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Dynamic Evaluation Method of Machining Process Planning Based on Digital Twin

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ABSTRACT Process evaluation is widely accepted as an effective strategy to improve product quality and shorten its development cycle. However, there has been very little research on how to evaluate the process plan with the dynamic change of the machining condition and uncertain available manufacturing resources. This paper proposes a novel process evaluation method based on digital twin technology. Three core technologies embodied in the proposed method are illustrated in details: 1) real-time mapping mechanism between the collected data in machining and the process design information; 2) construction of the digital twin-based machining process evaluation (DT-MPPE) framework; and 3) process evaluation driven by digital twin data. To elaborate on how to apply the proposed method to the reality, we present a detailed implementation process of the proposed DT-MPPE method for the key parts of the marine diesel engine. Meanwhile, the future work to completely fulfill digital twin-based smart process planning for complex products is discussed.

INDEX TERMS Digital twin, process planning, process evaluation, mapping mechanism, digital twin data.

I. INTRODUCTION

In the recent years, the Computer-Aided Process Planning (CAPP) technology is challenged worldwide with the amazing growth and advancements in the information and communication technologies (e.g. the Internet, artificial intelligence, big data, cloud computing, etc.) that allow easily to implement process evaluation and optimization by fusing the history data and real-time perception data, that is the basis of the smart manufacturing.

How to realize the interoperability and intelligent operation of physical and information world of the manufacturing is one of the challenges for promoting and applying the smart manufacturing. Digital Twin, as an effective mean to reflect the physical status in virtual space, has a significant promotion to realize the smart design and manufacture. It breaks the barriers between the physical world and the cyber world of manufacturing. Digital Twin technology is becoming the focus of global manufacturing transformation and upgrading. Gartner, the world's most authoritative IT research and consultancy consulting company, has listed Digital Twin as one of the ten strategic technology development trends in 2016 and 2017; Lockheed Martin, the world's largest weapons manufacturer, listed digital twin as the top 6 of the top defense and aerospace industry's top technologies in November 2017 [1]. In December 2017, the China Association of Science and Technology Smart Manufacturing Academic Consortium listed "Digital Twin" as one of the top ten technological advancements in the world of smart manufacturing at the World Smart Manufacturing Conference. Therefore, the digital twin has been recognized at international level as one of the strategical responses of the manufacturing companies to the technical upgrading.

CAPP has become one of the key technologies for enterprises to improve their core competitiveness. It is a bridge between design and manufacturing. To meet the requirement of current three-dimensional design and intelligent machining equipment, the Model Based Definition (MBD) technology which used 3D technology to upgrade the current manufacturing capacity has been widely used in

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processing and manufacturing enterprises. MBD is, at its core, a way of gathering and managing product/process data (e.g. geometrical, technological, etc.) inside of a three-dimensional model, in the form of annotations, parameters and relations. The MBD-based process planning method mainly cares about how to express the process information [2] and reuse the embedded manufacturing knowledge of the MBD process model in their repository [3], thus they are recognized as an effective strategy for 3D process planning with less time and lower cost. However, with the dynamic change of machining conditions and uncertain manufacturing resource, how to evaluate the predefined machining process becomes the key of improving product quality and shorting the development cycle.

Based on the motivations described above, a novel DT-MPPE method for complex parts is presented in this paper. Firstly, the mapping strategies between the perception data in the physical machining status and the data in virtual evaluation model are introduced. Secondly, a DT-MPPE framework which captures the multi-dimensional heterogeneous data is designed to fulfill dynamic evolution. Then, the evaluation method is presented to predict the machining quality based on the generated digital twin data. Finally, a DT-MPPE framework for key parts of marine diesel engine is proposed to predict, estimate, and analyze the predefined machining process planning.

The remainders of the paper are organized as follows: Section.2 investigates the development and application of the proposed key techniques. Section.3 analyzes the existing problems in process planning for machined parts and presents a framework of machining process planning evaluation. To fulfill the framework, Section.4 presents three key technologies in details. Section. 5 illustrates the implementation process of the proposed method for the key parts of marine diesel engine. The last part concludes the main contributions and discusses the research issues in the future.

II. RELATED WORK

With the development of digital manufacturing technology, CAPP technology and systems are extended and modulated, then they used in manufacturing enterprises extensively [4]. As the manufacturing process of the complex product becomes more and more complex, it is difficult to quickly create the machining planning by the traditional way. In order to reduce the process design cost and increase the consistency and efficiency, MBD-based methods have gradually attracted the attention of researchers [5]–[7]. Because it can better organize and manage a great deal of process knowledge, such as the geometric information of machining features, the precision information of surface and the topological relations, etc. According to the stored machining knowledge in their repository, MBD-based process planning could construct the process flow with less time and lower cost. However, the planner did not consider the actual processing conditions when designed the process planning. The complex, varied and dynamic manufacturing condition leads to low level of efficiency, sustainability, intelligence in the product process execution phases. Therefore, how to automatically evaluate and optimize the process planning becomes an urgent problem in smart manufacturing.

In order to quickly respond to the unexpected events without central re-planning, new ways are needed to handle the dynamic change of the machining condition and uncertain manufacturing resource availability. The new technology, accessing to realistic models of the current state of the process and their own behaviors in interaction with their environment in the real world is called the ''Digital Twin''. Digital twin is an integrated multi-physics, multiscale and probabilistic simulation of a complex product and uses the best available physical models, sensor updates, etc. to mirror the life of its corresponding twin [1]. The idea and concept of digital twin, which mainly contains the real-time data acquisition technology, data mapping technology and data-driven predict technology can realize the convergence between product physical and virtual space.

