a systematic development method based on a generic system architecture for CPMT was proposed to provide the guidance on advancing CNC machine tools to CPMT. An MTConnect-based CPMT prototype was developed to demonstrate the feasibility and capability of the proposed CPMT. In this paper, we propose a CPMT Platform based on both OPC UA and MTConnect. Firstly, the development method for OPC UA-based CPMT is proposed. The system architecture and generic OPC UA-based information modelling method for CPMT are studied. An OPC UA-based CPMT prototype is developed based on a 3-axis CNC milling machine (EMCO Concept Mill 105) to validate the feasibility of the proposed method. Secondly, a CPMT Platform that is compatible with both OPC UA and MTConnect is proposed. Communication interfaces between OPC UA and MTConnect are developed. A prototype of the CPMT Platform is established by integrating the OPC UA-based CPMT prototype with the previously developed MTConnect-based CPMT prototype. Furthermore, an advanced wearable HMI with Augmented Reality (AR)-

assisted process monitoring and simulation functions, and a conceptual framework for CPMT powered cloud manufacturing environment are introduced to demonstrate the potential of the CPMT Platform.

The remainder of this paper is organized as follows. Section 2 reviews the state-of-art work related to digital twin technologies as well as the implementation of OPC UA. Section 3 introduces the proposed OPC UA-based CPMT, including a generic information modelling method and an OPC UA-based CPMT prototype. The CPMT Platform is proposed in Section 4, and the integration of OPC UA- and MTConnect-based CPMT is demonstrated through a case study. Section 5 briefly introduces two applications for the CPMT Platform. Conclusions are given in Section 6.

2. LITERATURE REVIEW

Digital twin is a key component of any CPS. The core of a CPMT lies in its MTDT. Development of MTDT requires standardized information modelling technology and communication protocol. This research utilizes OPC UA as a key enabling technology to develop the CPMT Platform. This section reviews the state-of-the-art work on digital twin and OPC UA related research and identifies the research gaps in this field. A brief review of MTConnect-related work and the details of MTConnect-based CPMT can be found in [15].

2.1 Digital Twin related research

With the rapid development of CPS, the concept of digital twin (or cyber twin) has attracted more and more attention. The term “digital twin” was initially brought to public by NASA’s Modelling, Simulation, Information Technology & Processing Roadmap in 2010 [16]. Currently, there exist various definitions of digital twin from different perspectives such as lifecycle management, mission requirements, prognostics and diagnostics activities, and so forth [17]. A commonly used definition of digital twin was provided by Glaessgen and Stargel [18], i.e. ‘Digital twin is an integrated multi-physics, multi-scale, probabilistic simulation of a complex product and uses the best available physical models, sensor updates, etc., to mirror the life of its corresponding twin.’

Nowadays, digital twin is considered as a key enabler for Product Lifecycle Management (PLM), CPPS and Smart Factory in the era of Industry 4.0 [19–21]. Lee et al. [22] proposed a conceptual CPS architecture for a manufacturing system, where each critical component has a digital twin for capturing sensory data and synthesizing future steps. These digital twins are

then aggregated as a digital twin for a particular machine, endowing the machine with self-awareness, self-prediction and self-comparison capabilities. Tao et al. [20] proposed a new digital twin-driven approach to realize more efficient, smart and sustainable product design, manufacturing and service. Tao et al. [23] proposed a five-dimension digital twin model for the Prognostics and Health Management (PHM) of complex equipment. Advantages of the digital twin approach compared to traditional prediction methods have been validated through a case study of the fault cause prediction of a wind turbine. Aiming to develop digital-twins of virtual machine tools for cyber-physical manufacturing, Cai et al. [24] presented some techniques for extracting machining characteristics profiles using sensory data integration and machining information fusion. However, unified communication standard and information model were not implemented for data management. Schroeder et al. [25] presented a methodology to model the digital twin of a manufacturing device, making use of AutomationML at a high level. A digital twin of a valve was modelled to represent its physical components as well as some attributes. Urbina Coronado et al. [26] proposed a Shop Floor Digital Twin framework which represents parts, operators, capital equipment and consumables in the shop floor and allows decision-making support for different users. A Web-based Manufacturing Execution System (MES) was developed to collect and track materials, cutting tool usage, operator activities and work-in-process. STEP Tools Inc. [27] developed a digital thread solution which keeps the design, manufacturing, and inspection data of a product connected around a digital twin. 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 of the product while it is being machined.

2.2 OPC UA related research

The introduction of OPC UA in CPPS architecture is essential in the context of Industry 4.0. Reference Architecture Model Industry 4.0 (RAMI 4.0) has been proposed to provide orientations and standardization for Industry 4.0; OPC UA was the only standard being recommended in the communication layer [28,29]. Implementation of OPC UA for Industry 4.0 is partly standardized as an international standard IEC 62541. Since OPC UA provides both communication protocol and information modelling method, it can be readily utilized to model the digital twins of manufacturing facilities.

In the last few years, research on the integration of OPC UA into process monitoring and control has been extensively studied. Schlehtendahl et al. [30] proposed a holistic approach

to integrating existing production systems to the Industry 4.0 environment. OPC UA was validated as a critical enabler for discovering existing resources, enabling data communication through cloud-based gateways and eventually transforming current production systems to CPPS. Garcia et al. [31] presented a low-cost CPPS architecture in which OPC UA can be used to access field data in automation systems. An OPC UA-based information model for a plant-floor system was also proposed. Muller et al. [32] presented an open source and free implementation of OPC UA. A customizable OPC UA server developed on an Arduino microcontroller board enabled a closed-loop temperature control of the nozzle of a 3D printer. Imtiaz and Jasperneite [33] developed a Nano OPC UA server which can be integrated into low-memory devices and at the same time possessing all the features of a standard OPC UA server. The use of such Nano OPC UA servers demonstrated the scalability of OPC UA in low-level IoT-based devices. Luo et al. [34] proposed a three-tier architecture for a smart manufacturing process where OPC UA is utilized to integrate various industrial field networks into the top-level factory energy management system. Wu et al. [35] developed a fog computing-based platform for process monitoring and prognosis by integrating OPC UA and MTConnect with milling machines. Ayatollahi et al. [36] developed a semantic communication interface that allows remote control of a machine tool with a standard OPC UA client. Sequenced control commands can be executed by dragging methods or variables exposed by the OPC UA server. Pauker et al. [37] proposed a service orchestration method for flexible manufacturing cells based on service-oriented architecture (SOA) paradigm and OPC UA communication. Various services which represent the mechatronic functions of the equipment were defined in the address space of the OPC UA server, thus the flexibility of the manufacturing cells can be enhanced. OPC UA has also been extensively implemented as the communication protocol in power consumption monitoring and energy efficiency analysis systems [38–40]. Design and development of an OPC UA information model need to follow a model-driven approach. Pauker et al. [41] proposed a systematic and generic approach for developing an information model to represent the static and dynamic behaviour of a manufacturing system. Developing the information model for a complex manufacturing system requires a huge amount of programming work. Girbea et al. [42] proposed several algorithms that aid an efficient and automatic generation of address space in OPC UA servers. Owing to the generic and flexible information modelling method, OPC UA has also been implemented in various types of process monitoring and control systems in different industries such as Smart Grid [43], Oil and Gas production [44] and Public transportation systems [45].

2.3 Research gaps

The state-of-the-art work indicates an urgent need of developing digital twins for manufacturing devices for the realization of CPPS and Smart Factory. Previous work on digital twin mainly focused on products, manufacturing systems or shop floors; few studies were on machine tools. OPC UA has been extensively implemented in various types of manufacturing devices and systems as the communication protocol. Yet, implementation of OPC UA in machine tools is still not common. There has not been much attention paid to a generic OPC UA-based information model for machine tools. Furthermore, although OPC UA and MTConnect are both capable of being used for developing CPMT, they are not yet interoperable. Given the crucial role machine tools will play in the envisioned CPPS and Smart Factory, current CNC machine tools need to be advanced to CPMT with the implementation of standardized information models and communication protocols. This paper attempts to bridge these research gaps by developing a CPMT Platform. A generic OPC UA information model for machine tools is proposed to develop an OPC UA-based CPMT. As a part of the CPMT Platform, an interface between OPC UA and MTConnect is developed.

3. OPC UA-BASED CYBER-PHYSICAL MACHINE TOOL

3.1 Generic system architecture of OPC UA-based CPMT

The generic system architecture for an OPC UA-based CPMT is proposed (Figure 1). This architecture aims at providing a generic, systematic, extensible and customizable solution for developing OPC UA-based CPMT, based on the generic CPMT architecture proposed in our previous work [14]. This section introduces the main components and their functions in the proposed architecture. The detailed development principles and implementation strategies will be discussed and demonstrated in the case study that follows.

