Machine Tool Digital Twin: Modelling Methodology and Applications

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MACHINE TOOL DIGITAL TWIN: MODELLING METHODOLOGY AND APPLICATIONS

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ABSTRACT

Cyber-Physical Machine Tools (CPMT) represent a new generation of complete Cyber-Physical Systems (CPS)-based machine tools that deeply integrate machine tool and machining processes with computation and networking. CPMT have a higher level of connectivity, intelligence and autonomy compared to current machine tools. Digital Twin is a critical component of any CPS. The core of a CPMT lies in the Machine Tool Digital Twin (MTDT). This paper presents the methodology for modelling the MTDT based on open, unified and platform-independent communication standards such as MTConnect and OPC UA. Two applications of the MTDT are developed to demonstrate the advantages and potential of the proposed approach. The first application is a Web-based machine tool condition monitoring application that allows users to monitor the real-time status as well as the 3D model of the machine tool through web browsers on mobile devices. The second application is an advanced Augmented Reality (AR)-assisted wearable Human-Machine Interface (HMI) that provides users with intuitive and enhanced visualization of the machining processes.

Keywords: Digital Twin, Machine Tool Digital Twin, Cyber-Physical Machine Tool, Web-based application, Augmented Reality

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1 INTRODUCTION

Cyber-Physical Machine Tool (CPMT) is envisioned as a promising development trend of machine tools in the era of Industry 4.0 and Machine Tool 4.0 [1]. Based on recent advancements in Information and Communication Technology (ICT) such as Cyber-Physical Systems (CPS), Internet of Things (IoT) and cloud computing, CPMT represent a new generation of complete CPS-based machine tools that deeply integrate machine tool and machining processes with computation and networking [2]. Compared to current CNC machine tools, CPMT have a higher level of connectivity, intelligence and autonomy.

With the rapid development and implementation of CPS, a considerable amount of research on Digital Twin has emerged recently. Digital Twin is a critical component of any CPS. A commonly accepted definition of Digital Twin was provided by Glaessgen and Stargel [3], 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.'

As a typical CPS, the core of a CPMT lies in the Digital Twin of the physical machine tool, i.e. the Machine Tool Digital Twin (MTDT). Owing to the complex structures and diverse functions of CNC machine tools, modelling of the MTDT becomes a great challenge. First, various types of real-time machining data need to be collected from the CNC, PLC, different sensors and IoT-based data acquisition systems. These data need to be converted into a common format for efficient data management. Second, an information model of the machine tool needs to be developed as a framework of the MTDT that represents the logical structure of the machine tool. The information model should be able to provide structured and contextualized data that can be utilized by different applications such as databases, data analytics tools and machine learning algorithms. Third, practical use cases and applications for the MTDT need to be developed to demonstrate the advantages and potential of the MTDT.

This paper proposes the methodology for modelling the MTDT based on open, unified and platform-independent communication standards such as MTConnect and OPC UA. The functions, advantages and potential of MTDT are demonstrated through the development of two MTDT applications, i.e. Web-based machine tool condition monitoring application and Augmented Reality (AR)-assisted machining visualization and simulation. The remainder of this paper is organized as follows. Section 2 briefly reviews the related work. Section 3 introduces the MTDT including its definition and modelling method. Section 4 presents the development of two practical applications for the MTDT. Section 5 concludes the paper and indicates the future work.

2 RELATED WORK

The concept of CPMT was first coined in [1] where the definition of CPMT was given as 'the integration of machine tool, machining processes, computation and networking, where embedded computers and networks can monitor and control the machining processes, with feedback loops in which machining processes can affect computations and vice versa'. Liu et al. [4] proposed a systematic development method for CPMT. A generic system architecture was developed to provide guidelines for advancing current machine tools to CPMT, in which the MTDT was proposed as the core of a CPMT. To validate the proposed approach, Liu el al. [5] developed a CPMT prototype that allows diverse types of real-time manufacturing data to be effectively and efficiently collected and managed through the MTConnect-based MTDT. Deng et al. [6] proposed an open Computer Numerical Control (CNC) system-based CPMT using a low-power embedded platform. A health monitoring system for CPMT was developed as a case study. To enhance the autonomy and collaboration of CPMT, Zhou et al. [7] proposed a fog computing-based cyber-physical machine tool system (FC-CPMTS). The proposed approach was tested on a heavy-duty CNC machine tool and results showed the network traffic and calculation workload in the cloud platform were reduced.

