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Visualisation of the Digital Twin data in manufacturing by using Augmented Reality

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Abstract

With the wave of Industry 4.0, Digital Twin is attracting more and more attention world-wide. The term might have been coined some time ago, today the concept is increasingly being used in the field of smart manufacturing. Digital Twin provides advantages in different fields of manufacturing, such as production and design, remote diagnostics and service. Digital Twin relies on the continuously accumulated data and real-time presentation of the collected data to simultaneously update and modify with its physical counterpart. However, presenting a huge amount of collected data and information in a Digital Twin in an intuitive manner remains a challenge. Currently, augmented reality (AR) has been widely implemented in the manufacturing environment, such as product design, data management, assembly instructions, and equipment maintenance. By integrating graphics, audios and real-world objects, AR allows the users to visualise and interact with Digital Twin data at a new level. It gives the opportunity to provide intuitive and continual visualisation of the Digital Twin data. In this paper, an AR application that uses Microsoft HoloLens to visualise the Digital Twin data of a CNC milling machine in a real manufacturing environment is presented. The developed application allows the operator to monitor and control the machine tool at the same time, but also enables to interact and manage the Digital Twin data simultaneously, which provides an intuitive and consistent human machine interface to improve the efficiency during the machining process. The proposed application paves the way for further development of intelligent control process through AR devices in the future.

Keywords: Digital Twin; augmented reality; smart manufacturing; big data visulisations

1. Introduction

Nowadays, along with the wave of Industry 4.0, the rapid developments and advancements in digital technologies are challenging the traditional manufacturing industry worldwide. In the same time, the concept of Digital Twin has been introduced and increasingly used in manufacturing. Digital Twin is a virtual and real-time representation of manufacturing systems or components. It can represent the performance, operations, environment, geometry of product, and resource states based on the continuously collected data, updates and changes from its physical counterpart [1]. Digital Twin is also a burgeoning and effective method for real-time interaction and further convergence between physical space and information space [2]. However, with the vast amount of real-time data and information from Digital Twin, it is hard to represent them to the users and operators in an intuitive way. Augmented reality (AR) as one of the critical technologies in Industry 4.0 has been widely used in the manufacturing environment. AR allows the user to see the physical world, with virtual objects overlaid onto the physical world, rather than completely replacing it. It also enables the users to interact with the physical world, where the information conveyed by the virtual objects help them to perform tasks in the physical world [3].

Motivated by representing the Digital Twin data at a new level, this paper proposes a method to visualise the Digital Twin

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data by using AR technology in a real manufacturing environment. The remainder of the paper is organised as follows. Section 2 discusses the concept of Digital Twin. Section 3 introduces the technology of AR and its application in a manufacturing environment. Section 4 introduces the method to visualize the Digital Twin data by using AR. Section 5 illustrates the developed application based on Microsoft HoloLens. Section 6 concludes the paper and discusses future work.

2. Digital Twin

2.1. Definition of Digital Twin

The concept of Digital Twin firstly came from the aerospace field to analyse and predict the behaviour and performance of the aircraft on its digital model. The definition of Digital Twin has been given by different researchers from various aspects, such as product lifecycle management, mission requirements, and diagnostics and prognostics activities [4]. Currently, the most commonly used definition of Digital Twin was given by the NASA [5]: 'Digital twin is an integrated multi-physics, multi-scale, probabilistic simulation of a product or system that uses the best available physical models, sensor updates, etc., to mirror the life of its corresponding twin.' Digital Twin consists of three components: a physical part, a virtual part, and the connections between the physical and virtual part. The characteristics of Digital Twin can be summarised as follow [2]:

- Real-time reflection: both physical and virtual parts exist in Digital Twin, the virtual part can keep ultra-high synchronisation and fidelity to reflect the physical part.
- Interaction and convergence: it happens in both physical part, virtual part and between physical and virtual part. Also, the interaction and convergence between real-time data and historical data can make the Digital Twin data more comprehensible and useful.
- Self-evolution: Digital Twin can collect and update data in real time, the virtual part can continually self-improve by comparing virtual part with a physical part in parallel.