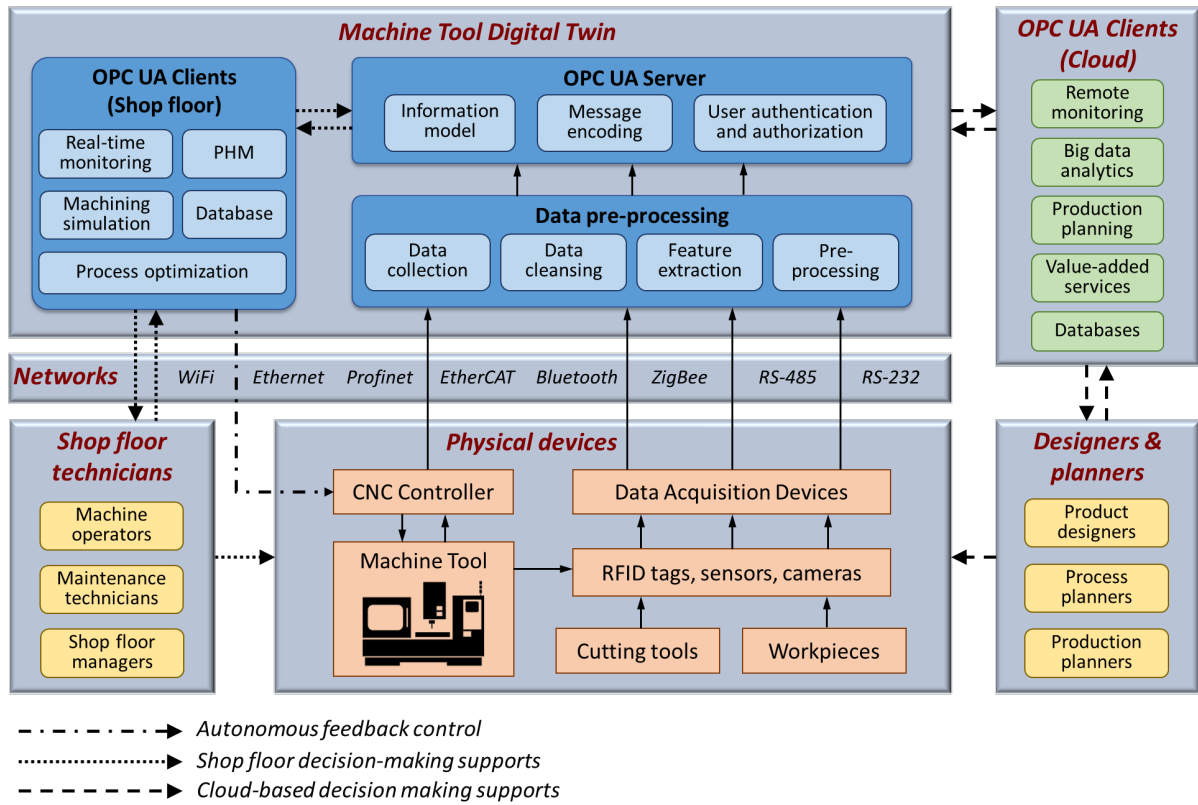


Figure 1. Generic system architecture of OPC UA-based CPMT

As shown in Figure 1, the physical devices include CNC machine tools, cutting tools, workpieces, sensors and data acquisition devices. These physical devices are responsible for carrying out machining tasks as well as transmitting the real-time machining data to the MTDT. Extracting data from CNC controllers often requires vendor-dependent tools, such as Application Programming Interfaces (APIs) or even hardware adapters. A recent trend has been observed that more and more CNC manufacturers and third-party developers are developing embedded OPC UA servers or OPC UA plugins for CNC controllers. For example, Siemens has integrated the OPC UA server in their SINUMERIK 828D and 840D controllers [46]. It can be predicted that OPC UA-based data acquisition from CNC controllers will be made easier in the near future.

In order to comprehensively represent the machining processes in a MTDT, external sensors are still needed to enable the provision of a more complete set of data for MTDT. Firstly, static properties of the machine tool and its critical components (size of the worktable, geometry of the cutting tools, etc.) need to be obtained from the shop floor. RFID tags and readers can be used to transmit these data to the MTDT. Secondly, some critical real-time machining data (cutting forces, vibrations, acoustic emissions, motor power, etc.) need to be collected using various types of sensors and data acquisition devices based on

specific needs of the users. These data represent the actual machining processes, hence providing the foundation of advanced data analytics in the MTDT.

With various types of data acquisition devices implemented in the shop floor, different networking techniques (Ethernet, WiFi, Profinet, Bluetooth, etc.) need to be implemented to transmit the data to the MTDT. MTDT is the core of the proposed CPMT consisting of three main modules: 1) data pre-processing, 2) OPC UA Server and 3) local OPC UA Client.

- 1) *Data pre-processing*: to reduce the amount of real-time data transferred to the OPC UA Server, the data obtained from various sensors need to be cleansed and pre-processed (e.g. using edge/fog computing methods) so that only useful data and features of the sensor signals are delivered to the OPC UA Server for further analysis.
- 2) *OPC UA Server*: the OPC UA information model that represents the logical structure of the machine tool is integrated in the OPC UA Server. Data obtained from the physical world are correlated to the nodes in the address space and grouped to their corresponding components in the information model. When other OPC UA Clients require data, the OPC UA Server encodes the required data into standardized messages (OPC UA Binary or XML defined by OPC UA standard) and sends them to the Clients while maintaining and securing the connections.
- 3) *Local OPC UA Clients*: these are customizable OPC UA Clients embedded in the MTDT. To achieve better real-time performance, these Clients are connected to the Server in the local (shop floor) network. They request data from the Server, analyse and process them with customized algorithms and provide decision-making supports for processes such as monitoring, machining simulation and PHM.

The proposed OPC UA-based CPMT enables three types of feedback control from the MTDT to the physical machine tool as indicated in Figure 1. In the autonomous feedback control, control commands are directly sent to the CNC controller from the MTDT. This is achieved by implementing real-time process optimization algorithms in local OPC UA Clients. These clients interface with the CNC controller through specific APIs or hardware adapters depending on the type of the controller. In the shop floor decision-making supports, local OPC UA Clients which provide decision-making support functions (e.g. visualization, monitoring, simulation, PHM) require the related real-time data from the OPC UA Server and provide corresponding functions to machine operators, maintenance technicians and shop floor managers to help them make efficient decisions during machining processes. Various types of HMIs such as laptops, smart phones and wearable devices can be utilized as OPC

UA Clients since OPC UA is platform-independent. In the cloud-based decision-making supports, various OPC UA Clients developed by third-party service providers can be provided as services in the cloud. These Clients can discover and be connected to the OPC UA Server in the MTDT in order to access the field-level manufacturing data through the Internet. Various value-added services such as remote monitoring, historical data analytics and production planning can be integrated into the Clients and provisioned to different users (product designers, process planners, production managers, etc.) through the Internet.

3.2 Generic OPC UA information model for CPMT

The information modelling method provided by OPC UA is generic and flexible. In general, OPC UA information model is represented using four main components, i.e. Objects, Variables, Methods and References. Objects are instances of an ObjectType which is equivalent to a Class in the Object-Oriented Programming term. ObjectType is used to define the base structure of an information model. The instance of an ObjectType is an Object which handles the data of the system that it is representing. Objects can contain variables and methods as their child components, mainly for characterizing and manipulating the data. References are used to define the relations between all these components. To build an OPC UA information model of a device, designers need to define all these components based on their understanding of the structure as well as the available data of the device. As a result, the design of an OPC UA information model, even though for a same device, can vary from one to another. In our proposed CPMT, the information model is one of the most critical components since it represents the structure and the available data of the machine tool. Although there exist various types of CNC machine tools, they usually follow the same logical structure and contain the same types of data. Therefore, a generic OPC UA information model that is particularly designed for CNC machine tools needs to be developed to provide the guidance for information model designers.

Recently, a Companion Specification – OPC UA Information Model for CNC Systems [47] was published by a joint working group of the OPC Foundation and the German Machine Tool Builders' Association (VDW). The specification defines an OPC UA information model to interface and exchange data with CNC systems. Although this information model contains a comprehensive set of data in CNC systems, it is not suitable for the OPC UA-based CPMT proposed in this research. On the one hand, this information model focuses only on the data within the CNC kernel of a CNC system. Some process data that are necessary for modelling the MTDT, such as the data from the Programmable Logic

Controller (PLC) and external data acquisition devices of a machine tool, are not included. On the other hand, the structure of this information model does not represent the logical relations of all the components and subsystems in a CNC machine tool. Since MTConnect standard has already defined a hierarchically structured data model specifically for CNC machine tools [48], a corresponding OPC UA information model needs to be developed in consideration of the interoperability between OPC UA- and MTConnect-based CPMT. The requirements of the generic OPC UA information model for a CPMT are defined as follows:

- 1) It should be a hierarchical structure, similar to the information model defined in MTConnect that indicates the logical relations of all the critical components and the available data of the machine tool;
- 2) Data from different data sources should be grouped into their related components to represent the static properties as well as real-time status of each component;
- 3) It should allow efficient mappings from MTConnect data sources to the respective OPC UA nodes;
- 4) Modifications and extensions of this generic model should be easily achieved for producing a more specific information model.