In the last few years, a considerable amount of research on Digital Twin has emerged. The significance of Digital Twin in manufacturing has been discussed by multiple researchers [8-10]. Tao et al. [11] proposed a digital twin-driven approach to enhance the efficiency, agility and sustainability of product design, manufacturing and service. To improve the accountability and capability for cyber-physical manufacturing, Cai et al. [12] presented the techniques for integrating manufacturing data and sensory data to build Digital Twins of machine tools. Urbina Coronado et al. [13] proposed a Shop Floor Digital Twin framework to realize decision-making support for different users in the shop floor. A Web-based Manufacturing Execution System (MES) was developed to collect and track the field-level manufacturing data that are used to model the Shop Floor Digital Twin.

With enormous real-time data gathered in the Digital Twin, various types of applications can be developed to provide advanced functions such as efficient decision-making support, intelligent monitoring and control and process visualization and simulation. Web-based applications for manufacturing systems have been extensively studied in the last two decades [14-16]. Recent advancements of AR technology have also shown great potential of improving human-machine interactions between humans and manufacturing systems [17,18]. The authors believe that Digital Twin technology allows the advantages of Web-based and AR-based applications for manufacturing systems to be significantly expanded.

It is noted that although Digital Twin technology is attracting more and more attention, there have been few studies on the Digital Twin of machine tools. There is an urgent need for a generic methodology that provides a feasible and universal solution to the modelling of the MTDT. On the other hand, the advantages and potential of MTDT need to be demonstrated through practical applications. This paper aims to address these issues.

3 MACHINE TOOL DIGITAL TWIN

3.1 Definition

Currently, multiple definitions of Digital Twin have been given by different researchers from different perspectives such as lifecycle management, mission requirements, prognostics and diagnostics activities [9]. In effect, it is difficult to give a specific definition of a Digital Twin due to the diversity of physical objects involved in a manufacturing system. Different physical objects, e.g. manufacturing equipment, workpieces, factories and humans, may need different types of Digital Twins with respect to the specific structures, function requirements and modelling strategies.

Since the focus of this research is on the MTDT, based on the function requirements, we define the MTDT as a digital abstraction of the machine tool that is capable of:

1. Representing static properties as well as real-time status of the machine tool and machining processes.
2. Monitoring and controlling the machine tool with built-in computation and intelligence.
3. Communicating with different Human-Machine Interfaces (HMIs) and software applications to provide efficient decision-making support for humans.

3.2 Modelling methodology

This paper focuses on the modelling of MTDT in the cyberspace. It is assumed that various types of real-time machining data were collected from the CNC, PLC and sensors in the physical level using different types of data acquisition devices. These data in different formats were transferred to the cyberspace through different networking technologies.

Based on the definition of MTDT, it is identified that modelling of the MTDT includes three most fundamental requirements. First, all the field-level data gathered from the physical level need to be converted into a common format to ensure effective and efficient data management in the MTDT. Open, unified and platform-independent communication standards should be applied to achieve this requirement. Second, an information model representing the logical structure of the machine tool needs to be developed as the framework of the MTDT. The information model should be of a tree structure in which each node represents a logical component or a data item of the machine tool. Third, based on the communication standard and information model used in the MTDT, specific data communication mechanism needs to be developed such that the MTDT can provide structured and contextualized data for different applications.

Recently, MTConnect and OPC UA have been widely used as the communication standards for CNC machine tools. MTConnect is a set of open, royalty-free standards that offers a semantic vocabulary for manufacturing equipment to provide structured, contextualized data with no proprietary format, developed by the MTConnect Institution [19]. OPC UA is another open standard that specifies information exchange for industrial communication particularly on devices within machines, between machines and from machines to systems, however targets a broader range of industrial equipment and systems [20]. Both MTConnect and OPC UA provide feasible solutions for the fundamental requirements for modelling the MTDT, although different technical approaches need to be taken regarding their standards. The main differences between MTConnect and OPC UA are summarised in Table 1.

