The Modeling Method of Digital Twin Models for Machining Parts

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Abstract. This paper introduces digital twin models for machining parts based on key features and gives the modeling method. In this paper we propose three layers structure of the digital twin model, including geometric layer, data layer and document layer, in order to make machining process optimization and quality prediction. The digital twin model realizes the expression of physical parts in digital space and the information correlation with theoretical processing features. Besides, this paper also analyzes the potential application scenarios and development trends of digital twin models of machined parts.

Keywords: Digital twin model; Machining; Key features; Processing quality.

1. Introduction
With the rapid development of communication level and information technology, digital representation of physical entities formed at various stages of industrial product manufacturing has become the trend of intelligent manufacturing [1]. At present, the Model of Definition (MBD) model can reflect the design size and design requirements of the design model according to the digital quantity, and on this basis, add the 3D mark and engineering annotation part. Some scholars solve many problems in the machining process by constructing part models of different machining stages.

Tian et al [2] proposed the concept of the process MBD model and its construction method; the process MBD model is divided into the three-level structure of “physical layer-extension layer-application layer”, and the annotation information and process attributes of the processing features are extracted. Hu [3] proposed the management method and application of the MBD model of the process based on the process steps in the product manufacturing stage. Liu et al [4] proposed a modeling method for 3D process models with process assisted features to improve the efficiency of process planning. The model technology has been widely used in the development of the product "design-manufacture-test", which greatly improved the manufacturing efficiency and quality of the product. The manufacturing based on the theoretical model alone cannot adapt to the changes brought by the process and environmental uncertainty of the complex product manufacturing process. The new generation of aircraft uses a large number of difficult-to-machine materials and integrated structures. The processing technology is complex, the deformation control is difficult, and the processing process is large. The
existence of uncertain factors poses a challenge to the product manufacturing model based on theoretical models.

With the development of sensor technology and various digital devices for different machining processes, processing data and quality inspection data such as the rotational speed, force and wear values of the tool can be obtained in the machining stage of the part. At present, these data have not been fully exploited and utilized, and have not been associated with design models and process models. They cannot effectively support the optimization and continuous improvement of product manufacturing processes, and have not formed a model closed loop of theoretical models and physical manufacturing processes, and processes oriented to manufacturing processes. The iterative optimization model with manufacturing instructions has not been formed, and the model technology needs to be extended to the physical manufacturing process.

Digital Twin refers to the use of digital technology to describe and model a process or method consistent with the physical properties, behavior, and performance of a physical entity, also known as digital twinning technology [5], which was first taught by GRIEVES, a professor at the University of Michigan, USA. Presented in the course of cycle management. In 2015, General Electric Company of the United States built a digital twin model of the engine that can be used to monitor the engine's operating status, check engine performance in real time, and provide maintenance and maintenance recommendations based on its operating status [6]. From the perspective of industrial applications, digital twinning technology has also received a lot of research and breakthroughs. Chen et al [7] proposed the idea of constructing an aircraft digital twin assembly workshop. The workshop can collect various data of the aircraft assembly process in real time, realize the virtual simulation of the aircraft equipment process and control the assembly process of the aircraft according to the collected data. The intelligence of the aircraft assembly process. Yu et al [8] applied the digital twin model to product configuration management, and proposed to use the ontology technology to construct the product digital twin model to express the product configuration information. This scheme can be used to solve the product configuration management problem under the full 3D development model. Production workshop manufacturing IoT [9] and data integration technology are the direction of digital hygiene research. Tao [10] used digital twinning technology to solve the problem of the fusion of massive data in the workshop and the fusion of multi-source heterogeneous data. Huang [11] made a research of the construction of the IoT in discrete workshops. Greycy N. Schroede [12] proposed the use of AutomationML modeling to construct digital twin attributes to realize the integrated CPS (Information Physics System) for future manufacturing systems and product service systems and give industrial application examples. At present, digital hygiene technology is mainly applied to processing equipment, production lines and workshops, and the research on digital twin model for process optimization is in a blank.

This article proposes to construct a digital twin model of machined parts in the physical manufacturing stage to solve the mentioned problems. The product development and quality control model based on the part digital twinning model (Fig.1) has the following characteristics:

1) Modeling and management of various theoretical and measured data of machined parts, fully exploited and utilized to improve design and process quality.

2) The part processing process is closely integrated with the measurement, the manufacturing process is dynamically optimized, and the equipment, tooling, and component deformation are fully measured and controlled.