2.2. The Digital Twin data

In order to achieve the characteristics of Digital Twin, the Digital Twin data needs to be more comprehensible, reliable and intelligent than traditional manufacturing data. The Digital Twin data can usually be divided into three categories, respectively, static property data, real-time data and measurement data [6]. Static property data stand for the basic properties of the physical part, such as the information of machines, cutting tools, workpieces, and the physical environment. This part of the data can represent the physical part of Digital Twin. For the real-time data, it can represent the status of the operation process from different aspects. The physical part can usually provide some real-time data during the operation. However, if we want to achieve ultra-high fidelity to reflect the physical part, the Digital Twin data requires a huge number of data acquisition devices (DAQs) and sensors to retrieve real-time data from the physical world. The retrieved real-time data and historical data can represent the virtual part of Digital Twin. Measurement data refers to the measurement results obtained from different measurement devices during the operation [6]. The measurement data can used to monitor and optimise the operation process, it will provide the useful information to Digital Twin to control both the physical part and virtual part of it.

Depending on the descriptions of the Digital Twin data, it is difficult or impossible for human and users to make decisions and actions based on this huge amount of data. Therefore, the visual representation is important for them to access the Digital Twin data and make better decision during the operation process [7]. Furthermore, visual representation can provide represent the Digital Twin data in a comprehensible and intuitive way.

2.3. Application of Digital Twin in manufacturing

The modern industrial production in the world market requires a further increase in variety of complex products in ever-shorter delivery times. Therefore, Digital Twin has been widely applied in different fields. It can be involved in the entire cycle of product including product design, product manufacturing, the usage of product and the maintenance, repair and overhaul (MRO) [8].

In the product design phase, the digital presentation of the product will be generated in the virtual world. The application of Digital Twin can not only show the expectations in the designer's mind but also the physical constraints from the physical world. It can help designers to easily adjust the design, to verify the design and also to improve and optimize the design by performing cross-examination in both virtual and physical worlds [9].

After the product design phase, the final design will be sent to the shop-floor for manufacturing. Starting with the raw material and ending up with the finished product, the entire manufacturing process can be managed and optimised by using Digital Twin technology [10]. However, not only the raw material and product required to have their Digital Twin, the Digital Twin of manufacturing environment, such as equipment, operator, machine tool, etc., also essential [11]. For example, Liu et al. [12, 13] implemented the concept of Digital Twin into CNC machine tool; Digital Twin can take full advantages of the real-time data collected from the physical world and allows the physical machine tool to get the intelligent and autonomous functionalities.

The usage of the product also requires Digital Twin to monitor and manage. The virtual model of the product required to continually represent its physical model. The virtual model keeps recording and monitoring the usage status data, environment data, operating data, etc. It also enables to accurately predict the product remaining life, failure, fatigue, etc. The originally concept came from airspace field was used to generate a more accurate prediction of fatigue for aircraft by

Table 1. Features of existing AR hardware.

	HMDs	HHDs	Monitors	Projectors	2D Smart Glasses
Mobility	√	√			√
3D Space Registration	√	√	√	√	
Hands-free	√		√	√	√
Real-time data transmission	√	√	√	√	√

US Air Force Research Laboratory [14]. Digital Twin has also been applied to generate the model of aircraft wings to detect and monitor the damages and defects in aircraft structure. The results have been approved to have higher efficiency and accuracy than traditional methods [15].

Apart from product design and product manufacturing, Digital Twin has also been applied in the area of MRO. Based on the prediction of health status, failures, fatigue, etc. from the previous stage, the proactive maintenance and repair can be realised to avoid unnecessary sudden downtime in the future. Furthermore, the high-fidelity virtual model of the product can efficiently identify the problem, and the problem would be visually diagnosed and analysed [16].