Table 1: Main differences between MTConnect and OPC UA

	MTConnect	**OPC UA**
Standard domain	Machine tools	Virtually any system
Information modelling method	Specifically designed for CNC machine tools; Structure of information model is specified as XML Schemas in standard	Generic and flexible; users can design their own information models and data types
Extensibility	Relatively low; can only be achieved through extension of the standard	High; any information model can be built upon the meta model
Definition of data	A dictionary of data in the field of CNC machine tools is concisely defined	No domain-specific data defined in the standard
Message encoding	MTConnect XML	UA Binary and UA XML
Security	Not integrated in the standard since it is read-only	Integrated in each layer of the communication stacks
Communication	Read only, one way	Read and write, Bidirectional
Application domain	Monitoring	Monitoring and control

Despite their differences, both MTConnect and OPC UA can: 1) allow field-level manufacturing data to be converted in an open and unified format, 2) create a tree-structured information model for the machine tool that holds and synchronize the real-time data, and 3) provide a server-client communication mechanism to publish the real-time data to different applications.

Figure 1 shows the simplified system architectures of MTConnect and OPC UA enabled MTDT. The communication architecture and main function modules in both MTDTs are similar, though MTConnect divides the functions into an Adapter and an Agent while OPC UA encapsulates all the functions into a Server. A major difference between the two MTDTs lies in the communication capability. MTConnect only supports one-way communication; OPC UA allows both reading and writing of the data. Thus, while both MTDTs support monitoring applications such as process visualization and data analytics, OPC UA enabled MTDT also supports control applications such as in-process control and optimization.

In the proposed modelling methods, the computation and data analytics functions are not included in the MTDT. Those functions that require high networking speed and computational power can be embedded in various types applications to reduce the network traffic and computation workload.

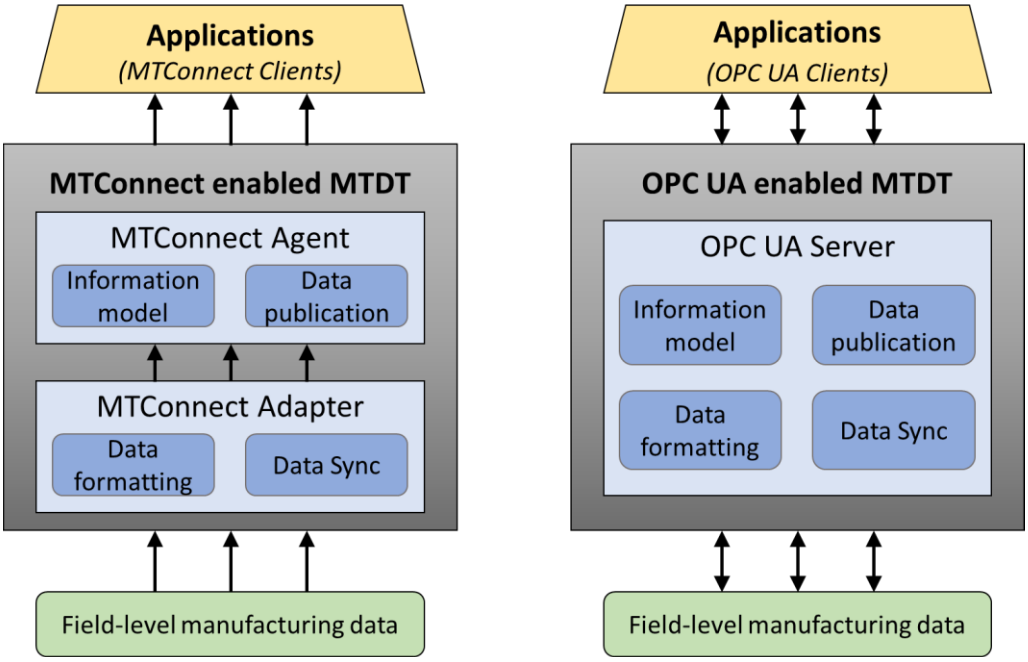


Figure 1: MTConnect and OPC UA enabled Machine Tool Digital Twin

4 APPLICATIONS OF MACHINE TOOL DIGITAL TWIN

To demonstrate the advantages and potential of the proposed MTDT, this section introduces two applications developed for an MTConnect enabled MTDT and an OPC UA enabled MTDT respectively.