Based on these requirements, a generic OPC UA information model for CPMT is proposed (Figure 2). Initially, TypeDefinitions (for the complete information model) need to be defined. TypeDefinitions explain the type information of the objects and data variables that can be obtained from a particular information model. In the proposed generic information model, the MachineToolType of BaseObjectType is defined as a complex ObjectType representing a CNC machine tool. It has four Properties as static string variables representing the static properties of the machine tool, i.e. the name, manufacturer and manufacture date of the machine and the name of its controller. MachineToolType has four SubObjectTypes as shown in Figure 2. ControllerType contains variables for handling real-time data that can be extracted from the CNC controller such as power status, alarms and feed rate. AxesListType handles the nodes of three SubObjectTypes namely LinearAxesType, RotaryAxesTpe and SpindleType. LinearAxesType and RotaryAxesType consist of variables to hold actual and commanded positions of the axis along with the corresponding engineering unit. SpindleType is used to handle information about the speed, override and motor power of the spindle. CuttingToolType is used to handle the information regarding the cutting tools, such as the identification, type, material and size of the cutting tool. Two SubObjectTypes, i.e. ToolVibrationType and CuttingForcesType are created to handle variables representing the

vibration generated from and cutting forces applied on the cutting tool. SystemsType handles the information about other subsystems of the machine tool. It has three SubObjectType, i.e. DoorType, ToolTurretType and CoolantType.

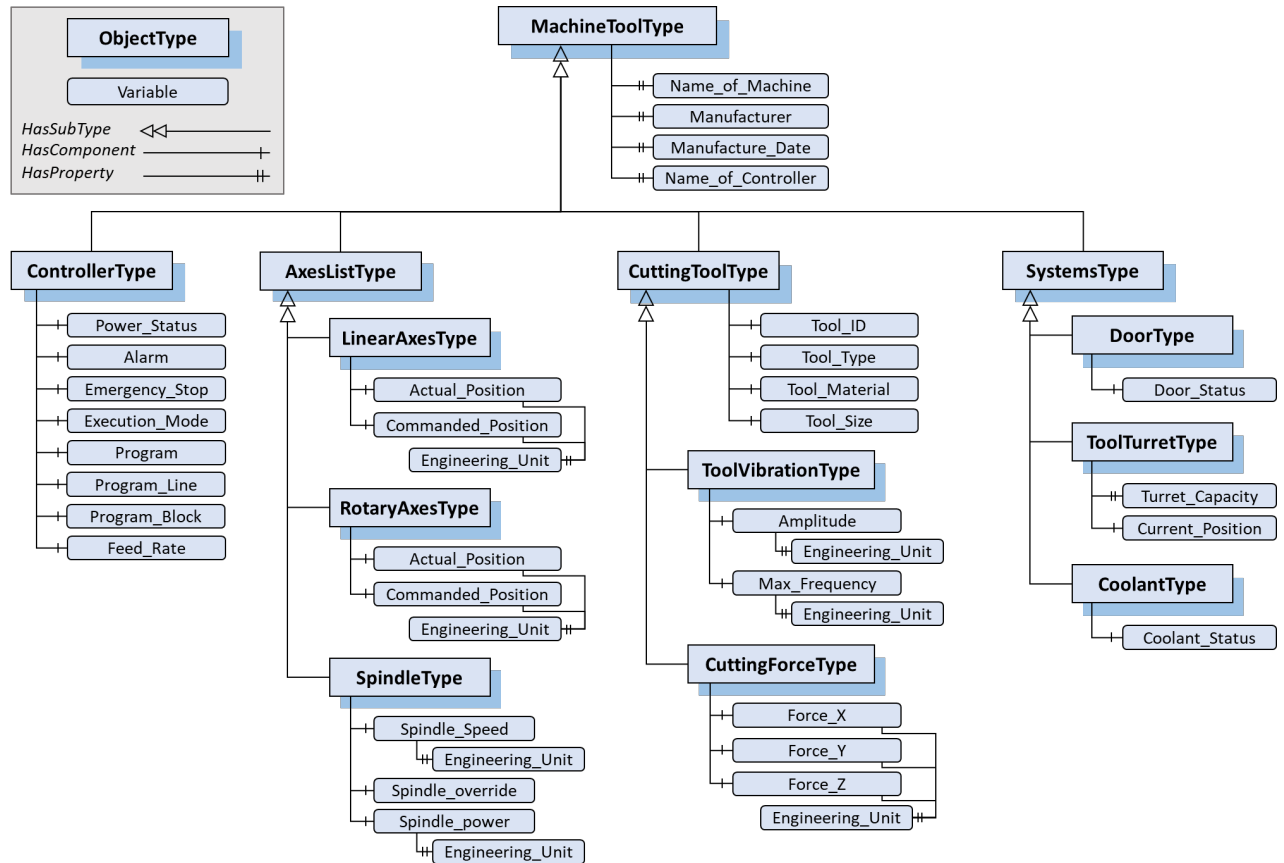


Figure 2. Generic OPC UA information model for machine tools

It is noted that this generic information model does not intend to be inclusive of all components and available data of a machine tool. Instead, it contains some common and critical components, subsystems and data of a typical CNC machine tool. A specific information model can be developed by modifying or extending this generic model, based on the actual structure and available data of the machine tool.

3.3 OPC UA-based CPMT Prototype

To validate the proposed system architecture and the generic OPC UA information model, this section introduces an OPC UA-based CPMT prototype. The system architecture, the specific OPC UA information model for the machine tool and the development processes of the OPC UA Server are illustrated. Since the OPC UA Client for this prototype is developed as the CPMT Platform application, it will be introduced in the next section.

3.3.1 System architecture

The system architecture of the OPC UA-based CPMT Prototype is described in Figure 3. It can be divided as three main modules, i.e. 1) machine tool and control software, 2) external data acquisition system, and 3) MTDT.

- 1) *Machine tool and control software*: the machine tool used for this prototype is a 3-axis milling machine (EMCO Concept 105 Mill). The simplified structure of the machine tool is shown in Figure 3. It is equipped with a Fanuc 21 CNC controller. The machine tool is controlled by the iWindow control software developed in our previous work [49]. iWindow can be treated as open source control software which sends control commands to the CNC and acquires real-time data from the CNC. The real-time data that can be extracted from the CNC include power status, execution mode, alarms, axes positions, spindle speed, feed rate, program information, and so on. These data are continuously transferred to the OPC UA Server through memory-mapped files.
- 2) *External data acquisition system*: in this prototype, several RFID tags are assigned to the machine tool and cutting tools to store their static property data. An Arduino Uno development board equipped with a RFID reader is used to obtain these data and transfer them to the OPC UA Server through serial communication. A 3-axis dynamometer (Kistler type 9273) is mounted on the work table to measure the cutting forces in X, Y and Z directions. A Piezoelectric accelerometer (PCB model 352C65) is used to measure the vibration of the cutting tool. Signals from the sensors are collected by a data acquisition card (NI PXI-1031) and pre-processed using LabVIEW. A TCP server is created in LabVIEW to transfer the sensor data to the OPC UA Server.
- 3) *MTDT*: it comprises an OPC UA Server and some local OPC UA Clients. The information model for the EMCO Milling machine is created in the OPC UA Server. The Server and iWindow run on a same host machine. The Server acquires real-time CNC data from iWindow using memory-mapped files. It also contains a serial receiver and a TCP client which receive real-time data from Arduino and LabVIEW respectively. All these data are correlated to their corresponding nodes in the information model. When the Server receives requests from OPC UA Clients, it encodes the requested data to standardized OPC UA Binary messages and sends them to the Clients. The local OPC UA Clients receive real-time data from the Server and perform various shop floor decision-making support functions such as process monitoring, data analytics and visualization and high-fidelity machining simulation.

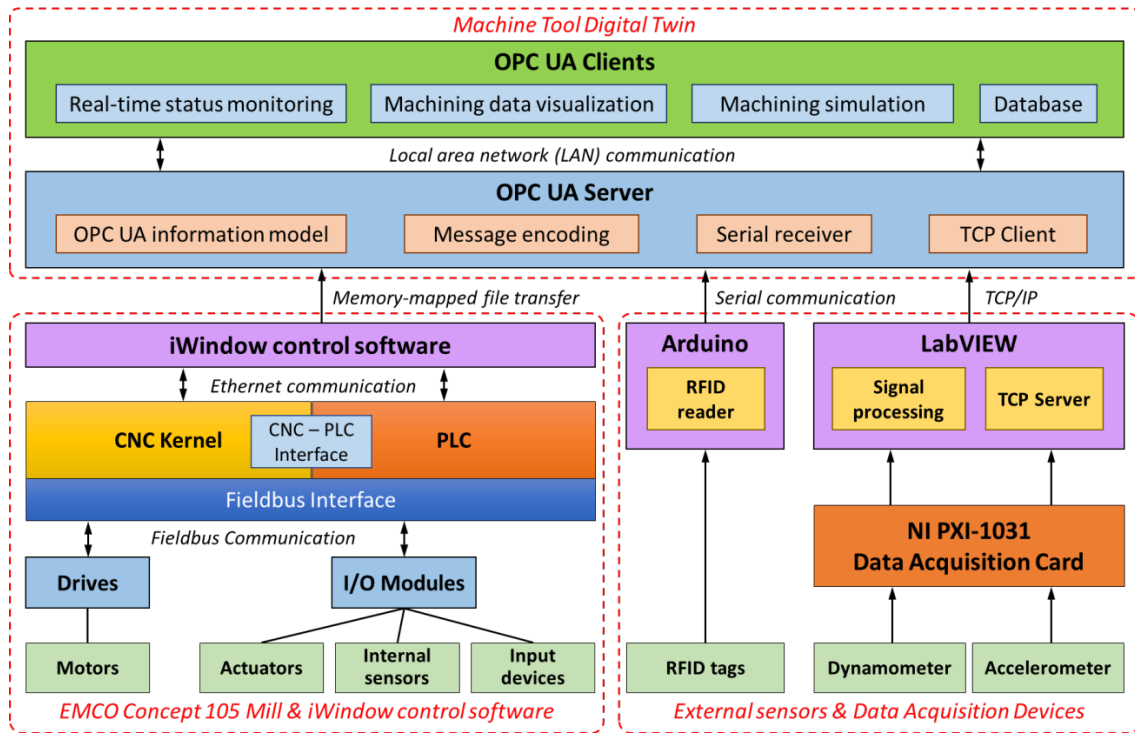


Figure 3. System architecture of the OPC UA-based CPMT prototype

3.3.2 OPC UA Server

The OPC UA Server can be divided into two main parts. The primary part is responsible for creating and handling the address space where the information model is implemented, as well as loading the address space to the main memory. The secondary part is responsible for handling the underlying system. The underlying system in this context refers to the CNC machine tool and the external data acquisition systems to which the server is connected. Data access from the underlying system is realized through memory-mapped file transfer, serial communication and TCP/IP communication.