3. Augmented Reality

Augmented reality is one of the key technologies in Industrial 4.0; it allows the user to see the physical world, with the virtual objects composited with the physical world. It includes multiple sensory modalities, such as visual, auditory, haptic, somatosensory, and olfactory [17]. AR technology usually has the following three characteristics: combining real and virtual world, interactive in real time, and registered in three dimensions space. It also has at least six classes of potential applications, including medical visualization, entertainment, manufacturing and maintenance, process planning, and military aircraft navigation and targeting [3].

3.1. Hardware of AR

There are various types of hardware that can deliver Augmented Reality to users, and they can be divided into five major categories: Head-Mounted Displays (HMDs), Hand-Held Displays (HHDs), monitors, projectors and 2D smart glasses. In general, there are four criteria to identify the features of AR hardware: mobility of the hardware, 3D-space spatially registration, the possibility of hands-free operation, and the real-time data transmission. Table 1 below shows the summary of embedded features of each significant category [18].

As shown in Table 1, HMDs is the only type of hardware that includes all these four features. In the manufacturing environment, HMDs have some distinct advantages compared with other types of hardware and traditional Human-Machine Interfaces (HMIs). Firstly, the mobility of HMDs can provide an intuitive interaction between the physical and virtual world from any position and angle inside the manufacturing environment. The operator can work more flexibly without staying in front of a particular machine or control panel for a long time. Secondly, the 3D-space spatially registration can help the AR hardware to recognise the relative position of the 3D environment and then integrate the virtual models correctly with the physical world. Thirdly, the possible hands-free operation for HMDs is extremely useful in the manufacturing environment. The operator can visualise and monitor the process of machines through HMDs. Furthermore, at the same time, they can also control the machines on the physical panels. These two processes can be achieved simultaneously without any interruption between each other. However, even if HMDs have all the critical features of the AR device, in different stages of manufacturing, other hardware may have their unique advantages for different tasks.

3.2. AR in manufacturing

Augmented reality is currently widely implemented in the manufacturing field, and manufacturing is one of the fields where AR can be used to improve the current techniques and provide solutions in the future [19]. With the rapid development of computer and manufacturing technologies, to allow users and operators to visualise and interact with the manufacturing information associated with the manufacturing processes becomes a trend. AR has the ability to combine the virtual world and information in real-time and integrate them into the physical world. This characteristic is especially useful for many manufacturing tasks, such as product design, assembly, training process, maintenance, and fabrication process [20].For example, AR has been used to improve the car interior design, it allows the designer to overlay different types of design onto a mocked-up car body and then decide the final design [21]. Furthermore, customers now can customise their own motorcycle through AR and visualise the finished product before sending to manufacturing [22]. In assembly and training area, AR can register the 3D space and then overlay the 3D building instruction or video stream onto the physical world, to allow the users or trainees to easily understand the process, which is much more efficient than traditional training method. Moreover, AR has been used to simulate the fabrication process, this high-fidelity simulation allows the user to control and monitor the machining process intuitively [23]. Based on the current technology, the challenges of using AR in manufacturing can be summarised to four aspects as follow:

1) Real-time reflection: Real-time data: there is a huge amount of real-time data transmission during the manufacturing process. To transfer, analyse and utilise these data will be very important.
2) 3D space registration: the real manufacturing environment is complicated. The perfection of recognising, tracking and following the target object(s) decide the quality of AR.
3) Reliability: in some extreme manufacturing environment, such as high temperature, low pressure and moisture situations, AR has to be reliable and robust enough to carry on the tasks.
4) Cooperation: using AR in manufacturing should consider multiple users and operators that monitor and

control the target at the same time. The cooperation functionality is critical for the AR applications

4. Visualisation of the Digital Twin data

The Digital Twin data are real-time data that reflect the physical counterpart. Digital Twins integrates and converges the real-time and historical data to provide more useful information to the system. It eventually has the self-evolution ability to improve itself. Depending on the characteristics of the Digital Twin data, the visualisation of the Digital Twin data using AR requires the following five critical components: physical part, virtual part, calibration process, augmented process, and control process.

