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Towards the Implementation of the Digital Twin in Machining Process: Opportunities and Challenges

Raoudha GAHA[1], Alexandre DURUPT and Benoit EYNARD
Université de Technologie de Compiègne Laboratoire Roberval, rue du Dr Schweitzer, CS 60319, 60203 Compiègne cedex France.

Abstract. The use of Digital Twin (DT) is adopted by manufacturers and have positive effects on the product manufacturing process. The use of Digital Twin (DT) is adopted by manufacturers and have positive effects on the product manufacturing process. The aim of this paper is to present opportunities and challenges of the application of DT concept in machining process extracted from a literature review conducted on the use of DT on CNC machining process. Hence, firstly, we review related studies based on existing DT orientations and usages for machining process. Secondly, a discussion about possible DT functionalities and opportunities is conducted, this allows to present a clear vision on gaps needed to be studied to enrich and propose a DT model for machining process. Finally, a conclusion and perspectives for future are presented.

Keywords. Machining process, Digital Twin, Industry 4.0 technologies.

1. Introduction

Today, Intelligent Manufacturing has become the trend of global manufacturing industry, and the core of the industry 4.0. Machining technology is the main way of mechanical manufacturing [1], to ensure the quality of product processing. Based on smart CNC machining, today, they allow supporting autonomous manufacturing by an intelligent simulating, predicting, controlling and optimizing strategy. As the manufacturing process of the complex product becomes more and more complex, smart CNC machining (SCNC) becomes expensive and time-consuming, when quickly respond to the unexpected events is required. Hence, to handle the dynamic change of the machining condition, the new technology called the Digital Twin (DT) can be used for accessing to realistic models of the current state of the process and their own behaviors in interaction with their environment in the real world [2]. Digital twin, as an effective way to reflect the entire life cycle of a physical device or product physical in virtual space and its digital counterpart, has a significant improvement to realize the smart design and manufacture [3] by resolving encountered problems and being a solution for some gaps found in machining process. Although, DT concept has been applied in many industrial fields, since it was proposed [1], its application to the machining process has not attracted enough attention and still at a very early stage. In this paper we present an overview of

[1] Corresponding Author. raoudha.gaha@utc.fr

DT/ Machining process researches. The objective of this work is to present opportunities and challenges in the application of DT concept in SCNC machining, in order to propose an SCNC machining Digital Twin model, covering the machining process requirements and connected to the digital thread in future researches.

2. Digital Twin in machining process: A literature review

In this paper, we categorize researches, focusing in machining-oriented digital twin, into two main categories; Digital twins' application in the machining process and the application of the digital twin in machining process monitoring, in order to determine the main research gaps that need to be treated in future DT / Machining process works.

2.1. Digital twins' application in the machining process: an overview

Due to the rapid development of communication technology, network technology, and computer technology, an intelligent manufacturing system (IMS) becomes a necessity in industries today. An IMS can realize the information perception, network communication, and data integration of the machining process [4]. The application of the Digital Twin in machining process can be realized into four levels: Product modeling, Machine tool, Process data, Process evaluation and machining systems.

From the product modelling level, Liu et al. [5] proposed a digital twin modeling method based on biomimicry, that can adaptively construct a multi-physics digital twin, for data modeling of aerospace components. From their side, Rosen et al. [3], proposed a future possible mode of DT-driven product manufacturing, which is exploited by Tao et al. [6] where they illustrated the mode on the drive shaft machining process.

From the machine tool level, digitalization becomes a necessity. A dynamic model of a machine tool presents a basic component for the setup of a digital twin of the working process [7]. The main features of the dynamic model are, the model of the cutting process and the model of the transmission chains and of the control systems [7]. Presenting a unified modeling method for multiple fields, a mapping method, and an autonomous strategy are important in a DT based-machine tool [8]. An intelligent machine tool (IMS) driven by digital twin, used for data analysis and visualization, has been also proposed by Tong et al. [9].

From the process data level, which is the key of the application of Digital Twin on machining process. It can be divided on two steps; data collection and data fusion.

For data collection, according to Zhao et al. [10], the acquisition and management process of real-time data is divided into four steps: (1) Identifying static information by using RFID tags and bar codes. (2) Obtain dynamic information based on multi-intelligent sensors and monitoring system. (3) Establishing data transmission network based on interface protocol to ensure efficient transmission find fusion of real-time data. (4) Use database software to store, manage and call all data. The data source and types are presented by Liu et al. [11]. For example, the workpiece contains material and process information which are static and structure data which can be collected from CAM database. Coronado et al. [12] proposed the workshop digital twin concept by collecting data generated by the MTConnect- enabled machine. Kong et al. [13] proposed a method that can provide data support for applying the digital twin system stably and efficiently.

Concerning data fusion, the data exchange between heterogeneous systems, is an important step to apply a machining simulation in Digital Twin. Schroeder et al. [14], discussed this exchange and introduced an AutomationML to achieve this. According to Cao et al. [15], the difficulties of applying machining simulation in Digital Twin can be summarized as three points, data integrity, cooperation with CNC system and efficient machining simulation algorithm.

For process evaluation and machining systems, the choice of static parameters to be evaluated will not achieve good results that we expect, as a result of the mismatching between the real-process and the static evaluation. The quality of product can be affected by disturbances during machining process. Therefore, how to automatically evaluate and optimize the process planning becomes an urgent problem in smart manufacturing. That's why, Liu et al. [2] proposed a novel method to evaluate the process plan in the real-time, where dynamic change of actual machining conditions and uncertainty of manufacturing resources are considered.