The structure of the OPC UA information model developed for the EMCO Concept 105 Mill is illustrated in Figure 4. This information model is created as an instance of a modified version of the generic information model proposed in Section 3.2. The object EmcoCNC represents the machine tool which has child objects as its components, including Controller, Axes and Cutting tool. Likewise, Axes has child objects as its subcomponents, including three linear axes and the Spindle. All these objects are instantiated from the ObjectTypes defined in the generic information model. The data that can be obtained from the underlying system are modelled as variables and correlated to their corresponding components.

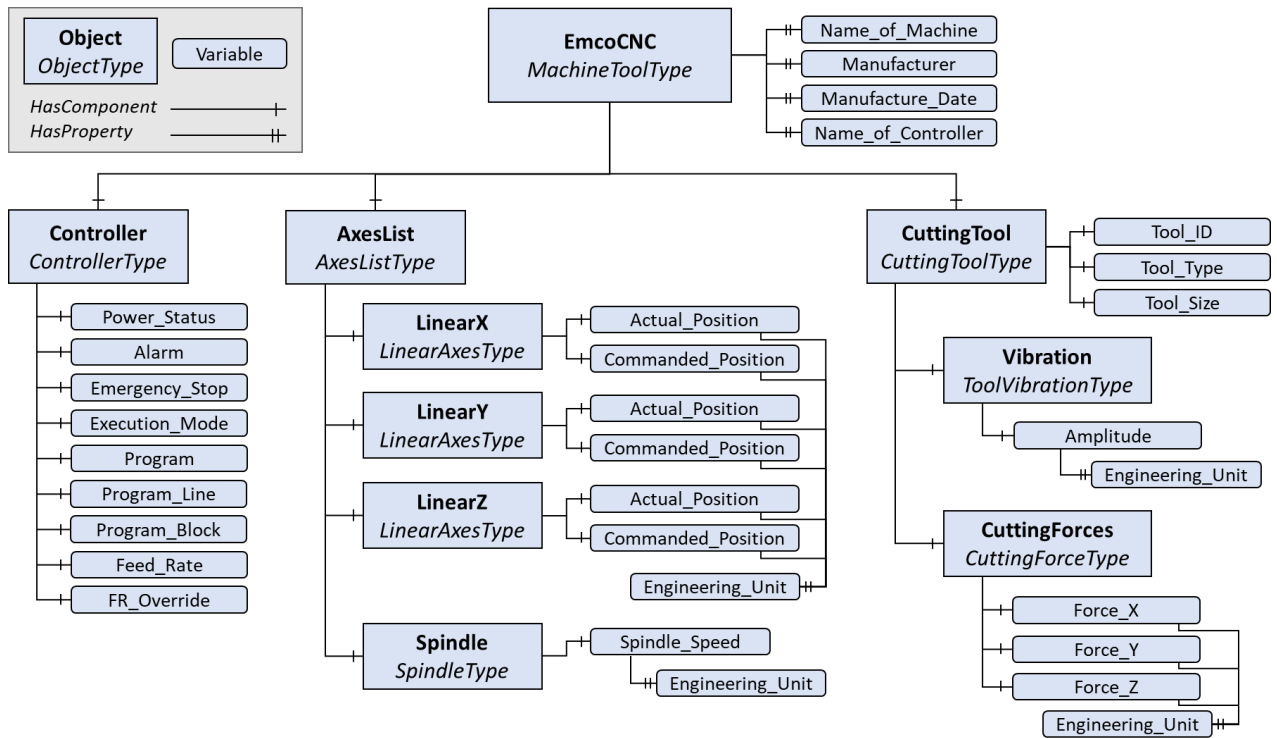


Figure 4. OPC UA information model for the EMCO Concept 105 Milling Machine

To illustrate some details of this information model, the attributes of the child nodes of the Controller object are listed in Table 1. These nodes are variables instantiated from the TypeDefinitions defined in the generic information model. They represent the real-time data that can be extracted from the CNC controller, and hence are modelled as the child nodes of the Controller object. For example, the Power_Status represents the power status (on or off) of the machine tool. It is a Boolean type read-only variable with 1000ms minimum sampling interval; while the Execution_Mode is a read-write string variable with 1000ms minimum sampling interval, indicating the execution mode (automatic, manual or Manual Data Input) of the CNC controller. All the available data acquired from the underlying system are similarly defined in the information model. The Parent Node attribute indicates to which object the data are correlated. The access level determines if the data can be read or write by the OPC UA Clients. Due to the huge amount of real-time data and the speed limit of the local network, the minimum sampling interval for all variables is set to either 100ms or 1000ms, depending on the real-time performance required by the OPC UA Clients.

Table 1. Nodes and attributes of Controller object

BrowseName	Data Type	Access Level	Minimum Sampling Interval (ms)	Parent Node
Power_Status	Boolean	Read	1000	ControllerType
Alarm	String	Read	100	ControllerType
Emergency_Stop	Boolean	Read-Write	100	ControllerType
Execution_Mode	String	Read-Write	1000	ControllerType
Program	String	Read-Write	1000	ControllerType
Program_Line	Double	Read	100	ControllerType
Program_Block	String	Read	100	ControllerType
Feedrate	Double	Read	100	ControllerType
FR_Override	Double	Read-Write	100	ControllerType

The Information model is an integral part of the OPC UA server and hence the hierarchical representation shown in Figure 4 needs to be represented in its respective source codes. In our case study we made use of an open source Information Model Compiler library that was provided as a part of the repository on Github by the OPC Foundation. The Information Model Compiler intakes an XML representation of the hierarchy and a comma separated value (CSV) file which enlists all the ObjectTypes, Objects, Variables and Methods along with an identifier value to every single component. The generated source code is then integrated as a part of the OPC UA Server. Since the OPC UA Clients developed for this prototype are mainly used in the local network, OPC UA Binary is used for the data encoding in this Server. OPC UA Binary has smaller size and allows faster encoding and decoding compared to XML, thus enabling more efficient data transmission between the OPC UA Server and local OPC UA Clients.

The User Interface (UI) of the developed OPC UA Server is shown in Figure 5. The Server endpoint URL is displayed as per it is defined in the XML server configuration file. Once the OPC UA Client establishes a successful connection with the server, details of the connection will be displayed in the Sessions module. This information can be used to identify the current users who are accessing the server for real-time data access. Once the user creates a subscription for a node on the OPC UA Client, the subscription details will be reflected in the Subscriptions module. More details regarding the status and overall performance information of the Server is shown at the bottom of the UI.

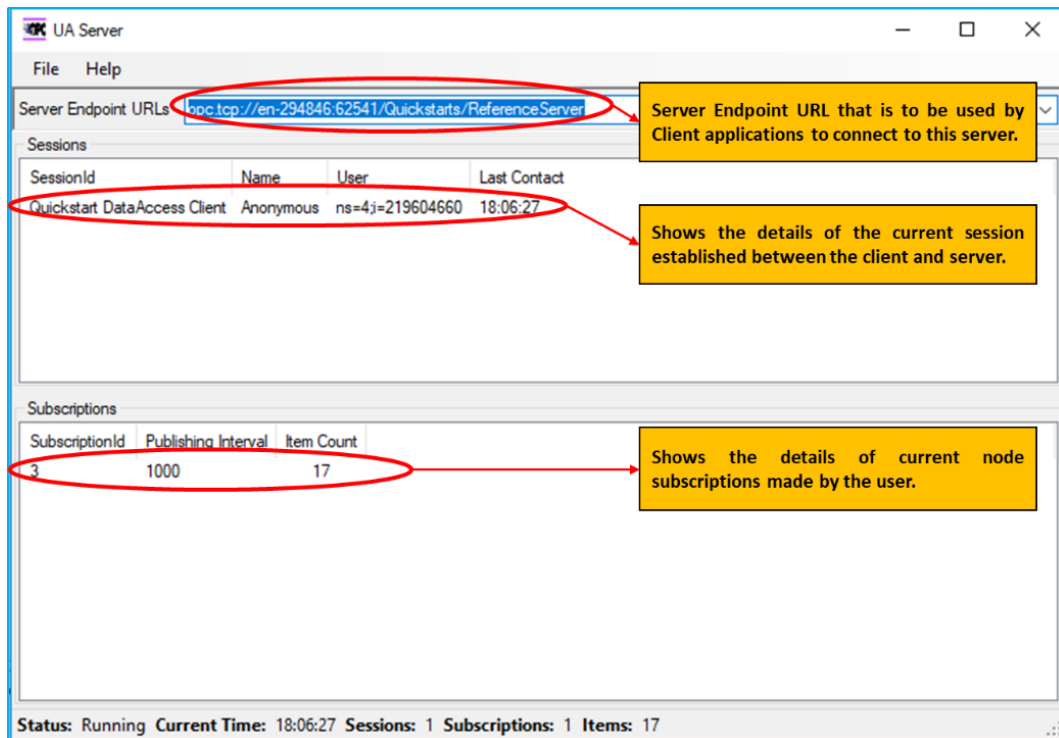


Figure 5. User Interface of the OPC UA Server

4. CYBER-PHYSICAL MACHINE TOOLS PLATFORM

The implementation of OPC UA and MTConnect in machine tools not only enables CNC machine tools to be advanced to CPMT, but also increases the interoperability throughout all machine tools in the shop floors. However, the proposed OPC UA- and MTConnect-based CPMT are not yet interoperable between each other, although they have similarly structured information models. In this section, we propose a CPMT Platform which allows MTConnect information models and data to be transformed to their OPC UA counterparts, hence enabling an interoperable data communication environment for both OPC UA- and MTConnect-based CPMT.