Figure 1 shows the framework of visualising the Digital Twin data by using AR. Physical part represents the physical objects in the real world, it can be a part, a product, a machine or even an entire factory. In addition, all the data acquisition devices and sensors are also included in the physical part. The physical part is the base of this structure, all the other parts are aiming to analyse, utilise, and update the information from this part.

The virtual part in the figure cannot be described merely as the 3D model of the physical part, it is beyond the 3D model. 3D models are essential to represent the physical part in the virtual world. However, apart from this, all the real-time data collected from sensors, data acquisition devices, machines, and inputs from humans belong to the virtual part. Moreover, to achieve a comprehensive visualisation of a Digital Twin, all the historical data stored in the server are important to be treated as the virtual part.

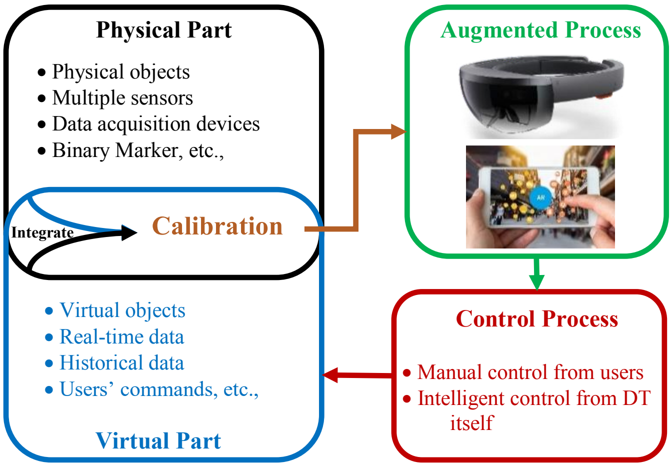

Fig. 1. Framework of visualising the Digital Twin data by using AR.

In order to achieve intuitive and flawless AR visualisation of Digital Twin, the 3D models in virtual part need to be perfectly aligned with the physical part. This relies on the calibration process to accurately integrate these two parts. There are many calibration methods in AR, the most commonly used is binary marker tracking method. In the physical part, the binary marker is placed in the physical world where the AR devices can visualise and recognise. In the virtual part, a cube is designed to align with the binary marker in the physical part. When the cube is perfectly aligned with the marker through the user's view, the calibration process is accurately done, the virtual world now is perfectly aligning with the physical world, which means all the 3D models in virtual part can be overlaid onto their counterparts in the physical part.

The responsibility of the augmented process is to provide intuitive AR visualisation of Digital Twin to users through AR devices. The AR device receives data from the virtual part and calibration results and presents them properly. This process is not simply displaying the entire virtual part directly onto the device. With different physical environment and objects, and different input commands from users, the augmented process will display different virtual objects on AR devices. For example, for different CNC machines in factory, the augmented process will display different information and virtual objects accordingly. With this filtering process, the Digital Twin data could be more comprehensible and useful to the users.

The final component is the control process. The control process allows the user to interact with both physical part and virtual part of Digital Twin. After getting intuitive and comprehensive visualised data from the augmented process, users can take advantage of this useful information to make decisions and control the physical part directly through the AR device. Through users' commands and inputs into the control process, which will establish a closed-loop control to directly improve and update the Digital Twin data, and then the modified and improved the Digital Twin data will keep displaying onto the AR device.