1) THE REAL-TIME ACQUISITION DATA TECHNOLOGY

The data collection during the manufacturing operations is the foundation of the factory automation and decision making [8]. Modern manufacturing shop-floors suffer from a bottleneck of capturing and collecting real-time field information. Without up-to-date information, it is impossible to make accurate shop-floor decisions. Therefore, real-time acquisition data technology has caused the attention of many researchers and some methods are provided, such as bar-coding based technology [9], Radio Frequency Identification (RFID) technology [10], automatic identification technology, etc.

Nowadays, the use of RFID technology is extended and applied in the manufacturing/assembly shop-floor, and it has a rising trend day by day [11]. And application of RFID is used to be integrated into some intelligent software to help to fulfill the automatic routine decision-making. In manufacturing field, in order to trace and track work in process items throughout the manufacturing processes, Mahir *et al.* [12] proposed a case study that RFID could be successfully implemented; Wang *et al.* [13] presented an example of RFID tracing systems to improve the efficiency of tracking tires in both warehouse management and production processes; To trace and monitor the product quality in the distributed manufacturing network, Lv *et al.* [14] proposed a new RFID-based CPN modeling method where the colored tokens were evolved to color-tagged tokens carry the product information of real-time status. For collecting and synchronizing the real-time field data from manufacturing workshops, Huang *et al.* [15] presented an affordable approach to improve the shop-floors performance which used wireless manufacturing. Based on the various industry areas, the application of RFID appears outstanding in aviation, building management, library, health and logistics and supply chain management.

Monitoring the machining process is becoming increasingly important for maintaining consistent quality in machined parts [16]. To acquire the actual status of the manufacturing resources and the workpiece, the sensor-based monitoring systems have caused a lot of attention. The variety of sensors are employed in monitoring the machine-tools [17]. 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 [18].

2) DATA MAPPING TECHNOLOGY

It is well known that it is not only the proper monitoring of the shop-floors signification and practical, but also the fusion of heterogeneous data are essential for reducing the number of incidents and improving the manufacturing efficiency. The principal objective of multi-sensor data fusion is to improve the quality of information output in a process known as synergy, which is widely used for combining sensor data or deriving data which are from sensory data to a common representational format to improve system performance [19]. Different types of equipment have different data capturing standardizations, which directly result in heterogeneous and uncertain data. Therefore, some methods such as Internet of things (IoT) middleware, feature extraction, and information integration methods have been researched to fuse the heterogeneous data. Based on different Computer Aided Design system, Computer Aided Engineering system and Computer Aided Manufacturing system, Yi *et al.* [20] proposed a semantic feature fusion-based heterogeneous model method to fuse the feature into one model. In the workshop monitoring, in order to overcome the ineffectiveness of CNC machining progress information extraction and its application restriction, a fusion method of multi-sources heterogeneous information which includes machining path, real-time spindle power information, manual input data and tool position were presented in [21]; Zhang and Ge [22] designed a fusion system by combining six conventional methods. In order to improve the computational efficiency and reliability of the fusion system, a new diversity measurement index was developed for fault detection.

3) MACHINING PROCESS PLANNING EVALUATION TECHNOLOGY

Generally, machining process evaluation methods can be divided into three categories: model-based methods, knowledge-based methods and data-based methods. To reduce the subjectivity and improve efficiency of the evaluation design process, Zhang *et al.* [23] proposed a quantitative evaluation through data-driven performance predictions. Based on extension theory and entropy weight, Yan *et al.* [24] proposed the sustainability assessment method of machining process which respected to a consistent set of environmental, economic and social criteria.

Although satisfactory results have been obtained in many evaluation processes by using those mature methods, the machining quality has not been effectively guaranteed. The state of process is usually the combination of many machining elements, which may cause performance deteriorations of those methods. In fact, it is obvious that sometimes 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. With the introduction of the concept of digital twin, it paves a potential way to realize the cyber-physical mapping, which creates high-fidelity virtual models for physical objects in digital way to simulate and evaluate their behaviors.

Currently, digital twin-related methodology and technology have been attempted in manufacturing field. The combination of smart manufacturing services and digital twin would radically change product design, manufacturing, usage and other processes [25]. For designing and multi-objective optimizing of hollow glass production line, Zhang *et al.* [26] presented a digital twin-based approach which merged physical-based system modeling and distributed real-time process data to generate an authoritative digital design of the system at pre-production phase for rapid individualized designing. To secure good geometrical quality in the final product, digital twin was developed and used for product and production system design in the concept phase and later on inherited for inspection preparation and process control in [27]. A comprehensive reference model, which was served as a digital twin of the physical product in design and production engineering was designed for the product life-cycle in [28]. To illustrate the application of digital twin in the product life cycle, Tao *et al.* [29], [30] proposed a new method for product design, manufacturing and service driven by digital twin.

Based on the description and application above, digital twin technology is considered as a feasible and effective approach in the product life cycle. Digital twin technology refers to the process or method of describing and modeling the physical entity's characteristics, behavior and performance by means of digital technology. It embodies an effective approach to realize the interaction and convergence between the cyber and physical worlds. Therefore, in order to improve the machining process's enforceability, the dynamic evaluation method which combines the real-time collected data and process information is developed.

III. OVERVIEW OF DIGITAL TWIN-BASED MACHINING PROCESS PLANNING EVALUATION METHOD

In this section, we introduce the existing problems in the process design for machined parts, then define some basic concepts and briefly outline our approach.