4.1 Conceptual framework of the CPMT Platform

The conceptual framework of the CPMT Platform is shown in Figure 6. An OPC UA Central Server is proposed as the server for all machine tools in the CPMT Platform. It receives all the data from different types of machine tools and data acquisition systems and communicates with the OPC UA Clients. In general, machine tools in the shop floor can be categorized into four types based on the communication capability of the CNC controllers. As shown in Figure 6, machine tool #1 directly communicates with the Central Server through

OPC UA APIs. Machine tool #2 has embedded OPC UA Server which communicates with the Internal Client. The Internal Client then communicates with the Central Server. Machine tool #3 and #4 send data to MTConnect Agents through external and embedded MTConnect Adapters respectively. The MTConnect to OPC UA Interface receives data from MTConnect Agents and converts MTConnect information models to OPC UA information models, and then sends the data to the OPC UA Central Server. In this way, each machine tool in the shop floor has an OPC UA information model in the OPC UA Central Server. Various OPC UA Clients can communicate with the Central Server, require real-time data of each machine tool and provide various services for all machine tools in the shop floor. Thus, an interoperable CPMT Platform can be realized.

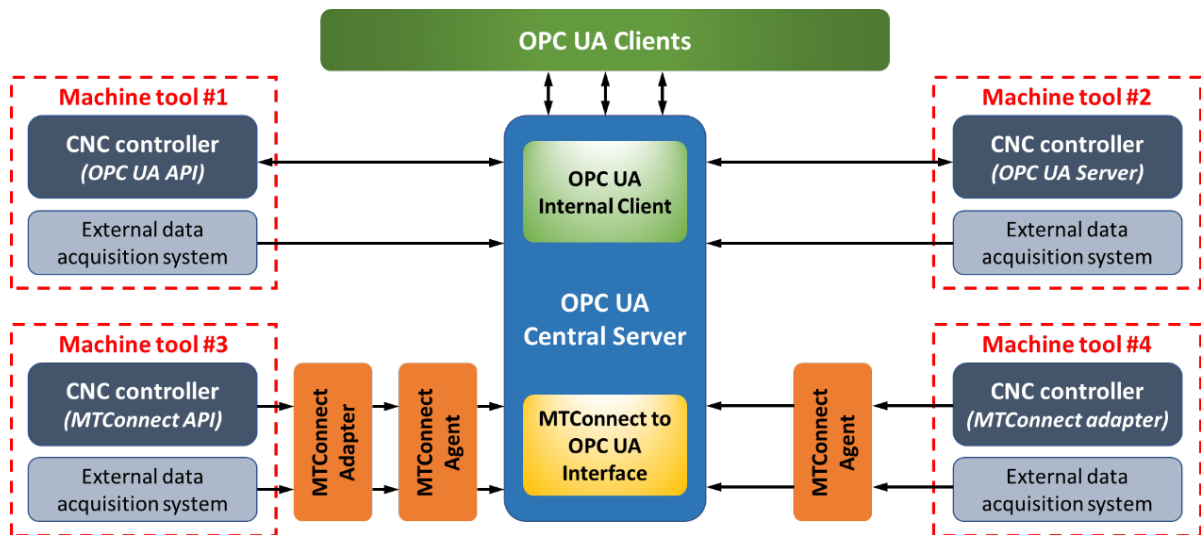


Figure 6. Conceptual framework of the CPMT Platform

4.2 MTConnect to OPC UA Interface

In order to make OPC UA- and MTConnect-based CPMT interoperable, the information models and the real-time data need to be transformed into either of these two formats. Since the structure of MTConnect information model and the types of MTConnect data are specifically defined for CNC machine tools, it is more reasonable and efficient to develop parsing algorithms which can transform MTConnect information model and data into the corresponding nodes in the OPC UA space address. Therefore, an MTConnect to OPC UA Interface is developed as a critical component in the OPC UA Central Server. The proposed MTConnect to OPC UA Interface consists of two main algorithms, i.e. probe XML parsing algorithm and current XML parsing algorithm. Initially, a probe request is sent to the MTConnect agent from the OPC UA Central Server to acquire the MTConnect probe XML

file which includes information of all the available components and data items in the MTConnect information model. Then the probe XML parsing algorithm parses the probe XML file and aids the designer to create the corresponding OPC UA nodes in the OPC UA Central Server. The specific mappings from the Structural Elements and Data Elements in MTConnect information model to OPC UA nodes follow the mapping rules defined in the MTConnect-OPC UA companion specification [50]. Thus, the OPC UA information model is created. Next, the current XML parsing algorithm is used to acquire real-time MTConnect data and send them to the related OPC UA nodes. The flowchart of the current XML parsing algorithm is shown in Figure 7. The OPC UA Central Server continually sends a current request to the MTConnect Agent according to the required minimum sampling interval. Once a response is acquired, the current XML file will be loaded for a thorough search to find the current data items. Hierarchically, a search on each level for the current data is done. If a data item containing current data of the machine is found, it will be stored in its corresponding OPC UA node in the OPC UA Central Server.