5. Application

In the era of Industry 4.0, machine tools become part of a platform that connects machines, systems, data sources and operators. All the decisions made by machine tool and operator are based on big data analytics and its Digital Twin. The modern industrial production in the world market requires a further increase in variety of complex products in ever-shorter delivery times. Machine tools are required to become more and more intelligent to handle this situation. The machine operator usually needs to handle the following tasks during the fabrication: preparation, environment setup, machining monitoring, and process optimisation. In order to help machine operators to manage all the tasks and information under complicated manufacturing environment, most CNC machine companies choose to place additional displays around the machine to show the information. However, experience shows that operators' attention can to be distributed to additional displays with inconsistent user interface. It is also hard for the operators to focus on the multiple displays at the same time, some useful information may be ignored.

Based on the current situation, there has been a need of AR enabled display for the machine operator to dominate the product changes and start-up phases faster and more accurate. The developed system can monitor and manage the machining data and provide high-fidelity machining process simulation though AR device. In addition, the developed system based on HMDs also aims to provide a consistent and advanced human machine interface to help operators reduce the complexity of working environment, while increase the efficiency during the machining process. Furthermore, the presented virtual model of Digital Twin can help the operator to easily and intuitively manage and interact with the Digital Twin data.

To demonstrate the advantages and potential of the proposed concept, an application has been developed. The aim of this application is to visualise the Digital Twin data during the machining process by using AR. The used AR device is the HoloLens. The HoloLens was released in 2016 by Microsoft, which is the first commercially available holographic HMD in market. This product was specially designed for AR and Mixed Reality (MR). Compared with other HMDs and HHDs, the HoloLens has some distinct advantages in manufacturing environment. Firstly, the HoloLens allows the user to free both hands, and users can easily control the device through voice commands and gestures. Secondly, the built-in central processing unit (CPU) and operating system allow the device to handle a huge amount of real-time data and historical data during the operation. Thirdly, the HoloLens is integrated with various sensors and camera system to allow more advanced AR application to be developed and deployed on it.

This AR application is set up on an EMCO 3-axis milling machine. The EMCO CNC machine is connected to a host PC through Ethernet cable. The host PC is also hosting a server that stores the real-time and historical data. The Server on the host PC can retrieve the real-time working data from the CNC machine and the extra data from external acquisition devices and multiple sensors. All the data transmission and connection between CNC machine, host server and HoloLens are based on TCP/IP. Furthermore, the server on the host PC can provide data to HoloLens through the Wi-Fi connection.

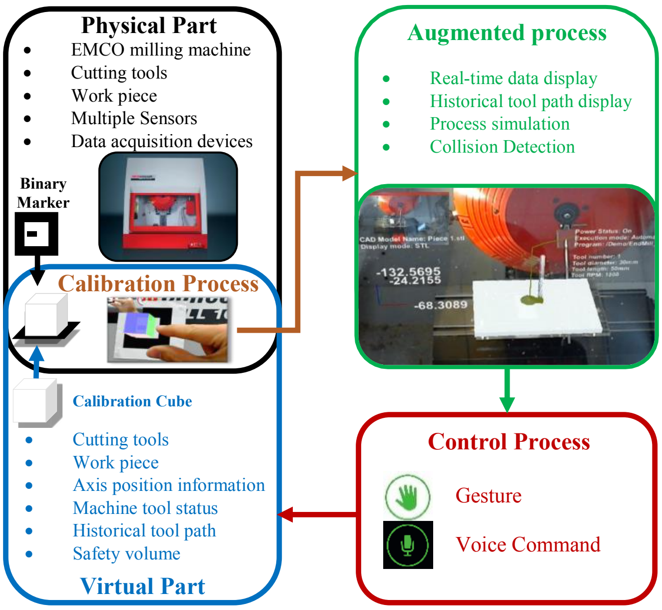

Fig. 2. Architecture and workflow of the AR application.