A. THE EXISTING PROBLEM IN THE PROCESS PLANNING FOR MACHINED PARTS

Traditional part processing has only a single, fixed routing. It is created based on empirical data from the enterprise's production. Due to the objective conditions of operators, generally, empirical data is not the optimal data. And since the dynamic information of the workshop is not considered,

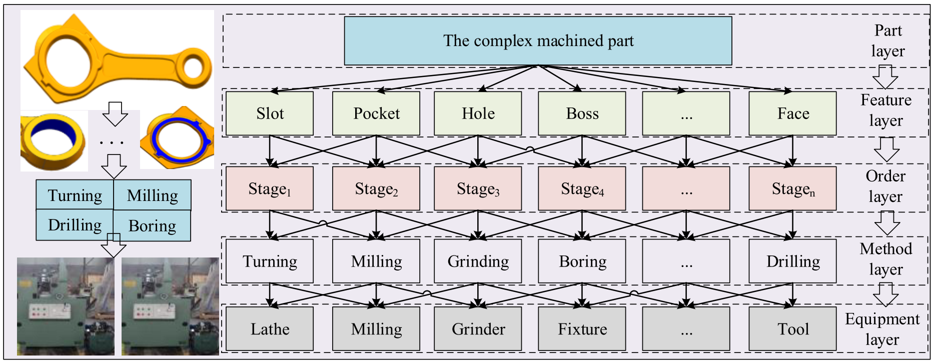

FIGURE 1. The basic structure of the process route.

the enforceability of the process planning in actual production is greatly reduced. In the manufacturing workshop of key parts of the marine diesel engines, the common practical production problems mainly include the following aspects.

1) Unpredictability of machining quality. The connection relationship model between processing parameters and processing results was not created, which caused it difficult to guarantee the quality of the machining process, for example size exceeds the limit, etc. Other than that, processing time cannot be accurately predicted too.

2) Uncontrollability of machining costs. The cutting parameters dynamically change in machining. However, the process parameters of the process planning are usually added based on the empirical data and these data remain unchanged. Therefore, the conservative machining parameters inevitably increase the production costs.

3) Uncontrollability of machining efficiency. In process design, the selected process equipment is ideal, but there are some uncertain factors in the actual process, such as equipment failure, occupied by other processes, etc. These problems often result in process route that cannot be performed smoothly. And the processes are delayed.

B. DEFINITION AND CONCEPTS RELATED WITH MACHINING PROCESS PLANNING EVALUATION

Definition 1: Digital twin-based machining process planning evaluation (DT-MPPE). According to the real-time acquisition data of the physical machining status, the machining process planning is judged whether reasonable and feasible or not. Evaluation content of the machining process planning mainly includes two parts: process route and process parameters.

The part route is made up of a reasonable ordering of machining feature elements (MFE) and shown in FIGURE 1. MFE refers to a collection of information which embeds in a machining feature. It includes five elements and is represented as follows.

$$\mathrm{MFE} = \{\mathrm{MF}, \mathrm{MS}, \mathrm{MM}, \mathrm{ME}, \mathrm{MR}\} \tag{1}$$

where MF refers to the machining feature which is the carrier of MFE; MS indicates the machining stage of MF; MM indicates the machining methods of creating the MF; ME indicates the machining equipment; MR indicates the machining restraint.

Under the process constraints and the real-time status of the available manufacturing resources, the priority relationships of machining feature are analyzed and evaluated, and then the process route is optimized based on the intelligent algorithm. Based on the processing dimensional accuracy and processing cost, the aim of process parameters evaluation is to optimize the cutting parameters such as feed rate, depth of cut, spindle speed, etc.

Definition 2: Digital twin data. The converged data between the real-time acquisition data of the manufacturing status and the process design information is called the digital twin data.

The collected data in the physical manufacturing status includes the real-time status of the machine and fixture, the wear state of the tool, the real-time geometric information of the process model, etc. The association information of the process model includes the attribute information of the process, the machining methods, the geometric information of the machining feature, etc.

C. OVERVIEW THE DT-MPPE METHOD

The proposed method is to help designers to obtain the better process route and process parameters based on the digital twin data, then the machining efficiency can be improved by combining the machining status and process information. Using the object-oriented technology, feature-based technology, digital twin technology and IoT technology, the DT-MPPE method is implemented. For efficiently evaluating the identified machining process, hierarchical data structure of perception data, the digital twin-based process model and the evaluation methods of the machining process are established. Comparing to the traditional process design, designers can adjust the process content based on the proposed method more clearly.

The data flow of DT-MPPE is divided into three layers as shown in FIGURE.2.

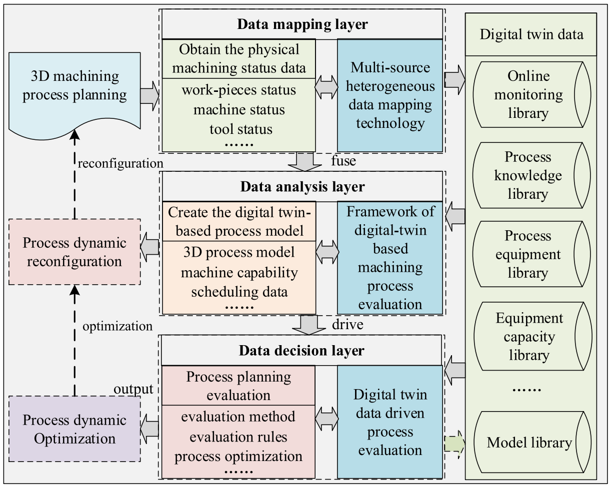

FIGURE 2. Data flow of the DT-MPPE.

1) DATA MAPPING LAYER

The main aim of this layer is to acquire, organize, manage and map the collected data in machining. These collected data is acquired by the multi-agent such as electronic tags, smart sensor. And these data are organized by object-oriented method.