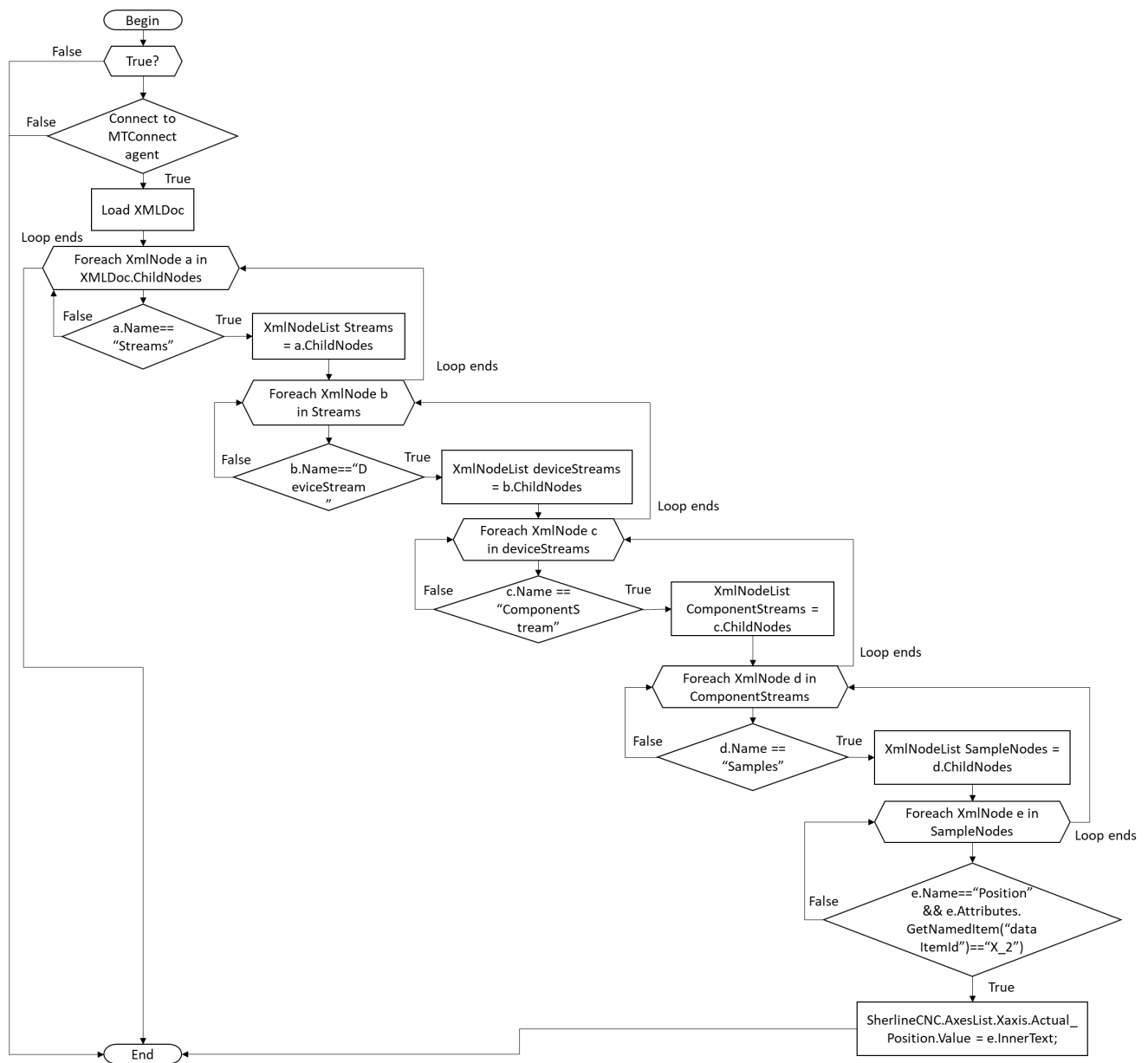


Figure 7. Flowchart of the current XML parsing algorithm

4.3 A Prototype of the CPMT Platform

To validate the feasibility of the proposed approach, a prototype of the CPMT Platform is developed based on an OPC UA-based CPMT and a MTConnect-based CPMT. The experimental setup of the prototype is described in Figure 8. The MTConnect-based CPMT is developed on a Sherline 3-axis mill. It is controlled by the LinuxCNC software on a Linux PC, through the parallel port. An MTConnect Adapter is developed on the Linux PC to retrieve CNC data from LinuxCNC software through the open source APIs. External sensors and data acquisition systems are implemented. The NI PXI 1031 collects all the sensor data and pre-process them using LabVIEW. The NI PXI 1031 is connected to the Linux PC

through Ethernet. A TCP Server is created in LabVIEW to send the sensor data to MTConnect Adapter on the Linux PC. All these MTConnect data from the Sherline Mill and external sensors are transmitted to the MTConnect Agent on the Windows PC using TCP/IP protocol. The OPC UA-based CPMT is the one introduced in Section 3.3. The EMCO Concept Mill 105 is controlled by the iWindow control software installed on the Windows PC, through Ethernet connection. The Windows PC is also installed with the MTConnect Agent and the OPC UA Central Server. A simplified flowchart is shown in Figure 9 to illustrate the workflow in the OPC UA Central Server. On the one hand, the MTConnect information model of the Sherline Mill resides in the MTConnect Agent. The MTConnect to OPC UA Interface parses the MTConnect XML files in the MTConnect Agent and assists designers to transform them into OPC UA nodes. Thus, the MTConnect information model and data are transformed to OPC UA information model and data in the OPC UA Central Server. On the other hand, the OPC UA information model of the EMCO Mill also resides in the OPC UA Central Server. CNC data of the EMCO Mill are extracted from the iWindow software and fed to the OPC UA Central Server using memory mapped files.

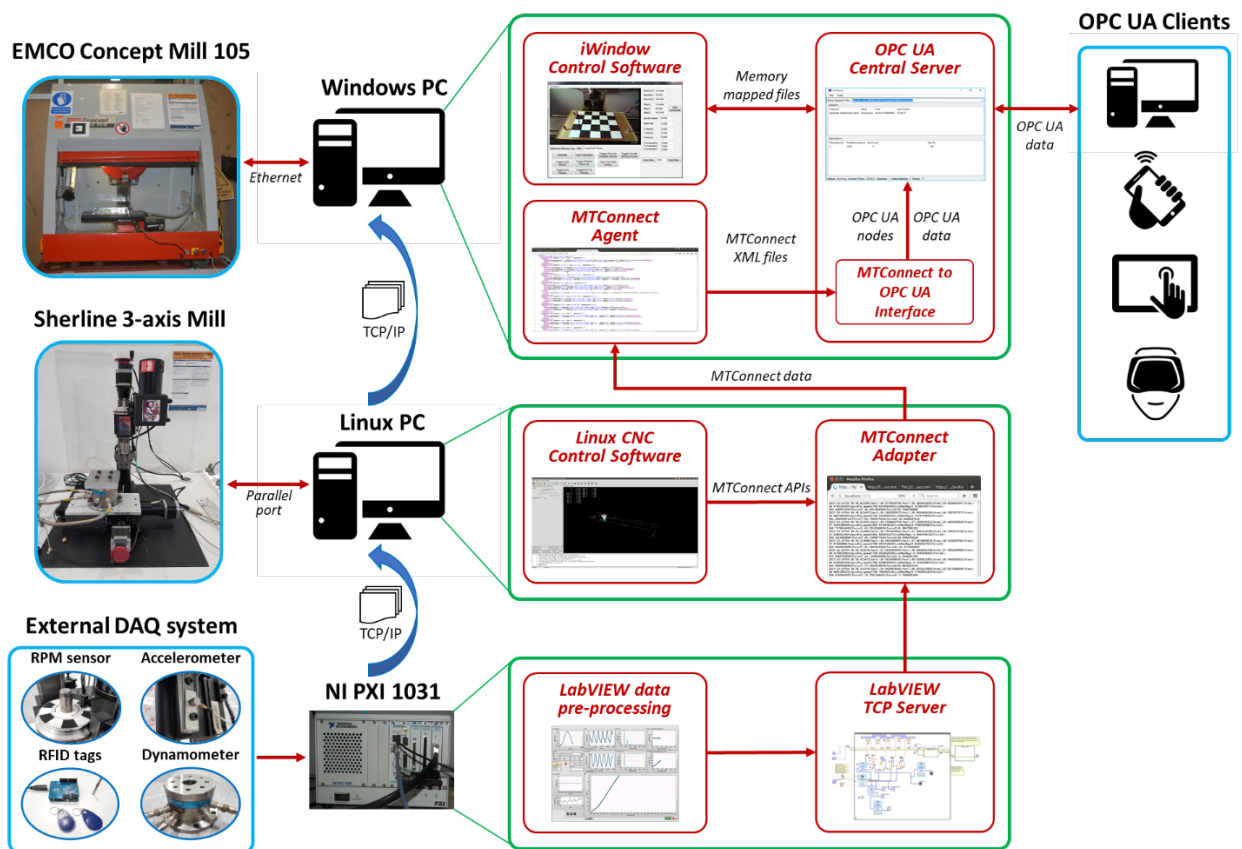


Figure 8. Experimental setup for the prototype of CPMT Platform

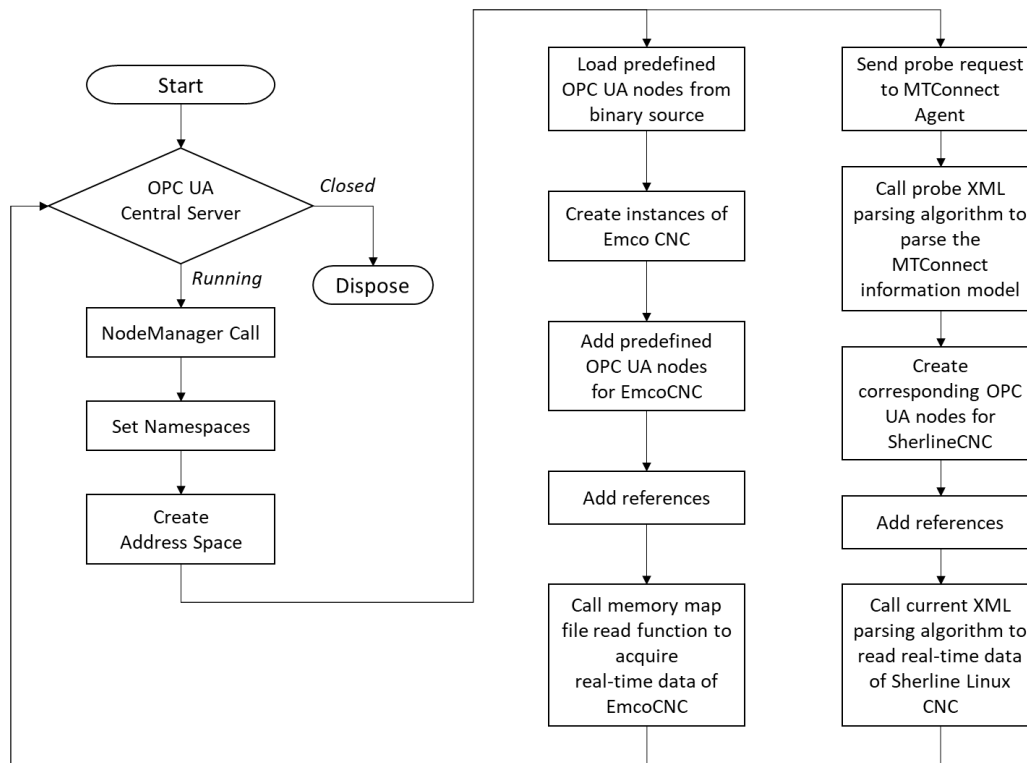


Figure 9. Simplified flowchart of the OPC UA Central Server

An OPC UA Client is developed for this prototype to demonstrate the advantages of the CPMT Platform. The Client runs on a laptop which is connected to the local network. It connects with the OPC UA Central Server on the Windows PC, requiring the real-time data of both machine tools using OPC UA protocol, and providing various monitoring and decision-making support functions for both machine tools. The User Interface of the Client is shown in Figure 10. It comprises five main modules marked from 1 to 5 with each module responsible for carrying out respective functions. Firstly, the URL of the OPC UA Central Server is typed into the address bar to build the connection between the Client and the Central Server. Once connected, the information model hierarchy of the currently connected machine tools are presented in Module 1. As shown in Figure 10, EmcoCNC and SherlineCNC represent the two machine tools connected with the Central Server. All the available components and their related data items are listed in the tree structures. Users can browse the information models to understand the logical structure of the machine tool and what data of the machine tools are available to be accessed. Details of a selected node in the information models are displayed in Module 2, including all the properties and attributes related to that node. Module 3 displays all the relevant real-time data of the respective machine tool selected from the Machine Tool selection menu. As shown in Figure 10, when EmcoCNC is selected, all the real-time data of the EMCO Mill are displayed in Module 3. This gives users a

comprehensive understanding of the real-time status of all the machine tools in the CPMT Platform. Once the user selects a node and decides to monitor it, the subscription details of the monitored node will be displayed in the Module 4. At the same time in the ‘Data Visualization’ tab in Module 5, a real-time plot of the parameter will be displayed. Module 5 also provides some data visualization and analytics functions, such as multiple data visualization that indicates the relevance between two machining parameters and machine tool utilization analysis based on the execution mode of the CNC controller. The refresh rate of the data of each node is the minimum sampling interval defined in the node attributes.