2.2. The application of the digital twin in machining process monitoring

The change of size, surface roughness, residual stress, and so on profoundly influence the final machining quality of complex mechanical products. Hence, monitoring the machining process is becoming increasingly important for maintaining consistent quality in machined parts. To capture the real-time status of the manufacturing resources and the workpiece, the sensor-based monitoring systems are necessary. The variety of sensors are employed in monitoring the machine tools [16]. For example, acoustic, vibration, force, etc. The monitoring system which applies the monitoring devices to track the availability of machine tools helps in an adaptive and holistic scheduling. Therefore, Digital twin machining technology can ensure machining quality by observing the machining process in real time. In Yi Cai's research [17] a virtual machine tool is constructed by fusing the sensor data to evaluate the surface roughness. Digital Twin is also applied to improve the intelligence in manufacturing process control. Li et al. [18] studied the visual monitoring technology of multi-source heterogeneous machine tool data during the machining process. Luo et al. [19] improved the operation mode, reduced the possibility of sudden failure, and improve stability based on the application of the digital twins of the CNC machine tool. Zhu et al. [20] proposed a web-based virtual turn milling system, which can help buyers and sellers better understand the product. It can enable planners and machinists to make decisions or verify CNC codes more accurately. Augmented reality is proposed by Liu et al. as a monitoring technology on the machining process based on the digital twin machining system, in order to facilitate the transmission of the useful processing information to the on-site technicians effectively [11].

3. Discussion

Surely, the application of DT concept in machining process, allows the improvement of machined parts in real time. The most opportunities extracted from the literature review above are presented in table 1.

Table 1. Opportunities of the application of DT on machining process

Opportunities of DTW on machining process	Tools	Comments
CNC machine process capacities, and availability, etc. can be collected.	RFID	Real time data collection
Iterative low-cost virtual simulation of the machining process based on the following data; the machining size, tolerance, the spindle speed, the feed rate, the position of groove, etc. [6]	Virtual machine	Allows the detection of existing problems, such as the interference and collision between the tools and workpiece.
Optimization of the machining plan through iterative test [6]	Algorithms	Lower energy consumption, shorter processing time, and higher machining accuracy, etc.
Reading the state of workpiece/tool position, spindle speed, feed rate, etc. [6]	Numerical control system	Real-time data reading
Tool wear, spindle vibration, workpiece surface roughness, etc. can be collected from external sensors. [6]	external sensors.	Process Data collection
Comparison of current states with the predefined plan. The inconsistence triggers the evaluation the machining process to find out problems [6].	Virtual machine	Problems caused by physical disturbance, like the spindle vibration, tool wear, material defect, or by unreasonable factors of plan simulation, like parameter setting and boundary and initial conditions.
Adjusting the machining plan to ensure the consistence between the two sides virtual and real process [6].	Virtual machine	Simulation of machining plans
Construction of a multi-physics digital twin based on biomimicry for predicting information and guiding production. [5]	Modeling, Sensors, Data acquisition.	Predict roughness in real time and provides suggestion or feedback.
Data Analysis and visualization [9].	Multi-sensor fusion technology is adopted for real-time data acquisition and processing	An intelligent machine tool (IMS).
Data collection [12]	MTConnect- enabled machine	Popularity of MTconnect on collecting data from machine Tool.
Stability and efficiency of collected data [13]	Guides, Sensors, DAQ, RFID, etc	Data construction method.
Data exchange between heterogeneous systems [14]	AutomationML	Modeling attributes related to the Digital Twin for an easier heterogenous data exchange.
Automatic evaluation and optimization of the process planning [2]	High-fidelity virtual models for physical objects in digital way.	Machining process evaluation methods can be divided into three categories: model-based methods, knowledge-based methods and data-based methods
Ensuring machining quality by observing the machining process in real time [16]	Variety of sensors	Acoustic, vibration, force, etc
Improving the intelligence in machining process control [17].	Sensors date and information fusion	Evaluating surface roughness.

Improving the operation mode, reducing the possibility of sudden failure, and improving stability [18]	Sensors, monitoring system	multi-source heterogeneous machine tool data.
Enabling planners and machinists to make decisions or verify CNC codes more accurately [19].	Web-based virtual turn milling system,	can help buyers and sellers better understand the product.

However, the current digital twin systems mainly adopt the display method of virtual-real separation. The human interaction is not yet considered it is introduced only in [11], by using Augmented reality technology based on the digital twin machining system. It can promote cooperation among the operators and the digital twin machining system, in order to avoid irreparable errors when the finished product is nearly completed.

At the end of this literature review some research gaps can be presented as challenges (table 2) to improve existing models in order to propose a DT machining process model based on opportunities cited above.

Table 2. Challenges in the application of DT on machining process

Challenges	Consequences/Solutions
Considering human interaction using based on the digital twin machining system based on Augmented reality technology and DTW [11].	C: Avoiding irreparable errors when the finished product is nearly completed.
The lack of research on processed products [11]	S: Important information related to the product directly Needed to be outputted.
The focus is only on monitoring machine tool's data [11].	S: Visualization method to promote cooperation between humans and the system is required.
There is a gap in terms of representing middle- and end-of-product lifecycle-related semantics [22]	C: Incompleteness of DT creation in machining process
Lack of research on modeling process. [22]	C: A gap in terms of describing the" reality" of the specific domain [22].

4. Conclusion

Digital industry, requires today the implementation a system that could manage easily the Big Bata through the digital thread, in the whole stages of the product development. Machining process is a key of high-quality products. For this, we focused on exploiting advanced technologies such the Digital Twin. In this work, we develop firstly a literature review to define the concept of DT. In the second step, with focus to DT/Machining process, we present related works, where the Digital Twin has had a key role to resolve real-time machining process problems. Finally, a discussion presents the different gaps found in the literature when introducing DT in machining process. However, works integrating DT/machining process could be exploited to introduce environmental constraints which become more and more important to be considered and can be developed in future works.

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