3) The execution process of the manufacturing instruction based on the model realizes closed-loop control by means of a model, which can be evaluated and predicted.
2. Method for Constructing Digital Twin Model of Parts

The digital twin model of parts provides a way to digitally reflect the state of the physical entities of the part during machining. In fact, each machining process stage of each part corresponds to a physical entity of the product, and corresponds to a digital twin model. Each digital twin model should contain all the information that can express the real physical state of the part.

For the digital twin model of machined parts, it needs to contain process information, machining information, inspection information, shape and material information, etc., and completely record the data and real geometric model of each feature that expresses the part will greatly reduce modeling efficiency, not only that, the huge amount of engineering data is also a very big challenge for computer hardware systems. To this end, this paper proposes a digital twin model based on key features. The key features refer to the typical structures and locations that are difficult to control in the machining of parts or that have a large impact on product quality and performance. These include the design key features (such as designing the separation surface, bearing axial surface, etc.), manufacturing key features (such as machining datums, positioning holes, etc.), testing key features. It is an effective and reasonable modeling method to sort and organize the information that needs to be expressed according to the key features. The construction of digital twinning model based on key features essentially embodies a modeling concept of demand-oriented digital twin model. This method does not pursue the large and complete model, and appropriately abandons some data that does not require special attention during the machining phase. The formation of a scientific, systematic digital twin model structure with key features as a carrier is effective and reasonable for recording the state of real machined parts.

The demand-oriented digital twin model modeling method closely combines the data content and structure of the model with the application requirements. The process digital twin model for process and instruction optimization not only needs processing information including measured key features, but also needs theory. The model implementation is closely related. The digital twin model proposed in this paper contains two parts: the theoretical model and the actual model for the part entity in this state. The theoretical data expressed in the theoretical model part of the digital twin model must be organized according to the established key features. The geometric modeling of the theoretical model can be performed only for key features. A part has only one digital twinning theoretical model under one process stage, but there are a series of digital twin measured models obtained with the batch variation or detection data changes. Such a theoretical model and a measured model together constitute a digital twin model of an actual machined part (Fig.2).
2.1. Three-layer Structure of Digital Twin Model

Digital twin modeling of machined parts can be performed at three levels. The resulting model is a model with a three-layer structure (Fig.3). The first layer is a geometric layer, which is mainly used to create and reconstruct geometric entities of key features, and obtains geometric entities with universal formatting such as valuable part models or triangular patches. Its purpose is to provide the corresponding geometric entities based on the characteristics of the machining simulation and process parameters optimization. The second layer is a data layer, which fills in the processing feature attributes for the detection data and the manufacturing processing data, and forms a digital twin measurement model information representation with the feature as a carrier. Its purpose is to track processing parameters online and to analyze the quality of the processing offline. The third layer is the twin model layer, which realizes the association between the theoretical model and the measured model, and stores the digital twin model in terms of parts, processes, batches, etc. It provides the data source and platform for process personnel to analyze big data based on parts or process flows.

In the digital twin model, the relationship between the model and the theoretical geometric entity needs to be established. The geometric entity in the theoretical model is used as the ‘virtual’ in the digital twin; and the key features of each real product are reconstructed by point cloud fitting or parameterization. The geometric entity is regarded as ‘real’; in the key feature attribute, the value in the theoretical entity is regarded as ‘virtual’; the value obtained by the actual measurement in each real product is regarded as ‘real’. It realized the "virtual and real" mapping of theoretical models and measured models.

2.2. Modeling Process of DTM
The process of selecting a machined product to create a digital twin model is divided into four parts. The first step is to define the key features of the product and define the corresponding attributes and
feature reconstruction methods for each key feature. This step can determine the content of the model geometry layer and data layer. The second step is to introduce the theoretical model and calibrate the theoretical values of the attributes of the key features. The third step is to calculate and determine the measured values of the attribute values of the key features when the part entity detection data and the online collection data arrive, and reconstruct the geometric parts for the key features that need to be reconstructed, and the obtained model organization Released as a whole to form a digital twin model. The fourth step is to organize and manage multiple digital twin models according to the standards of parts and processes, and provide data foundation for subsequent model calls. The modeling process is shown in Fig.4.

Fig. 4 Modeling data stream of DTM

From a usage perspective, the digital twin modeling tool opens two interfaces to provide two-part staffing. For designers, inspectors and process personnel, provide the ability to modify key feature (attribute) libraries, define key features under part or component CAD models, publish theoretical model files, import measured model files, and task-oriented output. Designers and technicians can perform optimization analysis on geometric or attribute metrics based on theoretical and measured models. For the machining technician, a data entry operation interface is provided, and an import interface is prepared for the automatically picked up data, and the non-structural data is manually entered.