4.1 Application 1: Web-based machine tool condition monitoring

The first application is a Web-based machine tool condition monitoring application for an MTConnect enabled MTDT. Figure 2 shows the system architecture of the application. The MTDT is developed for a Sherline Model 2010 3-axis vertical milling machine. A Kistler type 9273 3-axis dynamometer is installed on the worktable of the machine tool to measure the cutting forces. The machine tool is equipped with an open CNC controller that is controlled by the LinuxCNC software running on the host computer. An MTConnect Adapter and an MTConnect Agent are developed to model the MTDT. The MTDT runs on the same host computer.

Modelling of the MTConnect enabled MTDT follows the modelling method introduced in the previous section. The communications and functions in the MTDT are the same as described in Figure 1. Specifically, real-time machining data are transmitted to the Adapter where they are synchronized and converted into MTConnect format. Then these data are transferred to the Agent and correlated with their corresponding data items in the information model. Finally, the Agent publishes the data in MTConnect-defined XML format to the local network in our laboratory.

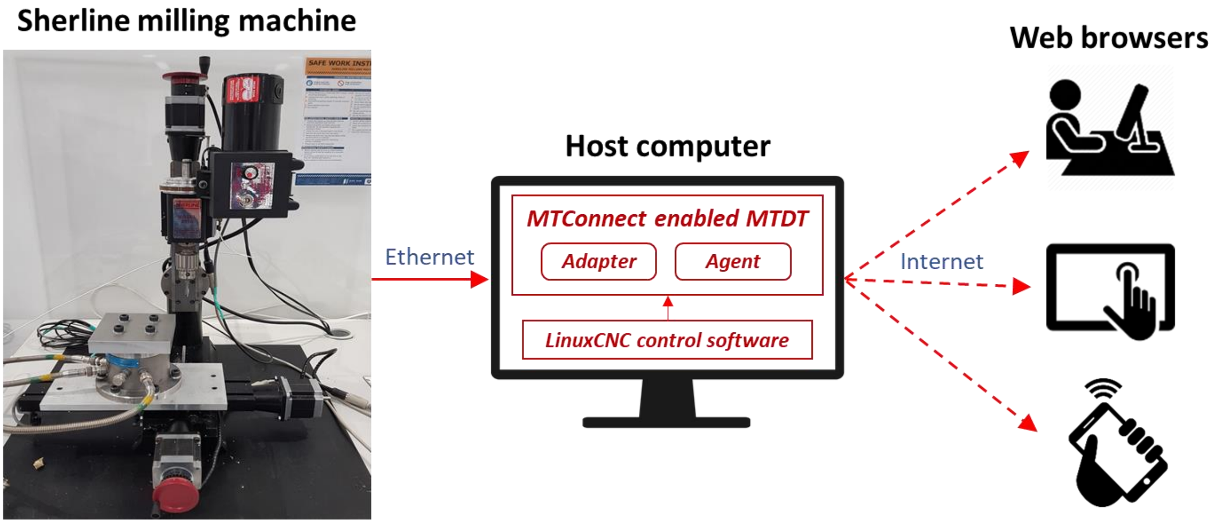
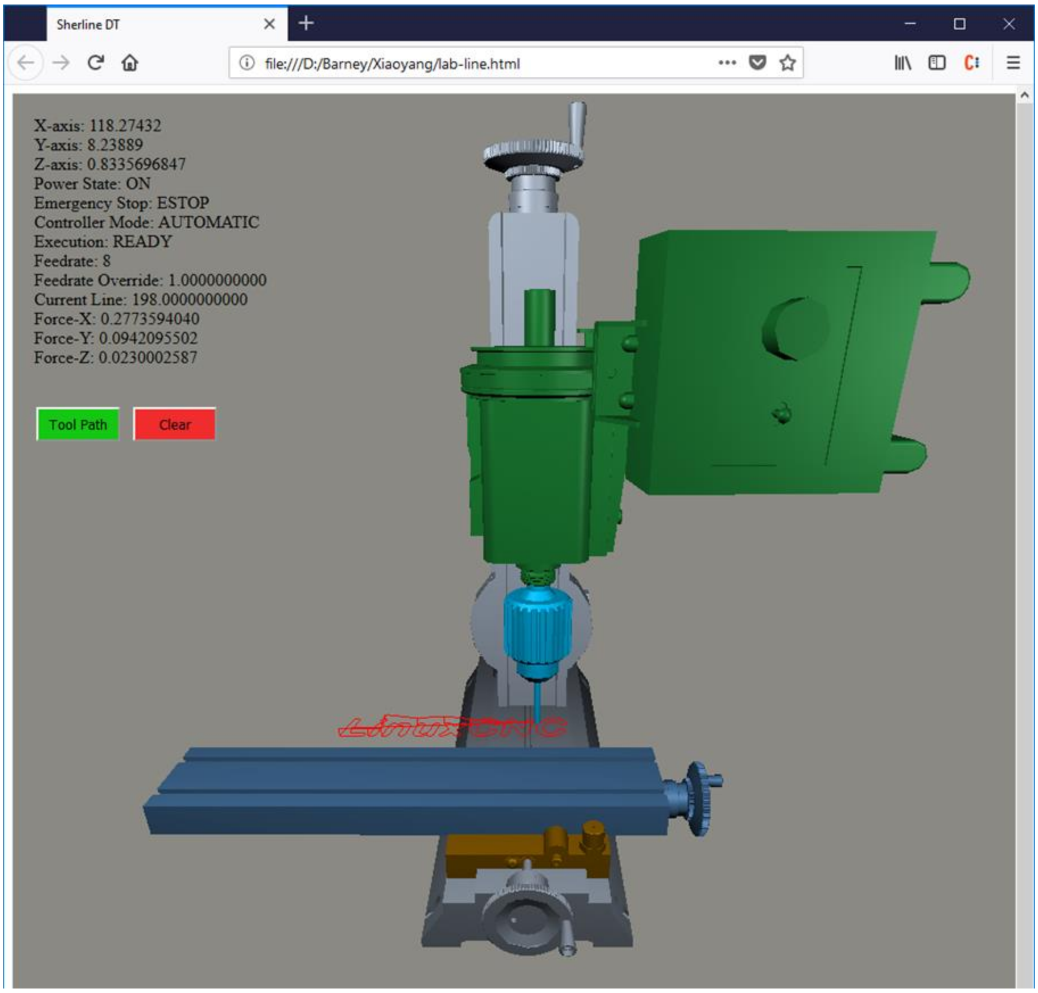