2) DATA ANALYSIS LAYER

This layer is in charge of the virtual, dynamic model creation in the virtual world that is fully consistent with its corresponding physical entity in the real world and can simulate its physical counterpart's characteristics, behavior, life, and performance in a timely fashion.

3) DATA DECISION LAYER

It is in charge of evaluating the machining process planning based on the proposed evaluation rules. And then the corresponding modified strategies of the machining process are stored and fed back to designers.

IV. THE DT-PEEM METHOD

Based on the proposed data flow of the DT-MPPE method, this paper illustrates three key layers in details. It contains three key technologies as follows: 1) Multi-source heterogeneous data mapping technology, 2) the framework of DT-MPPE method and 3) process planning is evaluated by digital twin data.

A. MULTI-SOURCE HETEROGENEOUS DATA MAPPING TECHNOLOGY

How to better acquire, organize and manage the multi-source heterogeneous data of physical machining status is the basis of DT-MPPE. Therefore, the mapping strategy between the perceived data and the process information needs to be established and shown in FIGURE.3. It includes three parts: multi-agent layout for process equipment, object-oriented

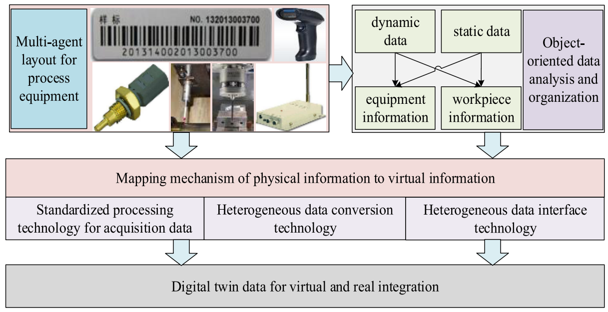

FIGURE 3. Flow chart of the physical data map to virtual data.

data analysis and organization, and mapping mechanism between physical information and virtual information.

1) ADAPTIVE SENSING FRAMEWORK OF MULTI-AGENTS FOR MACHINED PARTS

An efficient method to collect, perceive and manage the multi-source heterogeneous data is one of the main issues that prevent the manufacturing shop-floor for machined parts in its entry to the smart machining. In order to collect real-time information, we designed an adaptive sensing framework of multi-agents for machined parts as shown in FIGURE. 4.

With the advance of sensor network, wireless network, automation technology and analysis technology, a wide range of applications have been achieved in manufacturing shop-floors with RFID and multi-agent as a representative of IoT technology. This meets the needs of manufacturing shop-floors in real-time information acquisition. As shown in FIGURE.4, the adaptive sensing framework is divided into three layers: perceived data, transfer data and acquired data. In perceived data layer, the information between work-pieces and machining equipment is the main object of data collection. The attribute information between work-pieces and equipment is acquired based on the RFID technology; the dynamic information which evolves the process equipment and work-pieces is acquired based on the multi-agent such as inspection probe, size measuring instrument, tool-scope system, MDC system, etc. The second layer serves as a bridge between perceived data and acquired data. It consists of various networks, which include the wired network, wireless network, sensor network, RFIDs, Bluetooth and a cloud computing platform. In acquired data layer, these acquired data are divided into work-pieces information and equipment information. The work-pieces information includes the size, precision and process step; the equipment information includes the machine, cutting variable and the tool information.

2) OBJECT-ORIENTED DATA ANALYSIS AND ORGANIZATION

A large amount of data are generating during the processing of the machined parts and these acquired data have the characteristics of multi-source heterogeneity. In order to map these acquired data to the virtual models, we provided the

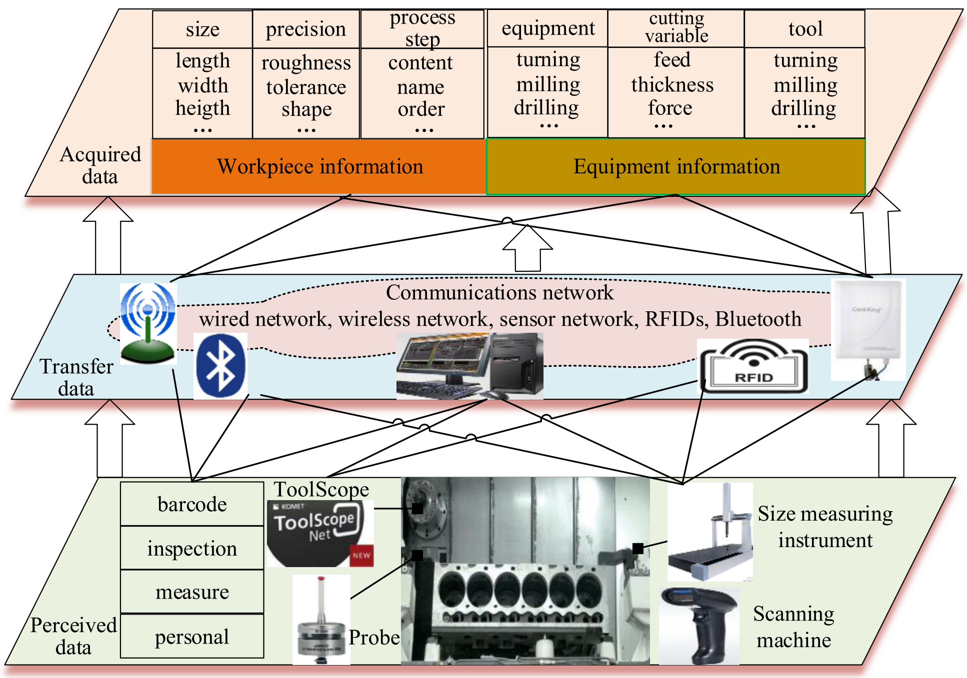

FIGURE 4. **Adaptive sensing framework of multi-agents for machined parts.**

standardization structure of manufacturing data. First, the collected data of the physical machining status are analyzed and classified into two types: static information and dynamic information; second, we study the association and matching mechanism of multi-source heterogeneous data; finally, the object-oriented data organization method of the collected data is created.