3. Key Technologies for DTM  
The key features in the digital twin model serve as the carrier of the part entity data, and the types need to be rigorously screened and determined. The data items contained in various key features, also called the attributes of key features, also require strict paradigms and definitions. The screening and definition must be adapted to the current state of the process and the application of the digital twin model. In addition, there are many methods for the construction of feature geometry entities in digital twin models. This chapter discusses the key feature libraries and geometric layer modeling methods of data layer features and feature attributes. Finally, the construction method of digital twin database is expounded.
3.1. Key Feature Library

Through the investigation of complex part processing technology and inspection process, the key features of manufacturing are defined on the basis of geometric features, such as the plane of component fitting, the axis and hole of assembly, and easy-scratched surfaces, etc., are constructed as key features in the digital twin model. Before establishing a digital twin model for each real part, you need to define a key feature library, that is, the type of key features and the attribute information contained under the features. For different machining processes, in-depth research on process methods, process inspection standards and process knowledge maps are carried out in advance, and then the types and information of key features are fully defined.

Among the attributes included in the key features, one is the geometric information of the features, such as the hole diameter, the surface normal, the height of the boss, etc.; the accuracy information such as flatness, roughness, verticality, plane gap; and the parameters that are customized according to process requirements are referred to herein as alternate feature parameters such as hole center point, axis minimum diameter, predefined assembly point position, and feature scan point cloud. According to the knowledge map of a certain combat wing box processing process, this paper abstracts five key features and defines related attributes as shown in Table 1. The other type is non-geometric information about features, including processing conditions, process documentation, and large amounts of data generated by machine tool processing. The author abstracts the processing information into the attributes quantified in Fig. 5 for modeling and storage.

| Feature | Hole Type | Plane Flatness | Surface Cylindricity | Pad Height | Slot Width |
|---------|-----------|----------------|----------------------|-----------|-----------|
| Attr. 1 | Type      | Type           | Type                 | Height    | Width     |
| Attr. 2 | Center point | Flatness       | Cylindricity         | Length    | Depth     |
| Attr. 3 | Diameter  | Parallelism    | Roughness            | Diameter  | Position  |
| Attr. 4 | Depth     | Roughness      | Concentricity        | Symmetry  | Symmetry  |

| … | … | … | … | … | … |

**Table 1. Key feature attributes**

**Fig. 5** Processing information of DTM

3.2. The Geometry Entity Construction of Key Features

The attributes of key features cannot truly represent the shape and exact location of key features. Many simulation optimization tasks must be performed based on the model geometry entities. Therefore, while
defining key features in the theoretical model, the extraction and association of feature geometric elements should be performed simultaneously. For example, the hole feature, while defining its precision parameter, geometric parameter, machining parameter and spare feature parameter, needs to extract the geometric elements such as the upper and lower surface of the hole, the inner wall cylindrical surface and the rounded corner on the theoretical three-dimensional geometric entity. In the measured model, the feature needs to be reconstructed according to the mode selected by the user, and then the reconstructed entity is associated with various parameters of the key feature. There are two main ways of feature reconstruction. One is to reconstruct the triangular patches, and the other is to reconstruct the feature entities. The flow of the two reconstruction methods is given in Fig. 6.

The method of reverse engineering modeling can preserve the true state of the measured features more accurately. The feature reconstruction method in Fig. 6 transforms the feature reconstruction method into the stitching and cropping after the surface reconstruction. In order to simplify the reconstruction steps of various types of surfaces (including plane, cylindrical, conical and NURBS surfaces, etc.), all the surfaces are transformed into the more common Non-Uniform Rational B-Splines (NURBS) surfaces in 3D computer-aided design modeling software for reconstruction. Use the NURBS surface representation [13] to fit the actual machined surface. The representation of the NURBS surface is:

\[ p(u, v) = \sum_{i=0}^{m} \sum_{j=0}^{n} d_{ij} \frac{\omega_{ij}N_{ik}(u)N_{jl}(v)}{\sum_{r=0}^{m} \sum_{s=0}^{n} N_{rk}(u)N_{sl}(v)} \]

Where \( d_{ij} \) is the control vertex; \( \omega_{ij} \) is the weight factor; \( N_{ik}, N_{jl} \) are the B-spline basis functions along \( u \) and \( k \) times, respectively.

To realize the reconstruction of NURBS surface, the values of control vertices, weight factors and node vectors must be adjusted according to the actual measurement points on the basis of the theoretical model to achieve the purpose of surface reconstruction. In this paper, the control point adjustment

![Diagram showing the process of feature reconstruction](image)
method based on constraint optimization is used to complete the surface reconstruction [14]. The specific steps are shown in Fig. 7.