Figure 2: System architecture of the Web-based machine tool condition monitoring

The Web-based machine tool condition monitoring application developed for this MTDT is essentially a web page developed using HTML (Hyper Text Markup Language) and JavaScript. Figure 3 shows a screenshot of the developed application. It provides two main functions: 1) display the real-time status of the machine tool, and 2) visualize the machine tool movement using the real-time axis positions and a 3D model of the machine tool.



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X-axis: 118.27432
Y-axis: 8.23889
Z-axis: 0.8335696847
Power State: ON
Emergency Stop: ESTOP
Controller Mode: AUTOMATIC
Execution: READY
Feedrate: 8
Feedrate Override: 1.0000000000
Current Line: 198.0000000000
Force-X: 0.2773594040
Force-Y: 0.0942095502
Force-Z: 0.0230002587
```

Figure 3: Web-based machine tool condition monitoring application

Firstly, the application connects to the MTDT to retrieve all the real-time data from the MTConnect Agent through TCP/IP connection. The application uses the port number and the IP address of the Agent to establish the connection. Once connected, the Agent keeps sending the real-time data to the application as XML files in the MTConnect-defined structure. The application parses the XML files as fast as possible to retrieve the real-time data representing the machine tool status and display them on the top-left corner on the web page. In this application, AJAX (Asynchronous JavaScript And XML) is utilized to read the real-time data in the XML files asynchronously without interfering with the display and behavior of the existing web page. As shown in Figure 3, data retrieved from the MTDT (axis positions, power status, controller mode, feed-rate, cutting forces, etc.) are displayed on the web page in real time.

Secondly, a virtual model of the machine tool that shows the machine tool movement is created using Three.JS. Three.JS is a cross-browser JavaScript library and Application Programming Interface (API) that is commonly used to create and display animated 3D computer graphics in a web browser. Initially, the Computer Aided Design (CAD) model of the machine tool, which is a STP assembly file, is divided into different components and converted to 3D objects (.obj) in a scene created by Three.JS. The 3D objects are rendered with textures and virtual lights in the scene to provide a natural view. The position of each component in the scene is updated using the real-time axis position data retrieved from the MTDT. Consequently, the movement of the virtual machine tool is exactly the same with the real machine tool.

In addition, the tool path is displayed in real time as a 3D line as shown in Figure 3. This is achieved by calculating the tool tip position from the axis positions and the cutting tool size. To improve the visibility of the virtual machine tool, an orbit control is embedded in the scene. Thus, the user can rotate the viewpoint around the virtual machine tool to see the process from different angles in the virtual 3D environment.

This application provides users with a comprehensive and intuitive understanding of the machine tool status. Since it is developed as a web page, users can access the application using any mobile device that is able to connect to the Internet (laptops, smart phones, tablets, etc.) and run standard web browsers such as Chrome and Firefox. Therefore, this application allows ubiquitous and easy access to the field-level machining data in the MTDT and provides intuitive machine tool condition monitoring functions.

