Digital Twin Construction and Application in Blade Measurement Process

Pu Yu, Xiaomei He*, Yizhang Wang
Changcheng Institute of Metrology and Measurement, Beijing, China
**Corresponding Author.*

Abstract: In order to solve the problems of visualization and condition monitoring of the blade measurement process, a digital twin construction method of the blade measurement process was proposed. By studying the digital twin construction method based on multi-dimensional data, a digital twin system of blade measuring equipment was established. Through the study of complex system condition monitoring technology, the connection between physical system and virtual system is realized. This method can achieve digital twin matching and synchronous calibration in the coordinate measurement process, solve the problem of difficult integration between information space and physical space, achieve digitalization of the measurement process and state monitoring, and provide a research foundation for subsequent data analysis.

Keywords: Blade; Measurement Process; Digital Twin; DMU Motion Simulation; Status Monitoring

1. Introduction

Against the backdrop of the proposal of " Intelligent Manufacturing" and the digital transformation of state-owned enterprises, the development of domestically produced new aviation engines and gas turbines is constantly advancing. In aviation engines, the precise measurement of the geometric dimensions of blade shapes affects the performance of the engine. Engine blades are components with thin blade profiles, complex surface distortions, and harsh working environments. It is crucial to solve the problem of visualizing the blade measurement process and achieve data monitoring throughout the entire life cycle of production, manufacturing, and maintenance.

This problem has been solved by the flourishing development of digital twin technology. Digital twin is a technology that integrates multiple physical fields, scales, and disciplines, with real-time synchronization, faithful mapping, and high fidelity characteristics. It can achieve interaction and integration between the physical world and the information world [1]. The concept of digital twins was first introduced in the product lifecycle management course taught by Professor Grieves at the University of Michigan in the United States [2], and was initially applied in the aerospace field. In recent years, research on digital twins has also developed. Proposed by the Beihang Tao Fei team. Li Hongkun et al. [3] proposed a virtual perception technology architecture for the global vibration state of rotating bladed discs based on the concept of digital twins, addressing the limitation of online vibration monitoring methods that can only obtain limited measurement point information; Zhou et al.[4] and Zhang et al.[5] respectively proposed application frameworks for manufacturing centrifugal impellers and aircraft engine blades driven by digital twins; Liu Xinda et al.[6] proposed a digital twin modeling method for robot assembly units based on data fusion and knowledge reasoning, and studied the high fidelity mapping of robot assembly units from physical space to virtual space; On the basis of studying the real-time embedded development of PowerPC processors, the design concept of digital twin technology has been adopted by Bloomberg et al.[7] and they completed a super real-time virtual simulation system with functions such as fault simulation and injection, collaborative simulation and modular programming; Ma Chuangye et al.[8] designed a digital twin drive model construction method for industrial robot intelligent milling equipment to address the limited perception and detection methods for service status and intelligent control capabilities of industrial robot intelligent equipment.

The digital twin virtual construction and calibration technology for blade measurement in China is in a blank state. This technology can achieve state monitoring of the blade measurement process and provide effective data support for the full life cycle state monitoring of the blade. Realize unmanned operation in the inspection workshop, liberate personnel and labor, and facilitate remote control of coordinate measuring machines for unmanned operation, achieving integrated clamping and measurement. Facilitate the accumulation, analysis, and early prediction of blade process quality for subsequent measurement data, and facilitate the development of remote coordinate measuring machine calibration technology.

2. Construction of Digital Twin Virtual Model based on Multidimensional Data

2.1 Geometric Construction of Digital Twin Virtual Models

The engine of digital twins is a multidimensional twin model [9], and the twin models in virtual measurement platforms are mainly divided into parts to be measured, measuring instruments, auxiliary measuring equipment, etc.

