Engine Modeling and Assembly Technology Based on Digital Twin

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Abstract

Digital twin communion achieve interaction with the physical state of the virtual model, modeling studies engine assembly techniques, discussed configured, functions, processes, analyzes the key technologies and assembly process example based authentication. The researched technology not only helps to improve the intelligence, proactiveness, and predictability of engine modeling and assembly process and technical status control, but also promotes decision-making and optimization based on physical status, improves assembly efficiency and standardization, and improves once The consistency of assembly success rate and quality performance provides theoretical basis and technical reference for the research and system development of engine modeling and assembly technology based on digital twins.

Keywords: *Digital twin, engine system, virtual assembly, intelligent control, virtual and real interaction, example verification*

I. Introduction

The digital twin (DT) digitally creates virtual models of physical entities [1], with real-time synchronization, faithful mapping, and high-fidelity characteristics, promoting the interaction and integration of the physical world and the information world, and adding or expanding new models for physical entities the ability [2-4]. Based on the digital twin of engine parts, this paper improves the intelligence, initiative and predictability of the engine assembly process through the interaction and integration of the physical process of engine assembly and the digital model, and promotes the further improvement of assembly quality and level.

The design and manufacture of engines reflects a country's industrial foundation, comprehensive national strength and technological development level [5]. Modeling assembly is one of the most important links in the engine manufacturing process, and its technical level significantly affects the performance, reliability and life of the engine. The new generation of engines has the characteristics of complex structure, high efficiency, long life, high reliability, low fuel consumption, low noise, etc. Under working conditions, the thrust (power) is high, the air pressure ratio is high, the gas temperature is high, and the mechanical speed is high [6]. The key indicators such as the fit state, assembly accuracy, connection reliability, coaxiality, and stator gap put forward higher requirements. Independent research on assembly technology and process methods, development of assembly core equipment, and construction of advanced assembly production lines are of important strategic significance for enhancing my country’s independent engine research and development capabilities and enhancing the international competitiveness of my country’s industries.

Due to the lack of sufficient research foundation and technical accumulation, the technical level of engine assembly in my country is low, the assembly process, tooling, and tools are backward, the production organization mode is far behind foreign advanced enterprises, and the efficiency is low, the quality level is poor, and the cost is high. It is difficult to meet new requirements. The needs of the development of a generation of engines. At present, engine digital modeling basically only considers the surface geometric errors generated during the part manufacturing process, and does not include information such as feature registration constraints and physical properties [7-9]. The virtual assembly simulation results based on this digital model will be quite different from the actual assembly.

II. Engine Assembly Technology Driven by Digital Twin

As shown in Figure 1, the engine assembly technology driven by digital twins consists of a physical assembly process, a virtual assembly process and twin data. The virtual assembly process is the real mapping of the physical process, and monitors, predicts, and controls the actual assembly process. The twin data includes data sets related to the physical assembly process and virtual assembly process, and supports the deep integration and interaction of virtual and real data [10]. Through the two-way mapping and interaction between the physical assembly process and the virtual assembly process, the engine assembly process driven by the digital twin can realize the integration and fusion of the two, realize the iterative operation of the engine execution state and the technical state between the physical reality and the virtual model, and support Intelligent optimization and decision-making of the assembly process, process parameters and installation status to achieve precise execution and optimal control of engine assembly.