4.2 Application 2: AR-assisted machining visualization and simulation

The second application is an AR-assisted machining visualization and simulation application on a wearable HMI for an OPC UA enabled MTDT. The MTDT is developed for an EMCO Concept 105 3-axis milling machine. The machine tool is controlled by a Fanuc 21 CNC using a self-developed control software – iWindow [18]. A radio-frequency identification (RFID) tag and an Arduino Uno micro-controller are used to store and transfer the cutting tool information to the MTDT. The wearable HMI used in this case study is a Head Mounted Display – the Microsoft HoloLens.

Figure 4 shows the overall system architecture of this case study. The machine tool is connected to a host computer through an Ethernet cable, where the iWindow software and the MTDT are hosted. An OPC UA Server is developed to model the MTDT of the milling machine. The OPC UA Server retrieves real-time machining data and cutting tool information from the iWindow software and the Arduino micro-controller, and then converts all the data into OPC UA Binary format. The application on the HoloLens requests the real-time OPC UA data from the OPC UA Server through WiFi connection.

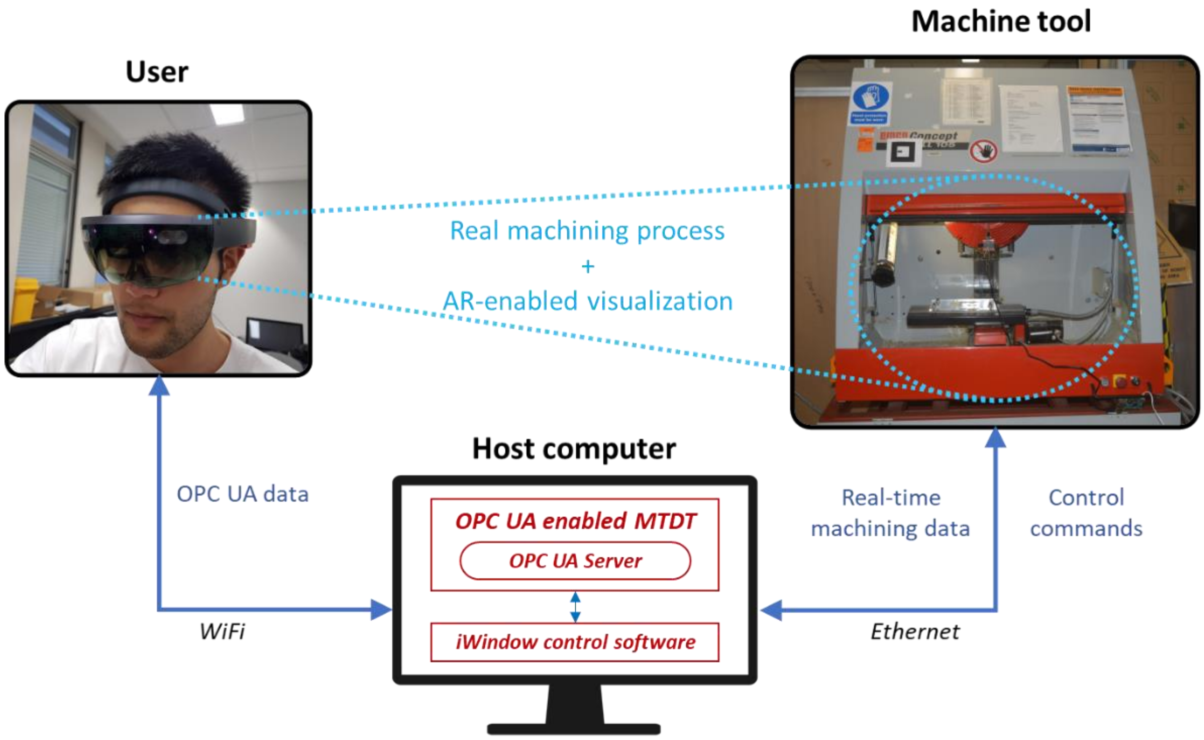

Figure 4: Overall system architecture of the AR application

The AR application enables intuitive machining visualization as well as high-fidelity machining simulation though the HoloLens. The design process and workflow of the AR application are described in Figure 5. There are four main components in this structure: Virtual module, Physical module, Calibration process, and AR module.

The design process starts with the generation of 3D models for the virtual module. Initially, the CAD models of the cutting tool, raw material and workpiece are generated by Creo Parametric in STP file format. To import the 3D models into the AR application on HoloLens, they are converted to the object file format (.obj) and transferred into the Unity 3D game engine which is used to program the AR application. In addition, the data display model that is responsible for displaying real-time machining data (axis positions, machine tool status, etc.) in the virtual module is also created by the Unity engine.

In order to provide an intuitive AR-assisted process visualisation, the virtual module needs to be accurately aligned with the physical module. This is achieved by the calibration process. From the virtual module, a cube painted in different colours on each face is generated in Unity. In the physical module, a binary marker placed on the CNC machine can be recognized through HoloLens. When the multi-camera system on HoloLens recognise the marker, the cube in the virtual module will pop up and overlay on the marker. Once the cube is perfectly aligned with the marker in the user's view, the user can use the voice command “calibrate” or the “tap” gesture to finalise the calibration process. Thus, all the 3D models in the virtual module can be overlaid onto their counterparts in the real machining environment.