CMM and compressor blades are focused by the digital twin construction of blade measurement process. Based on the analysis of the type architecture of coordinate measuring machines and the construction of physical spatial coordinate measurement systems, the digital twin virtual model of coordinate measuring machines is completed. The blade measuring equipment in physical space is a three-axis+two axis blade measuring machine: Scanning probe, Blade customization fixture, Blade and Information collection system for monitoring and measuring the process. In this measurement system, multi-source heterogeneous measurement data generated in physical space is effectively processed and transmitted to virtual space through a user interface. Meanwhile, the measurement machine information can be retransmitted from virtual space to physical space. For example, using blade synchronization simulation and analysis technology to track and locate blades with quality problems, analyze the causes of quality problems, generate feasible solutions, and feedback the final results to the blade measurement system. In physical space, the three-dimensional solid model of engine blades is defined according to the aviation industry modeling standards, and the information of the blade measurement system, including geometric dimensions, tolerances, and technical requirements, is explained using model definition technology as the basis for subsequent blade measurements. Using three-dimensional lightweight modeling technology, establish a corresponding measuring machine model, construct a complete machine model, and form a virtual measurement system for the measuring machine body, measuring seat, measuring head, fixture, and the blade to be tested.

The basic principle of a coordinate measuring machine is to place the measured object in the measurement space of the machine, and obtain the geometric coordinates and dimensions of each measurement point on the measured geometric surface. Based on the spatial coordinate values of these points, mathematical methods are used to calculate the geometric dimensions, shape, and position errors to be measured. The structure of CMM is usually shown in Figure 1, where 0 is a marble base that is fixed in place; 1 is the workpiece to be tested; 2 is the gantry, moving along the Y-axis; 3 is the slider, moving along the X-axis; 4 is a column, moving along the Z-axis; 5 is the measuring head.

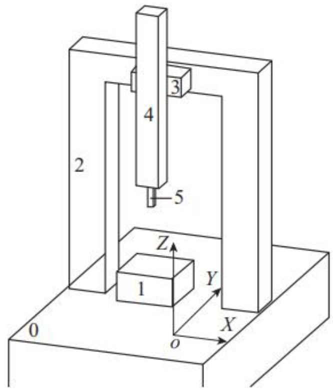


Figure 1. Structure of Three Coordinate Measuring Machine

The geometric model of an object can generally represent the composition layer structure, allowing us to decompose a geometric object using a top-down approach, or reconstruct a geometric object using a bottom-up approach [10]. According to the characteristics of the mechanical structure of a coordinate measuring machine, it can be decomposed into several components (sub objects). In a virtual reality environment, the geometric model decomposition hierarchy of a coordinate measuring machine can be represented in Figure 2.

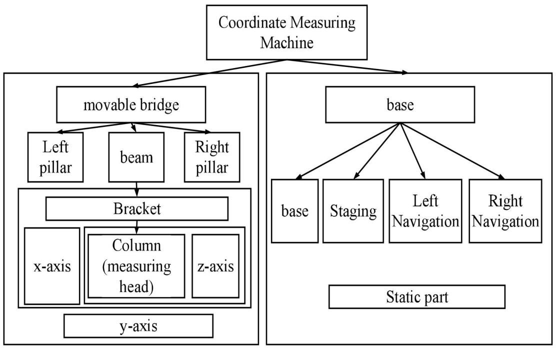


Figure 2. Layered Structure Diagram of Geometric Model of Coordinate Measuring Machine

The construction of a digital twin virtual model for blade measurement using CATIA software requires the use of CATIA's sketch module and assembly module. According to the factory dimensions and actual parameters of the coordinate measuring machine, use sketch drawing, length angle position and other planar geometric constraints, project 3D lines, protrusions, box opening, chamfering, rotating body and other commands in sequence. Based on the hierarchical structure diagram of the geometric model shown in Figure 2, complete the construction of geometric virtual models for parts such as the measuring head, column, support plate, crossbeam, left column, and right column. According to the constraint relationship of the hierarchical structure diagram, use commands such as contact constraints, shaft sleeve constraints, and contact offset to assemble the virtual part geometry in a bottom-up order of structure and function, and complete the geometric model construction of the coordinate measuring machine. Finally, conduct visual modeling to define the colors, lighting, materials, textures, etc. of each component, making the constructed coordinate measuring machine natural and realistic.

Using CATIA for digital twin CAD modeling, importing the standard model of compressor blades, and constructing the completed digital twin virtual model of blade measurement process is shown in Figure 3.