![Diagram](image)

**Fig. 7** Reconstructing surface method according to measurement points

According to the needs of the craftsman to simulate and calculate the machining process of the model, the method of feature reconstruction is selected, and the obtained real geometric model is the geometric layer of the digital twin model. The geometry contained in the geometry model thus obtained is only a key feature inside the part. This layer of work can be done with tools such as Geomagic, Polyworks, and Catia.

### 3.3. Data Management of Digital Twin Model

Data management for digital twin models is divided into three main categories. The first category is the key feature library, which contains the attribute fields and types corresponding to several key features. The second class stores information (part-feature-attribute) according to the tree structure, so that the part number and batch number can be used. The feature number, the attribute number finds the corresponding value; the third type is the model file information, which contains the time information of the file, the file type, and the like. The first type of information stores the established key feature attribute table, and the reserved field is used by the subsequent model to customize the feature attribute. The second type of tree structure can be designed as a theoretical feature table and an actual feature table. These table contents are defined by the key feature definition personnel through the interactive interface and stored in the database, representing the attributes of each defined feature. Shown. The third type of file information to be stored includes a theoretical model, a measured model, and a measured data file package, wherein the data file is hung in the form of a path under the feature attribute field, and a data table is created for the theoretical model and the measured model.
4. Digital Twin Modeling Tool Based on Catia CAA

The Product Digital twin modeling tool provides users with two functions in a CATIA environment, based on key features. The first function is to create key features and select the concerned attributes and the way of model reconstruction according to the key feature library. At the same time of creation, through the information reading of the theoretical model, key feature sets are generated on the CATIA feature structure tree. The theoretical value of the attributes, the way of reconstruction, and the time of feature creation are attached to each feature geometry set. After all the features have been created, you can click the release command to publish the key feature data structure and CATPart file to the database to maintain the data persistence; this process obtains the theoretical model in the digital twin model. The second function is to import the measured data of the part according to the part number, batch number and time number, and reflect the real feature attribute under the feature geometry set, and use the feature point cloud file according to the previously set reconstruction mode. Structural features. A part of the machine plus feature attributes need to be combined with the geometric model for calculation, and then hung under the CATIA tree geometry set; after the creation, the newly generated CATPart file is imported into the database; this process obtains the measured model in the digital twin model.

4.1. CATIA CAA

In order to correlate, extract and manipulate information in key features, CATIA software can be used for display, reconstruction and analysis. CATIA has opened a component interface CAA for secondary development programming, which can be programmed with features such as features, inputs, outputs, interactions, and structures in the component to implement digital twin modeling tools.

![Fig. 8 CATIA CAA developed tool](image)

The interactive interface operation is designed with the CATDialog module, and an interface for modifying the key feature database, creating features, publishing the theoretical model, and importing the measured model data is designed. Use the CATMechanicalRootFactory module to create and edit geometry sets for key features and their properties; use the CAPIPARAmeterEditor module to create and edit property parameters. The CATICGMFactory module is used to extract and construct the topology based on the theoretical model, and the feature point cloud is reconstructed using the CATIGSMFactory module. File input and output are programmed using the CATDocument module and the standard template class std. Use the MYSQL module to read and write to the database. Features are labeled using the CATIPSDDocument module.
The theoretical and measured feature data are associated with the feature identification number and are linked under the same Catia structure tree.

4.2. Database System of Digital Twin Model

The digital twin model database is built based on MySQL, which provides the technician with an interface for detecting measurement data and stores all the information of the digital twin model.
5. Summary
This paper introduces a digital twin model of machining parts, which can effectively apply the digital virtual model to each process by modeling the state of real products in the machining process. In order to streamline manufacturing data, standardize model paradigm and improve modeling efficiency. This paper puts forward the concept of key features and analyses the attributes of key features. It uses key features as the carrier of manufacturing information, and expounds the storage methods of key feature information and its geometric reconstruction methods. This paper elaborates on the three-level structure of the digital twin model and briefly analyses the application method. The digital twin model integrates and integrates the information in the process. It is oriented to the process flow of the part machining, and the theoretical model and the measured model can be used to analyse and optimize the process parameters.

At the end of the article, an example of a digital twin modeling tool using CATIA CAA is introduced, which basically achieves the intended purpose. Its engineering application value remains to be developed. Faced with the environment of intelligent manufacturing, the author still needs to continue to explore the relationship between data and technology in the manufacturing process, enrich the digital twin model, and apply the model to continuous improvement and innovation in production.

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