The AR module is responsible for providing an intuitive real-time process visualisation to the user through the HoloLens. As shown in Figure 2, the HoloLens reads real-time data from the OPC UA Server to the AR application. These data are assigned to the corresponding 3D models in the virtual module and updated in real time. On one hand, the position of each 3D model is updated by the axis position values such that the virtual objects can be dynamically aligned with their physical counterparts during machining processes. For example, X and Y position values are assigned to the virtual workpiece and Z position value is assigned to the virtual cutting tool. On the other hand, other useful data such as power status, spindle speed and feed-rate are assigned to the data display model which displays the real-time machining data in the application. Furthermore, these data can also be used to calculate and display the historical tool path, to detect tool collision and to simulate material removal processes.

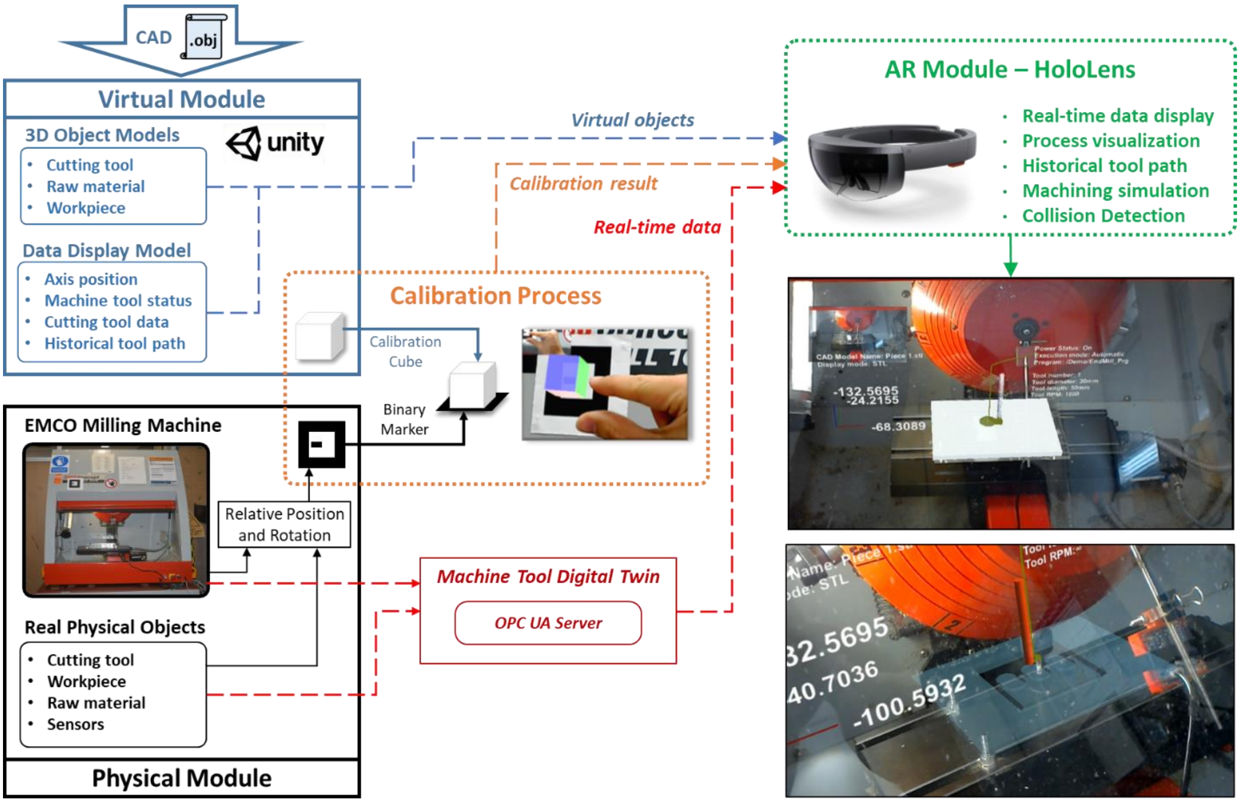

Figure 5: Design process and workflow of the AR application

Two screenshots of the developed application captured during machining and simulation process are shown in Figure 5. It can be seen from the screenshots that when the user wearing the HoloLens looks at the machining environment during machining processes, a comprehensive and intuitive understanding of the machining process can be realized. The virtual cutting tool and workpiece are overlaid on their physical counterparts and driven by the real-time position data. The toolpath is clearly indicated by a virtual line based on the real-time tool tip position. Hence the visualization of the cutting processes can be significantly enhanced especially when coolant or chips obstruct the process. In addition, the real-time data representing the machine tool status, cutting tool attributes and axes positions are also augmented in the machining environment to provide users with a comprehensive perception of the entire machining process.

Another distinctive advantage of this application is that it allows users to observe the AR-enabled machining process in a real 3D environment. For example, the virtual workpiece, virtual cutting tool and virtual fixtures can be overlaid on the worktable during a dry run. In this situation, all the virtual objects are driven by the actual axis 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 who wears the HoloLens can then observe the simulation process from different angles and distances in the real 3D environment. Thus, high-fidelity and intuitive machining simulation based on real machining parameters can also be achieved.

5 CONCLUSIONS AND FUTURE WORK

Digital Twin is considered as a key enabling technology for smart manufacturing systems. Modelling of the Digital Twin for complex manufacturing devices, such as machine tools, remains a challenging task. This paper proposes the methodology for modelling the MTDT based on open, unified and platform-independent communication standards such as MTConnect and OPC UA. To demonstrate the feasibility and advantages of the proposed approach, a Web-based machine tool condition monitoring application and an AR-assisted machining visualization and simulation application are developed. Results from the case studies have proven that the proposed MTDT enables the development of various types of applications that can improve the connectivity, intelligence and human-machine interactions of machine tools, and hence enhancing the overall machine tool efficiency and effectiveness.

Future work will focus on the development of more advanced applications for the MTDT. Implementation of advanced data analytics and Artificial Intelligence in the MTDT will be conducted. Direct feedback control from the MTDT to the CNC of the machine tool will be achieved. Moreover, the proposed methodology can be extended to model the Digital Twin of other manufacturing devices such as industrial robots and 3D printers.

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