The application includes five critical components as described in Section 4. Figure 2 shows the architecture and workflow of the AR application. The physical part consists of the EMCO milling machine, cutting tools, work piece, and other DAQs, such as camera, RFID, and dynamometer. The virtual part consists of all the 3D models generated by CAD software, all the 3D models need to be converted to object file format and transferred into the Unity 3D game engine, which is used to build the AR application in this case. In addition, all the collected data from CNC machine and DAQ devices belong to virtual part. It includes axis position data, machine tool status, cutting tool data, historical tool path data, cutting force data, and safety volume data.

The calibration method has been used is the binary marker tracking method. A binary marker has been placed on the front of the CNC machine to do the calibration. The Microsoft HoloLens has been used in the augmented process to show the Digital Twin data to users in this application. HoloLens can receive real-time data from machine and server, the real-time data transmission allows the augmented process to dynamically integrate and update the physical part and virtual part under the real manufacturing process. The augmented process can assign collected data to the corresponding part in the virtual world and then display the virtual parts correctly. For example, the axis position data will assign to work piece and cutting tool to update their information of the position in AR. The safety volume data will assign to the entire machining environment and indicate the unsafety area through AR. In addition, some other useful data such as spindle speed, feed rate, and cutting force will assign to the data display model, which can display these data as text in a real-time environment. 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.

Lastly, the control process can also be achieved through HoloLens. Gestures and voice commands can be used by users to control the virtual part of Digital Twin, and then the command will affect the counterpart in the physical world. The control process is the critical process that allows the operator to easily and intuitively interact and manage the Digital Twin data. In addition, the hands-free operation would be much more efficient for the operators during the machining process. Through HoloLens, the operator's actions and commands allow to display the information that they need at the right time without touching or interacting with the physical machine tool. Therefore, the operator can monitor and control the machine tool and manage and interact with its Digital Twin simultaneously.

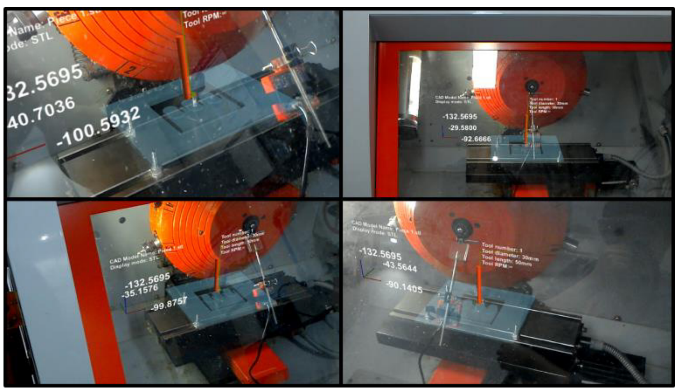

Fig. 3. Captures of the HoloLens view taken from different angles and distances during machining simulation.

Figure 3 shows some views from HoloLens during the machine process. It can be seen from the captures that AR through HoloLens can provide an intuitive and comprehensive view of the Digital Twin data under manufacturing environment.

6. Conclusion and Future Work

Digital Twin and AR are considered as the key technologies for smart manufacturing. Visualising the Digital Twin data by using AR technology can integrate and converge the physical part and virtual part of Digital Twin in a more intuitive and comprehensive way. The proposed framework indicates five critical components in this process. Each component is not isolated with each other; the framework shows the close connections between them. This framework can be applied into most AR applications to visualise the Digital Twin data in manufacturing environment. It also serves as a guide during the design and development of the application. The demonstrated application in this paper shows the great potential and advantage to visualise the Digital Twin data using AR in a real manufacturing environment. The augmented Digital Twin data can provide more useful and comprehensive information to users through the AR device. Users can take advantage of these data and information to perform efficient decision-makings and higher level machine control. Therefore, the proposed process not only improves the efficiency and effectiveness in manufacturing, but also brings the connection between the virtual part and the physical part of Digital Twin to another level.

Future work will focus on the development of intelligent control through AR on Digital Twin. Currently, the application only provides some simple control and modification functions, more advanced and intelligent control functions and decision-making supports will be designed and implemented into the current framework.

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