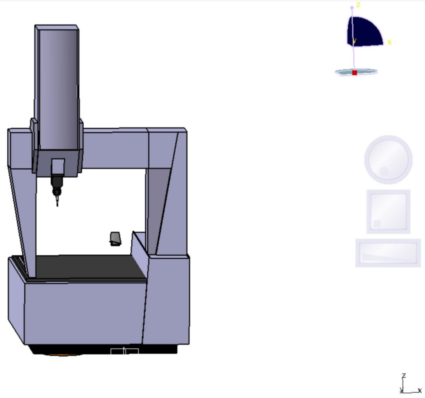


Figure 3. Digital Twin Virtual Model Diagram of Blade Measurement Process

2.2 Digital Twin Virtual Model Motion Simulation

The coordinate measuring machine model in the digital twin of blade measurement is an assembly, and the motion model is built on the basis of the assembly model. The hierarchical relationship between components expressed using a hierarchical tree is shown in Figure 4.

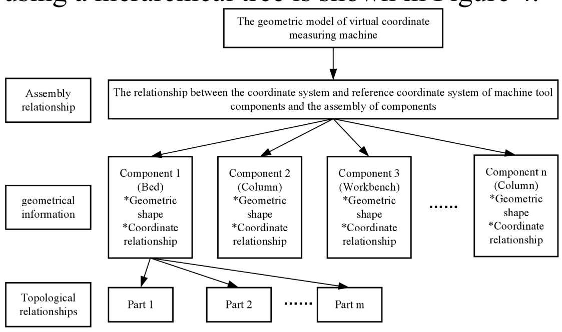


Figure 4. The Hierarchical Structure Diagram of the Geometric Model of a Coordinate Measuring Machine

Due to the fact that the coordinate measuring machine is composed of three mutually perpendicular movable X, Y, and Z coordinate axes, based on the hierarchical structure of the geometric model of the coordinate measuring machine shown in Figure 4, the motion model of the active bridge coordinate measuring machine can be determined, and the motion relationship of the coordinate measuring machine can be described. When the Y-axis moves, the left column, crossbeam, right column, support plate, column, and measuring head all need to be translated accordingly; When the X-axis moves, only the support plate, column, and measuring head need to be translated accordingly; When the Z-axis moves, only the probe needs to be translated accordingly.

Simulate motion analysis of digital twin virtual models using CATIA's DMU motion mechanism. Firstly, perform the conversion of assembly constraints, dividing the assembly constraints constructed in 2.1 into fixed components and moving components. Convert assembly constraint commands in fixed components to rigid body constraints, and add motion pairs to assembly constraints in active components. Add a moving pair to the translation motion of the XYZ axis, and the measuring range of this coordinate measuring machine is 500mm × 700mm × 500mm, the coordinate system direction is the standard coordinate system. Determine the axial motion of the virtual model based on the range, and determine the direction of motion based on the coordinate system direction. Adjust the initial position of the digital twin virtual model to the machine zero position, which is the coordinate origin position. The measuring head system used in this coordinate measurement system is the Renishaw PH10 two-dimensional measuring base and SP25 scanning measuring head, with an A angle range (0,105°) and a B angle range (-180° , 180°). Rotating pairs are added to the two rotation angles, and a positive rotation direction is added according to the physical system direction of the coordinate measurement machine.

After the rigid body constraints and motion pairs are added, the above-mentioned motion mechanism is treated as a motion whole, and a mechanical mechanism is added. Drive commands are added to the translation and rotation motion parts, and the base is set as a fixed part. At this point, the degree of freedom of the digital twin virtual model is 0, and mechanical simulation motion can begin. The set position coordinates and probe angles are shown in Table 1, and the virtual motion model of the coordinate measuring machine is shown in Figure 5. In the figure, the probe moves from the zero position of the coordinate measuring machine to the starting point of the blade leading edge arc measurement.