Although the current version of our OPC UA Client only supports some basic status monitoring, data visualization and analytics functions, it has validated the great advantages and huge potential of the proposed CPMT Platform. Since the information models and real-time machining data of different machine tools can be efficiently managed in the CPMT Platform at the same time, various OPC UA-based shop floor decision-making support applications can be developed to improve the performance, efficiency and effectiveness of the machine tools. It is worth mentioning that the security of data exchange is not the focus of this research since the experiments are conducted in a local network. The cyber security issue in the proposed CPMT Platform needs to be addressed in future research.

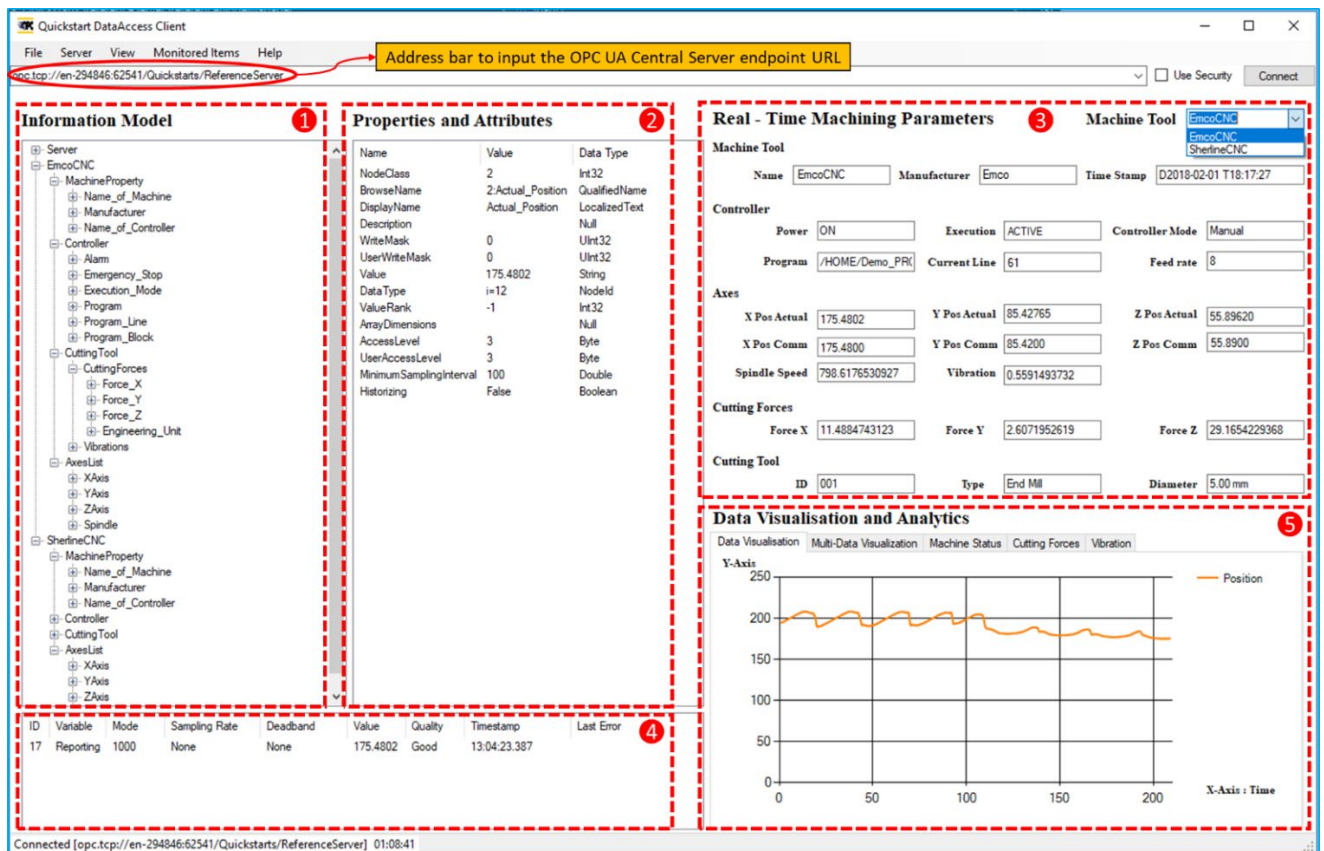


Figure 10. OPC UA Client for the CPMT Platform

5. APPLICATIONS OF THE CPMT PLATFORM

This section briefly introduces two applications for the proposed CPMT Platform to further demonstrate its advantages and potentials. The first application presents AR-assisted machining process monitoring and simulation functions developed on a wearable device – Microsoft HoloLens. This application demonstrates the advanced shop floor decision-making supports enabled by the CPMT Platform. The second application, on the other hand, introduces a conceptual framework for a CPMT powered cloud manufacturing environment which enables dynamic information exchange between various cloud-based services and the CPMT Platform.

5.1 AR-assisted process monitoring and simulation

Recent advancement in AR technology has shown great advantages in developing intuitive HMIs for manufacturing facilities. The CPMT Platform allows all the available data of the machine tools to be accessed in real time, thus providing a solid foundation for implementing AR technology. In this application, AR is implemented in our CPMT Platform to develop an intuitive HMI on a Microsoft HoloLens. This advanced HMI not only provides users with intuitive perceptions of the real-time machining processes, but also supports high-fidelity machining simulations based on the actual machining parameters.

The experimental environment and the workflow of this application is described in Figure 11. The HoloLens is connected to the host machine in the local network through WiFi. It acquires real-time machining data of the EMCO Mill from the CPMT Platform Application. The user “taps” the marker fixed on the machine tool to calibrate the positions of the virtual objects (virtual workpiece, cutting tool, tool path and text information) to be overlaid. The real-time axes positions acquired from the CPMT Platform Application are used for tracking the movements of the cutting tool and the workpiece. On the one hand, when the user wearing the HoloLens looks at the machine tool during machining processes, a comprehensive and intuitive understanding of the machining process can be realized since the real-time machine tool status, program information, cutting tool information, etc. are displayed in real machining environment. The virtual cutting tool and tool path can also be overlaid during machining, such that the visualization of the machining processes can be enhanced when coolant or chips obstruct the process. On the other hand, the virtual workpiece, virtual fixtures and virtual cutting tool can be overlaid on the worktable during a dry run. In this situation, all the virtual objects are driven by the actual axes positions

obtained from the machine tool in real time. Interactions among these objects such as material removal and tool collision can be calculated and simulated. The user can also observe the simulation process from different angles and distances in the 3D environment. Thus, high-fidelity and intuitive machining simulation based on real machining parameters can be achieved. Although this application is developed for the EMCO Mill, it is obvious that it can be implemented on all the machine tools in the CPMT Platform, since the real-time data of all machine tools can be accessed from the CPMT Platform Application.