These data are composed of static management information and dynamic state information. During machining, a large amount of static attribute information mainly contains the blank, the intermediate model, the finished product, the process equipment, etc. And the real-time collected data which mainly include the machining accuracy, size, equipment and the operating state of other system is called dynamic process data. These data possess complex characteristics such as multi-source heterogeneous, distributed storage, real-time changes, correlations, etc. In order to rapidly map the physical information to virtual model, we have broken through the related technologies such as data normalization technology, heterogeneous data transformation and organization technology, data fusion and decision making technology. These collected data are organized by the multi-level structure tree and they are stored by the XML (eXtensible Markup Language) format, because it stores engineering information following the object-oriented paradigm and allows the modeling of physical and logical plant components as data objects of encapsulating different aspects. An object may contain other sub-objects and may be a part of a larger composition or aggregation. The real-time collected data can drive shop-floor managers to dynamically evaluate the machining activity and then the newly developed machining process planning is fed back to the physical machining shop-floor and guides the production second round.

3) MAPPING MECHANISM BETWEEN PHYSICAL INFORMATION AND VIRTUAL INFORMATION

The digital twin can monitor and control the physical entity. Meanwhile, the physical entity can send data to update its virtual model. In order to exchange the physical data and virtual data, we decide to use the XML format. Because it is a markup language that defines a set of rules for encoding documents in a format that is both human-readable and machine-readable. And it has been introduced and used in a variety of tools and data models.

This section aims to contribute a methodology that allows the construction of physical sensing unit by using the created XML management model for information exchange. The main proposal is to create the model which is used to exchange information with others in the developed system. The method is divided into three part: first, the standard real-time data description format is created; second, taking the perceptual attribute as the research object and the relationship between the perceptual attribute and the perception object is studied; finally, the collected data are managed by object-oriented approach, which is used to update the process model.

B. THE FRAMEWORK OF DT-MPPE METHOD

Based on the mapping mechanism, we propose a framework of DT-MPPE for machined parts and it is shown

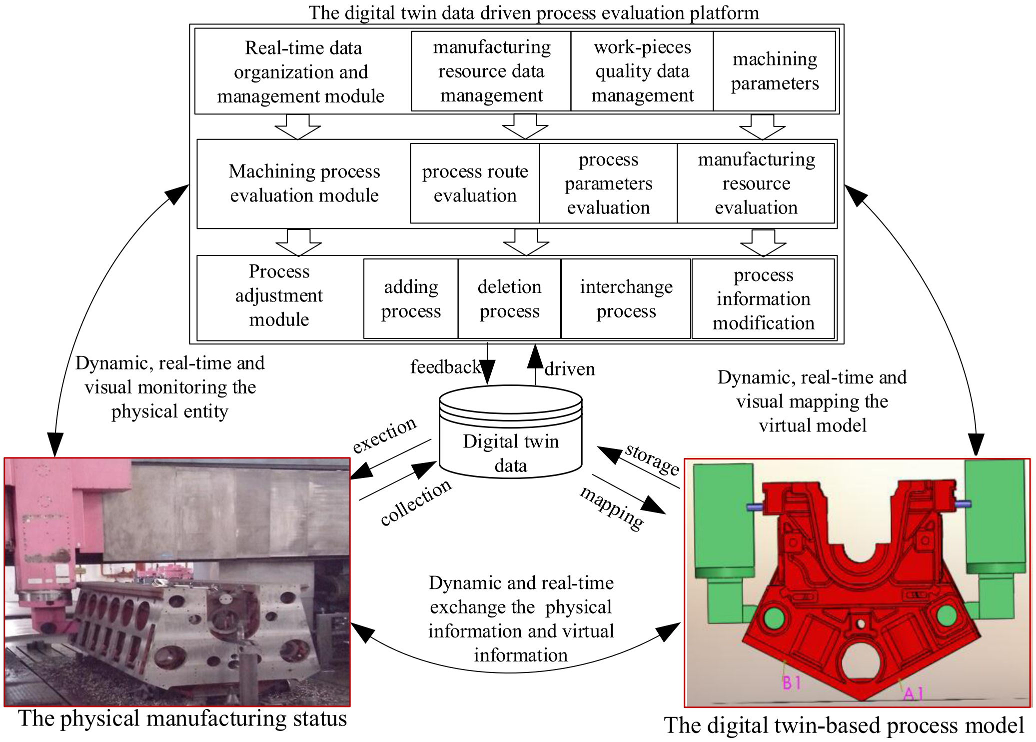

FIGURE 5. Framework of DT-MPPE method.

in FIGURE.5. The framework includes four parts: the physical manufacturing status, digital twin-based process model, the digital twin data and the digital twin data driven by process evaluation platform. The physical manufacturing status is the real-time collection of the process equipment and work-pieces. The digital twin-based process models which can truly express the manufacturing status are created in virtual space. According to the digital twin data, the process planning evaluation platform is developed. On this basis, the developed platform can realize dynamic, real-time evaluate the process route and optimize the process parameters in processing.