Table 1. Set Position Coordinates and Probe Angle

	Axis X /mm	Axis Y /mm	Axis Z /mm	Angle A/°	Angle B/°
Zero Position	0	0	0	0	0
Final Position	442	420	-494	-120	84

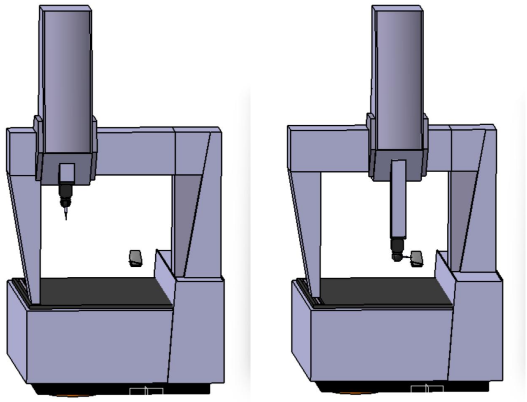


Figure 5. Schematic Diagram of Coordinate Measuring Machine Motion Model

3. Implementation of Data Synchronization Collection and Status Monitoring

Data is the core driver of digital twin systems.[11] During the blade measurement process, due to the different communication protocols and specifications of equipment, instruments, and other hardware, the underlying data on site exhibits multi-source heterogeneity. For the digital twin measurement process monitoring system, multi-source heterogeneous data collection includes static and dynamic data such as equipment operation status, parameter data, measurement physical environment data, process quality data, on-site working condition data, etc. Real time data collection and transmission are achieved for the entire life cycle process of blades, providing core drivers for building a digital twin system.

To achieve consistency and synchronization between the measurement process of the digital twin and the coordinate measuring machine, it is necessary to collect the status of the coordinate measuring machine in real time and input it into the digital twin for synchronous driving operation. For this digital twin system, the data source exists in multiple workstations based on the general TCP/IP communication protocol, and the Ethernet network connecting the equipment and server is achieved through industrial switches. Through secondary development of the software development package, the various parameter values of the equipment in the open address and the internal stored data are obtained, and the industrial Ethernet collection gateway and data summary are achieved.

Based on real-time data-driven device

geometric behavior mapping method, in order to achieve real-time synchronous motion between virtual production lines and physical systems, it is first necessary to collect data from each device on the production line using industrial Ethernet to provide data support for the movement of devices in virtual scenes; Then store and analyze the collected device data, and establish a data transmission channel for the virtual monitoring system; Finally, based on the secondary development of CATIA CAA, real-time data is used to control the movement of the 3D model of the equipment in the virtual scene of the production line, achieving the goal of real-time mapping of the geometric behavior of physical entity equipment.

The system database MySQL is used to store various measurement data, status data, and assembly quality data collected from industrial sites, providing a data foundation for future historical data queries and fault quality prediction.

4. Application Verification

Based on the research content of this article and the analysis of system functional requirements, a digital twin system for blade measurement process is constructed. The blade measurement process coordinate measuring machine and the digital twin virtual model can achieve synchronous operation. The system's functions mainly include the following three parts.

4.1 Digital Twin Basic Unit Module

The basic unit module of digital twin provides model and data support for the implementation of the entire digital twin system application. As shown in Figure 6, the basic unit module manages modules such as models, data, multi task scheduling, and measurement processes.

Figure 6. Basic Measurement Part of Digital Twins

4.2 Digital Twin Simulation Control Unit Module

The digital twin simulation control unit module is mainly divided into support module and simulation control module. As shown in Figure 7, the support module is responsible for coordinating control and task scheduling in the virtual system, enabling various parts to cooperate with each other to complete tasks such as loading and unloading, testing, analysis and evaluation of parts. It also reasonably allocates and arranges the current tasks executed by each device according to task requirements, process procedures, equipment capabilities, etc. At the same time, it can also achieve a simulation and debugging function of the virtual device. The simulation control module receives and analyzes the original program code of the measuring machine, decodes the control instructions, converts them into the positions of each axis of the measuring machine at each time node, and transmits the axis positions to the information space for script driving, realizing corresponding simulation actions and maintaining real-time linkage with physical entities in the physical space.