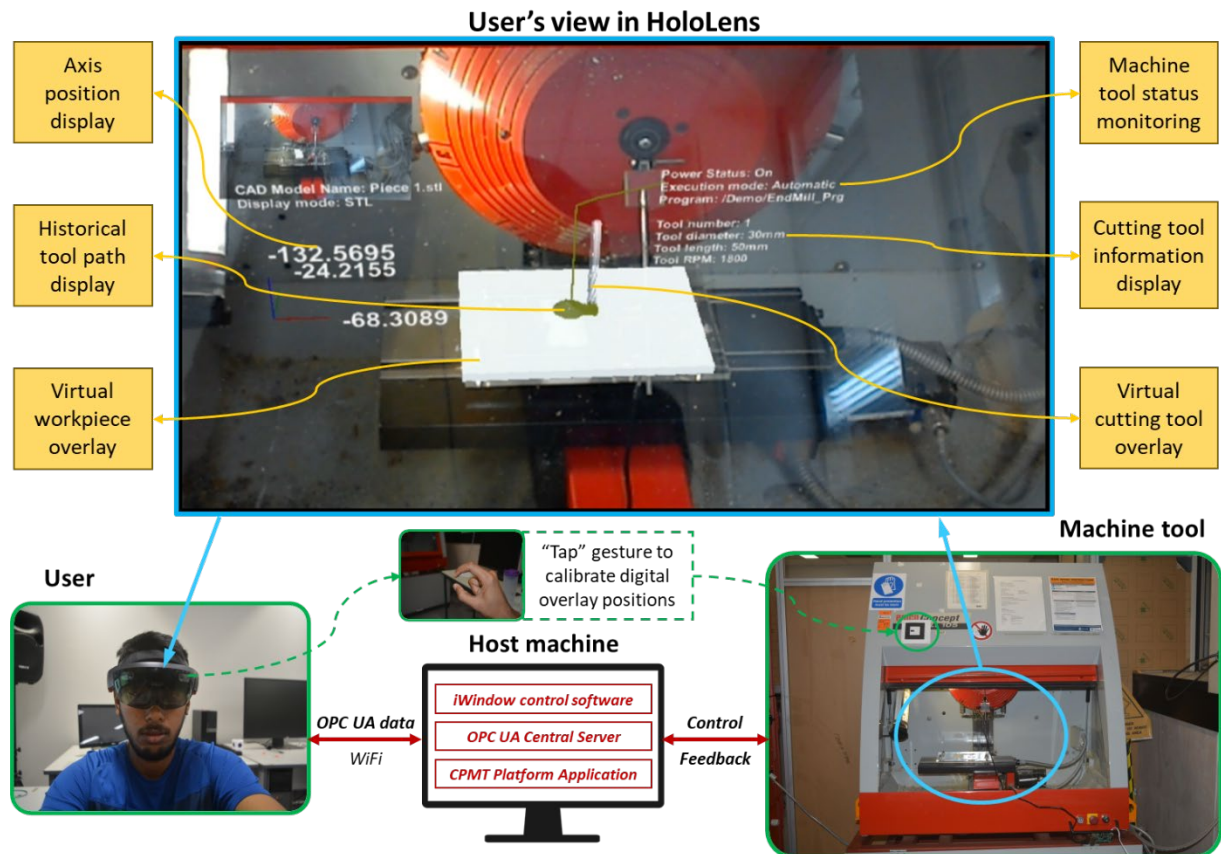


Figure 11. AR-assisted process monitoring and simulation using HoloLens

5.2 CPMT powered cloud manufacturing

The proposed CPMT platform can also play a significant role in enabling horizontal integration [5] together with cloud manufacturing. Cloud manufacturing as a trend of future manufacturing is envisioned to provide cost-effective, flexible and scalable solutions to companies by sharing manufacturing resources as services with lower support and maintenance costs [51]. In a traditional cloud manufacturing architecture, manufacturing resources are abstracted as virtual entities in the cyberspace via resource virtualization technologies with an emphasis on extracting the capability information of connected

manufacturing resource [52,53]. These virtual manufacturing resources in the cloud are encapsulated as on-demand manufacturing services that can be consumed on a pay-as-you-go pricing model. A significant challenge in cloud manufacturing is that virtual resource information is not always in sync with physical resource capability and availability information. Therefore, service scheduling and resource coordination in the cloud cannot be always guaranteed as optimal decisions due to a lack of understanding of dynamic machine tool status.

With the assistance of the proposed CPMT platform, virtual manufacturing resources are twinning with their physical counterparts and a network of CPMTs can communicate with each other and self-configure themselves to collaboratively undertake a manufacturing job. Figure 12 below depicts a conceptual framework for integrating the proposed CPMT platform with a cloud manufacturing environment. Real-time machine status streamed from the physical entity will enable a cloud manufacturing system to make context-adaptive decisions in the cloud. Specifically, an optimal combination of machine tools based on real-time machine condition will be selected to deliver high quality manufacturing services in the cloud. On the other direction, any status update from the cloud that occurs on a machine tool will also be feedback to the physical machine tool via the communication channel between the physical machine tool and its digital twin in the cyberspace.

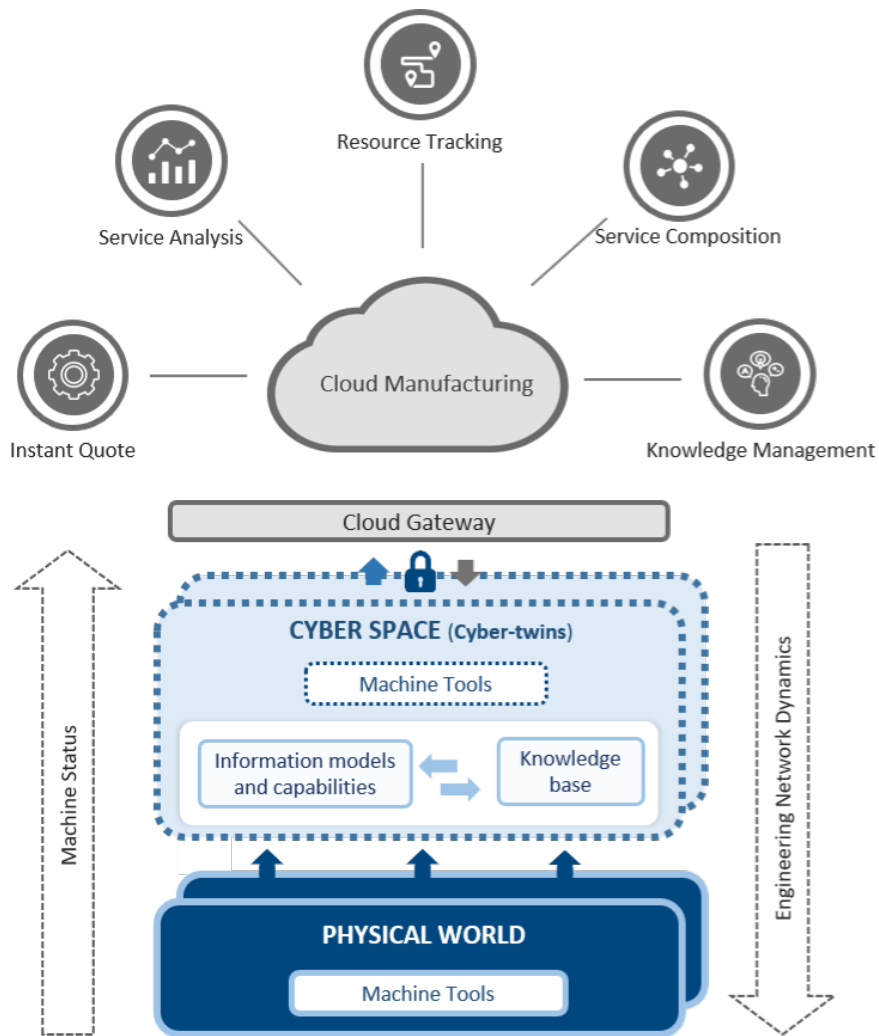


Figure 12. Conceptual framework for a CPMT powered cloud manufacturing environment

6. CONCLUSIONS

Industry 4.0 envisions the next generation of manufacturing systems as CPPS that comprise various smart, autonomous, cooperative and interconnected manufacturing facilities. Given the critical role machine tools play in any manufacturing systems, there exists an urgent need to advance existing CNC machine tools to a higher level of connectivity, accessibility, intelligence and autonomy, i.e. Machine Tool 4.0. Based on recent advancements in ICT such as CPS, IoT and cloud technology, CPMT is considered as a promising development trend for machine tools in the new era of Machine Tool 4.0. The core of a CPMT lies in the digital twin of the machine tool, i.e. MTDT. Modelling of the MTDT is a critical yet challenging task since it requires standardized information modelling method and communication protocols for machine tools. OPC UA and MTConnect both provide feasible solutions for this task.

Our previous work has proven the feasibility of developing an MTConnect-based CPMT. Due to the lack of a systematic development method for OPC UA-based CPMT and the interoperability issue between OPC UA and MTConnect, this paper proposes a CPMT Platform to bridge the research gaps. The main contributions of this research are summarized as follows. First, a development method for OPC UA-based CPMT is proposed based on a generic OPC UA information model for CNC machine tools. It serves as a guideline for developing digital twins of machine tools using OPC UA. Second, a CPMT Platform using both OPC UA and MTConnect is proposed to address the issue of interoperability between the two standards. Based on the two widely used standards, the CPMT platform enables interoperable data communication among various types of machine tools and software applications. Third, different applications are developed to demonstrate the advantages and potential of the proposed CPMT Platform, including an OPC UA Client, an advanced AR-assisted wearable HMI and a conceptual framework for CPMT powered cloud manufacturing environment. Experimental results have proven that the proposed CPMT platform not only improves the interoperability and efficiency of data communication, management and analysis, but also provides a great potential for machine tools to become more intelligent and more autonomous.

Recently, OPC UA and MTConnect are attracting more and more attention in both industry and academia. With the rapid increase of OPC UA and MTConnect implementations, more and more CNC machine tools in the shop floors can be advanced to CPMT. The proposed CPMT Platform can thus enable an interoperable communication environment for the envisioned CPPS and Smart Factory. It is noted that the development of CPMT and CPMT platform is still at an early stage. The focus of the future work in this area is envisioned as the implementation of Artificial Intelligence in the CPMT platform. First, advanced data analytics based on recent advancements of machine learning can be implemented into the proposed CPMT platform to provide more intelligent decision-making supports such as predictive maintenance. Second, direct feedback control loop from the MTDT to the CNC needs to be developed to allow autonomous in-process machining optimization. Furthermore, cooperation between the CPMT platform and other manufacturing devices such as industrial robots and logistic systems needs to be investigated for the realization the envisioned CPPS and Smart Factory.

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