According to the constructed digital twin-based process models, the work-pieces status and the manufacturing resources in the physical manufacturing status can be dynamically, realistically and accurately mapped in the virtual space. Therefore, various types of the manufacturing status, such as process equipment allocation, process route, the geometric shape and size of the work-pieces and process parameters in the physical machining can be simulated, evaluated and verified through the digital twin-based process models in the virtual space. This provides an effective tool to choose and conduct an optimal process route and parameters based on digital twin evaluation results.

Digital twin data. Large amounts of real-time data (e.g., machine operation data, sensor data, tool status parameters, and size data) and unstructured multi-sources data (e.g., the attribute of machine and tool, and process step) in processing are abounded. These data have three characters: volume (large amount of data), velocity (high data generation speed) and variety (various types and form of data). The generated digital twin data not only include the physical manufacturing status, but also include the process model in cyber space. The latter contains the model data and operation data, e.g., geometric data, process information, prediction data, evaluation data, optimal result. To fuse these data effectively and accurately, there are some rules needed to be studied: (1) the association rules between the physical models and geometric models. These rules are the basis of the digital twin-based process model which can guarantee the coherence with its physical counterpart; (2) evolution rules of the work-pieces. It accurately reflects all the information of the processing route; (3) the operation rules of the physical model. It ensures accurate execution of the optimized data. These rules ensure the operating mechanism of digital twin-based process model which can match real situations and truly simulate the physical manufacturing status's behavior.

The DT-MPPE platform. It refers to the collection of technologies that supports the functional and target requirements of dynamic evaluation of the machining process. The platform includes monitoring, prediction and optimization of process route and machining parameters. The DT-MPPE platform provides dynamic evaluation of the machining process for the physical machining status. It is composed of the real-time data organization and management module, machining process evaluation module and process adjustment module. The real-time data organization and management module comprises manufacturing resource data management (e.g., machine, tool, fixture, inspection equipment, etc.),

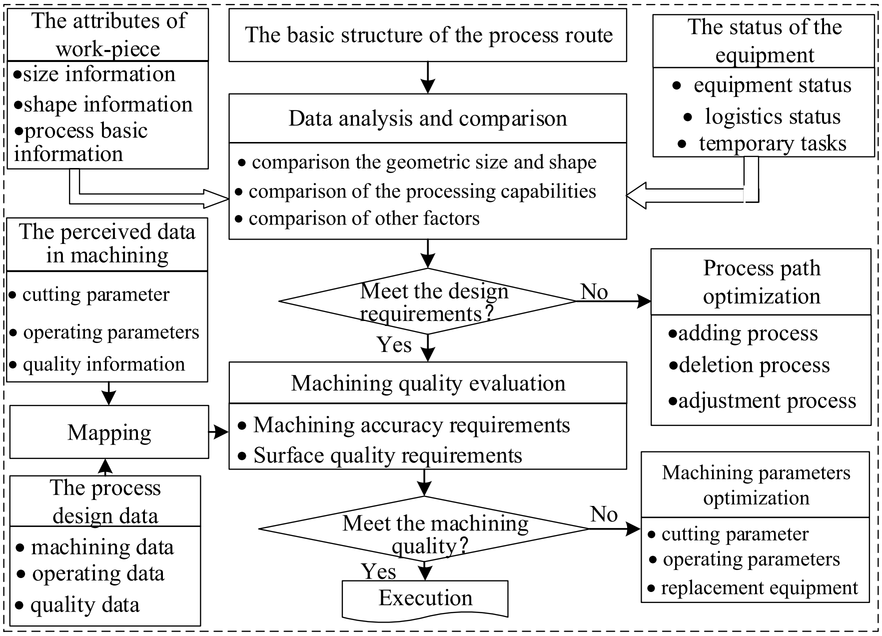

FIGURE 6. **The evaluation method of the machining process planning based on digital twin data.**

work-pieces quality data management (e.g., size, rough, tolerance, shape, etc.), machining parameters (e.g., feed rate, cutting speed, rotating speed), equipment maintenance, etc. The machining process evaluation module incorporates functions of process route evaluation (e.g., process/step contents, method, etc.), process parameters evaluation (e.g., feed rate, cutting speed, etc.), manufacturing resource evaluation (e.g., machine, tool, fixture, inspection equipment, etc.), shop scheduling, etc. The process adjustment module comprises adding process, deletion process, interchange process, process information modification, etc., and this module is a result of the process evaluation. The process data management platform is the premise of processing execution, which provides foresight information for the process evaluation platform. On this basis, the DT-MPPE platform can realize dynamic and real-time management, evaluation and optimization of process route and parameters.

C. DIGITAL TWIN DATA DRIVEN PROCESS EVALUATION METHOD

At present, machining evaluation is mainly applied to the processing quality and manufacturing cost, which include equipment processing capacity, processing stability, green evaluation, work-hour, etc. However, it is rarely involved in the machining process planning stage. It is an urgent demand to realize evaluation and optimization in process design for machining enterprises. In comparison with traditional "static" data analytical tools, the dynamic evaluation has the following characteristics: (1) from single data evaluation to multi-source data evaluation. With the multi-source heterogeneous data, the digital twin-based process model for optimization and decision-making is transformed from only single data (e.g., carbon emission, effectiveness or cost, etc.) to the multi-source data. This provides a comprehensive approach with process optimization and decision-making, especially with multi-step, multi-resource, multi- dimension combination and optimization problem. (2) From passive processing to active evaluation. With the real-time data, it is possible and feasible to evaluate and optimize incoming disturbances (e.g., work-pieces quality problems, equipment failure, temporary machining tasks added, etc.) at the beginning of process execution. The operators can take action proactively to prevent or resolve the possible disturbances in advance. Moreover, expect for the above mentioned, DT-MPPE method not only takes advantage of existing information to establish the digital twin-based process models, but also utilizes virtual simulation technology to explore and predict the unknown world. It provides new concepts and tools for machining process planning innovation too.