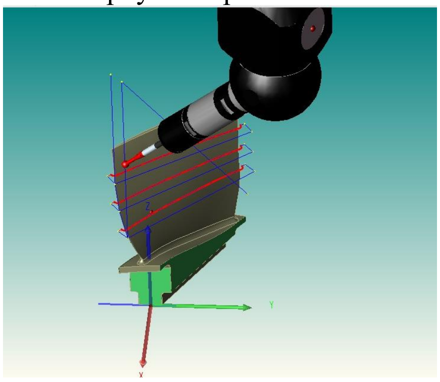
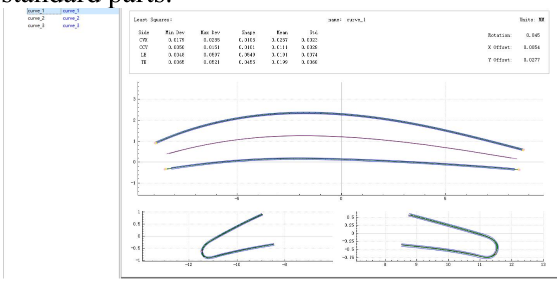


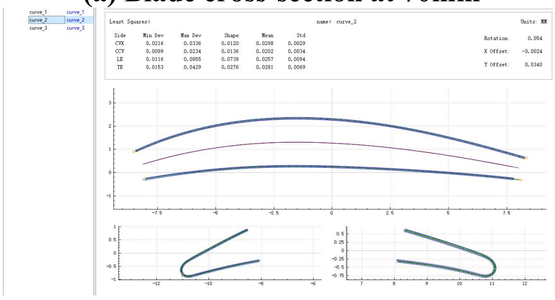
Figure 7. Digital Twin Simulation Operation Section

4.3 Digital Twin Real-Time Monitoring Unit Module

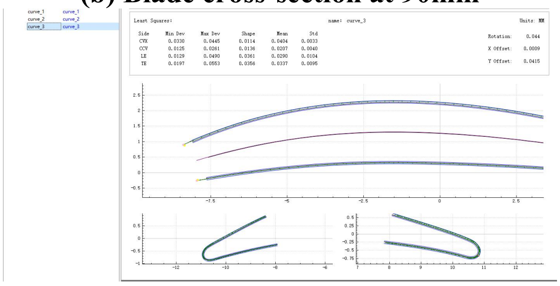
The digital twin real-time monitoring unit module is mainly divided into equipment status monitoring, 3D virtual scene twinning, measurement monitoring, data model comparison, and fault diagnosis module. As shown in Figure 8, integrate each submodule into the same interface for display. The module should support real-time status monitoring and display of each device, including basic information, operating mode, operating history data, alarm information, etc; At the same time, it provides a full scene 3D virtual model display for the measurement process, which can obtain real-time position and status information of CMM, and update it in real-time in the information space; It should also support visual display of measurement data, display measurement results, and be able to compare quality data with the measured gold standard parts.



(a) Blade cross-section at 70mm



(b) Blade cross-section at 90mm



(c) Blade cross-section at 110mm

Figure 8. Digital Twin Data Analysis Section

On the basis of completing the functional verification of the above three modules, carry out the application verification of the entire digital twin system. The verification content includes: the degree of realism of the simulation action sequence, the synchronization performance of the digital twin system, and the functional completeness of the digital twin performance.

5. Conclusions

The important process of constructing digital twins in blade measurement is to import the constructed coordinate measuring machine model and standard blade model into the measurement simulation software of the physical system, and obtain the control signals and data generated by the lower computer through the control software. When the lower computer receives the measurement control signal generated by the measurement software, the virtual coordinate measuring machine model takes action and performs virtual measurement in the virtual environment, which can verify the correctness of the measurement instructions and the feasibility of the measurement process.

After verification, the digital twin system can fully simulate the multi axis motion of the measuring machine and the scanning measurement action of the measuring needle in the simulation environment; Fully simulate the position trajectory characteristics during the measurement of action sequences, as well as the collision and contact characteristics with the scene and parts; The interaction process between the fully simulated probe and the virtual part scanning measurement generates measurement data for analysis and evaluation.

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