Then the DT-MPPE method is proposed based on digital twin data and is shown in FIGURE. 6. The evaluation method is elaborated as follows: (1) according to the real-time data such as the real-time status of manufacturing resources and work-pieces, the machining process route is evaluated by the analysis and comparison method based on the static data; (2) if the current manufacturing status does not meet the process requirements, process order will be optimized. For example adding process, deleting process, etc. If it can be achieved, the machining parameters will be evaluated; (3) according to the dynamic data between the machining parameters and the work-pieces information, the machining parameters are evaluated based on the machining quality analysis method. If the inconsistence is existed, the machining parameters are evaluated, and the problems (such as the spindle vibration, tool wear or by unreasonable factors of plans, etc.) will be found out. With the evaluation results, the process planning system can reconfigure the machining process planning. When the process task is completed, the final produces are yielded, then the operator prepares for the next operation.

V. A CASE STUDY

FIGURE. 7 depicts the implementation process of the DT-MPPE method for the key parts of marine diesel engine. The process contains three main phases: real-time data collection, establishment of digital twin-based process model, machining process planning evaluation and optimization.

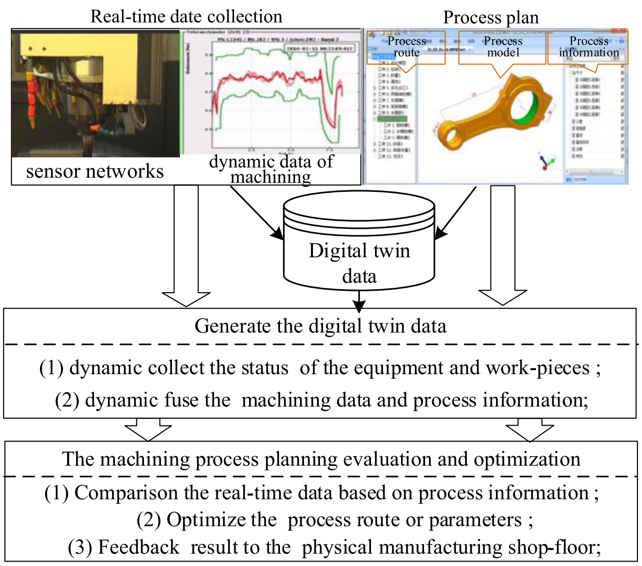

FIGURE 7. The procedure of DT-MPPE method for diesel engine connecting rod.

A. REAL-TIME DATA COLLECTION

According to the requirement of dynamically evaluating machining process for diesel engine connecting rod, sensor network system should be established to realize the real-time data perception and acquisition (as shown in FIGURE.8). It enables to real-time and dynamic monitor and track of manufacturing status. The concrete realization method is divided into four steps: 1) Identify the static information (such as manufacturing resource, the basic information of process model) uniquely by using RFID tags and bar codes, so that the static information can be acquired based on mutual mode. 2) Obtain the dynamic information (such as machine operating parameters, work-pieces geometry size and shape, process execution data) based on the multi-smart sensor (e.g. laser range finder, coordinate measuring instrument, etc.) and monitoring system (e.g. tool scope system, MDC system, etc.). 3) Build data transmission network based on the OPC interface, which guarantees the efficient transmission of the collected data. 4) Object-oriented data organization and management. The related data to manufacturing resources

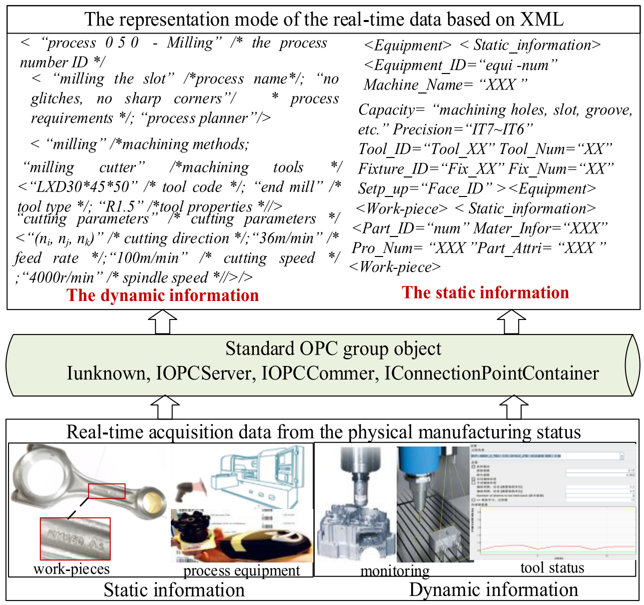

FIGURE 8. The data collection network for diesel engine connecting rod.

status/work-pieces states can be well organized and managed based on the specification format in XML.

B. CREATE THE DIGITAL TWIN-BASED PROCESS MODEL

The digital twin-based process models can truly reflect and mirror the machining status of the machining shop-floor. The machining status can be reflected by the work-pieces status and working progress of manufacturing resources (tool, machine, fixture, measure tool, etc.). The digital twin-based process model contains three functions: 1) the real-time collected data in the machining shop-floor should be associated with digital twin-based process model. In this case, the planners can visually and dynamically track and monitor the machining status of the physical shop-floor; 2) digital twin-based process model can simulate the future's machining operation of the physical machining shop-floor; 3) the evaluation results are generated and fed back to the process reconfigurable module.

C. MACHINING PROCESS PLANNING EVALUATION AND OPTIMIZATION

During manufacturing, physical shop floor transmits the real-time data to virtual shop floor, which updates itself to flow up the physical changes. Meanwhile, the process evaluation platform compares the current production process with the predefined plans in virtual space. If the actual status is not inconsistent with the production plans, the process evaluation platform can provide services to find out the existing problems and judge which part should be adjusted based on the physical disturbance data, simulation conditions data, environment data, etc. FIGURE.9 shows process planning evaluation interfaces for diesel engine connecting rod. The real-time perception data of manufacturing resources are

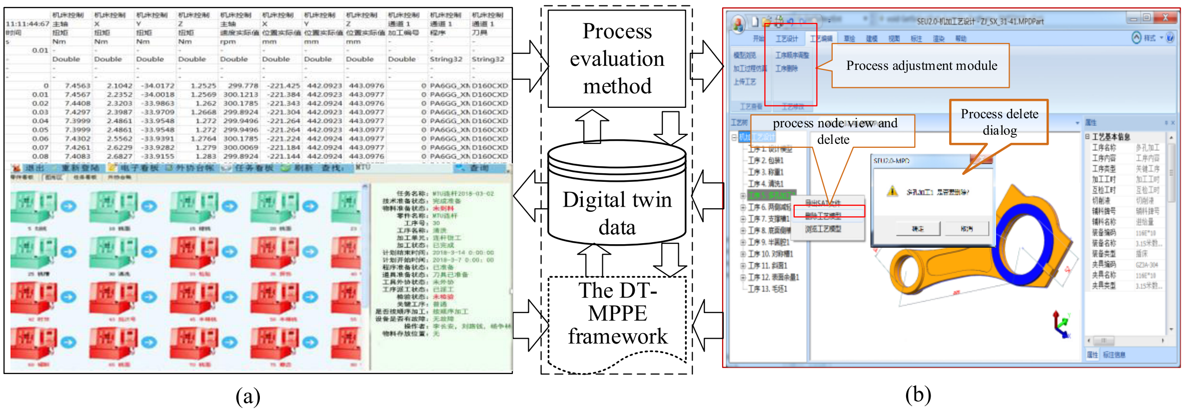

FIGURE 9. Process planning evaluation interfaces for diesel engine connecting rod.

TABLE 1. The comparison results.

Items for comparison	Total number	Process modification quantity	Process modification time (hours)	Deferred waiting time (hours)	Total time(hours)
The traditional method	200	>35	>6	>15	>21
Our proposed method	200	<10	<1	<0.5	<1.5
Reduced repair rate	>12.5%				

collected by RFID and sensors. And manufacturing data collection & status management system, the collecting data interfaces of machine are showed in FIGURE.9 (a). According to the proposed process evaluation method, the machining process can be dynamically adjusted by our developed MPD-Processor [31] and its interface is showed in FIGURE.9 (b).

D. DISCUSSION

In manufacturing workshop, if the machining equipment failed or added the temporary machining tasks, the process planning need to be modified and lots of time will be cost. In order to demonstrate the significant improvement of our method in efficiency, we take the diesel engine connecting rod as the statistical analysis object, the comparison with the traditional process design methods [5], [7], [32] which have not process evaluation are listed in Table 1. While tracking the process execution of 200 connecting rod, about 35 process plans need to be modified or deferred, and it will take at least 20 hours (conclude the process modification time and process delay time) to adjust the process plan. However, with the DT-MPPE method, about 10 process plans need to be modified, and it takes less than 0.5 hours. It can be seen that the process execution rate is increased from 82.5% to 95%. The proposed method can save about 20 hours.

Comparing with the traditional method, there are some advantages in the proposed method. 1) The process execution rate is improved significantly because the deferred waiting time is greatly reduced. 2) The equipment utilization has been greatly improved. The real-time status of the equipment are obtained and they can be arranged in time. 3) The developed system facilitates to transfer and maintenance the manufacturing information.

VI. CONCLUSION AND FUTURE WORK

Machining process planning evaluation has become an increasingly important role in maintaining consistency of processing quality for the machined parts. The product quality can be affected by the unplanned factors in machining. With the unforeseen disturbance events, evaluating the current process planning is the key to improve its enforceability. Digital twin technology has provided a promising opportunity to implement machining process planning evaluation by integrating the cyber and physical space in manufacturing. It has gained wide attention from domestic to international scholars and companies. Thus, it is innovative to apply digital twin technology for the process planning evaluation stage.

The main contributions of this paper are concluded as follows: 1) the paper presents an innovative DT-MPPE method, which can simulate and evaluate the process route and parameters; 2) The proposed DT-MPPE method is promised for the real-time process planning evaluation and optimization. 3) We take the connecting rod of marine diesel engine as the example to illustrate how to evaluate the process planning, and the test results show that this method can effectively improve processing efficiency.

This research attempts to explore and certify the application method of DT-MPPE for machined parts. At present, this study is in its infancy and still requires a lot of work. It still needs much more work to improve and enrich the methods of DT-MPPE modeling and adaptation. Future research on this topic needs to be undertaken as follows: 1) to build a more comprehensive digital twin to evaluate the machining process. The digital twin can continue to accumulate the knowledge in the design and manufacturing, which can be reused and improved continuously. 2) to construct the IoT network in machining shop-floor. The real-time data are the basis for dynamic decision making. 3) to create the efficient mapping mechanism between the physical data and virtual data.

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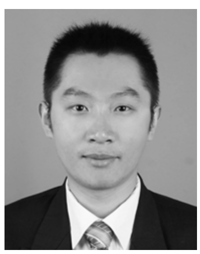

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