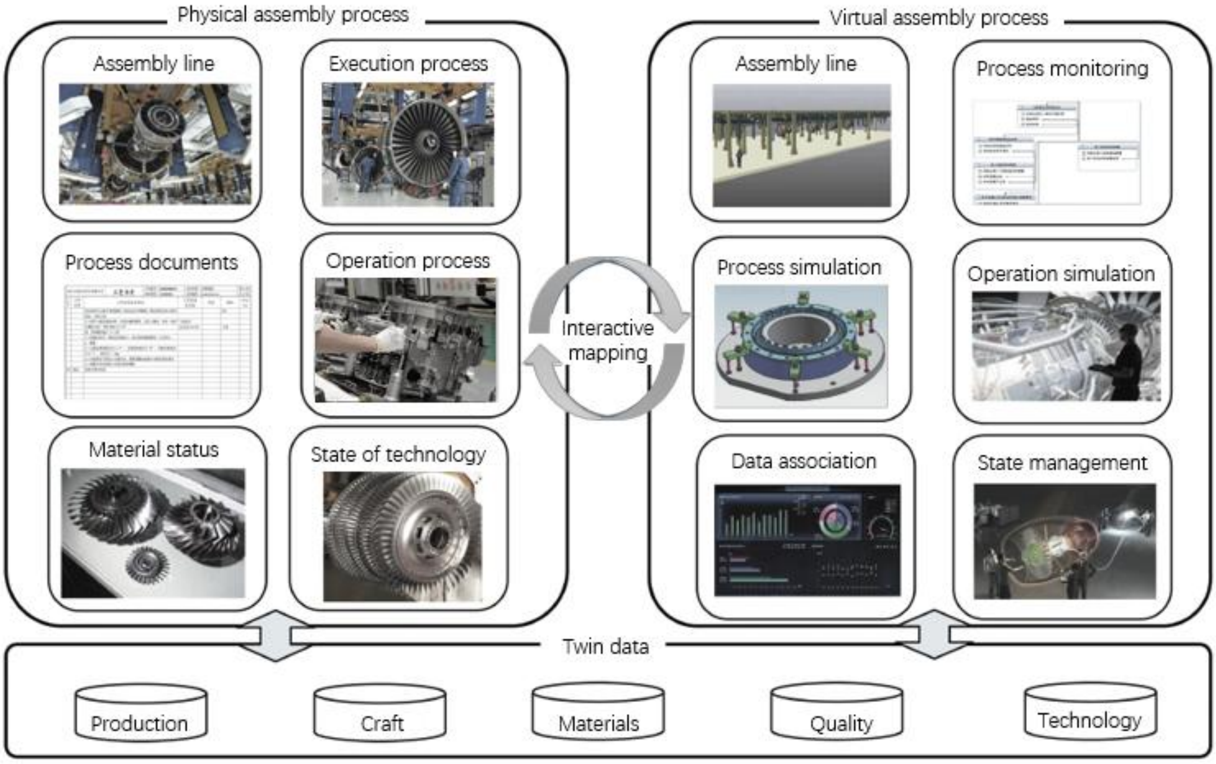

Figure 1. Engine assembly technology based on digital twin

Digital twin engine assembly technology encompasses multiple types, multiple time scales, and multiple granular elements, behaviors and rules related to the assembly process, involving different time dimensions before, during, and after assembly execution, including process models, data models, and calculation programs , Optimization algorithms and other different types, covering the assembly process, assembly tasks, assembly process, assembly history, etc., as well as details such as out of tolerance and zeroing [11]. The above content is very complicated and difficult to achieve through a single model. Sub-models must be established for different levels and application fields. The sub-models of the digital twin for engine assembly include: assembly process model, process technology model, installed material model, technology status model, correlation analysis model, etc.

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From the beginning of assembly, an engine has a corresponding digital twin model, which is accompanied by every assembly, disassembly and reassembly. The digital twin model for engine assembly truly depicts the assembly process of each engine, truly reflects the formation and evolution of the technical status of each engine during the assembly process, proposes reliable parts selection and process parameter optimization schemes, and accurately evaluates engine assembly Quality provides a basis for assembly decision-making and optimization.

Driven by the digital twin, the main steps of engine assembly include:

(1) Data model definition. Based on the digital twin model of engine assembly, an independent model is instantiated for each engine to realize the virtual and real mapping with the target engine.

(2) Assembly process control. Driven by the workflow engine, the assembly execution process is controlled through workflow instances, the execution of the assembly process is monitored and controlled in real time, and the triggering and iteration of the process is realized through variable assignment.

(3) Technical status control. In the virtual space, it truly reflects the effectiveness, over-tolerance, through-change, zero-return, etc. of engine assembly technology, actively identifies various abnormalities, and triggers processing sub-processes.

(4)Data association analysis. Based on structured and unstructured assembly and test data, analyze and discover the relationship between the physical state of engine parts, the state of assembly technology, and the test performance, and promote the optimization of process technology.

(5)Iterative optimization. Through repeated iterations, mutual integration, and faithful mapping between the physical assembly and the virtual model, the intelligence, initiative, and predictability of the engine assembly process management and control are improved.

III. Key Technology

3.1 Hierarchical decomposition and modeling of part information based on digital twin

The information in the manufacturing process of parts mainly includes two categories: accuracy specifications and material properties. The former is determined by tolerance type, tolerance value, accuracy grade, surface roughness and other parameters, and the latter is determined by material name, number, mechanical properties and heat treatment method. Such as the project composition, they jointly determine the performance of the part in the assembly process.

The part twin body includes two parts: physical parts in the real world and digital parts in the virtual world. According to the representation of part information in the assembly process, the digital model in the virtual environment is divided into three layers: geometric shape layer, pose constraint layer, and physical state layer. It is superimposed with the ideal design model to reflect the current complete information state of the real part, and thus map with the real world parts to form a part twin.

3.1.1 Geometry layer modeling of part digital twin model

The surface feature points of the part must all fall within the tolerance design interval. Therefore, it is necessary to calculate the distance of each discrete point from the ideal feature, compare the measured error of the scanning point cloud with the design tolerance, and evaluate whether the part meets the design specification.

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Align the scanning point cloud of the part with the CAD design model, and use the feature recognition software to make the two reach the closest state. The ideal feature shape of the part surface is relatively regular. Generally, the feature coordinate system is determined along the edge of the feature, and the function *f*(x,y,z)=0 is used to represent the ideal feature surface. The positional relationship between the broken discrete point and the ideal feature. If the discrete point is below the ideal feature, the distance between it and the ideal feature is recorded as a negative value, that is:

$$d = -\sqrt{F_{min}} = -\sqrt{(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2}, \ \ z_i < z \tag{1}$$

The measured error on the surface of the part is the difference between the maximum and minimum distance between the discrete point and the continuous feature. Compare it with the design tolerance T to evaluate whether the part meets the standard:

$$\begin{cases} \delta = d_{max} - d_{min} \le T, & \text{conform} \\ \delta = d_{max} - d_{min} > T, & \text{contradict} \end{cases} \tag{2}$$

For some surface features that can be regarded as stretched in a certain direction, using linear error to describe the surface topography helps to reduce the computational complexity. According to the hierarchical model of the real feature information of the part, the actual measurement discrete point cloud data of the surface line features of the stretched part is obtained, and the least square method is used to perform polynomial fitting on the measuring points, thereby reconstructing the continuous curve function closest to the actual part surface shape.

If the coordinate matrix of all control points of the part curve feature is C, it has a relationship M·C=B with the coefficient matrix M and the coordinate matrix B of the meter sample point. Generally, M is not a square matrix. In order to solve the control point coordinate matrix C, multiply the matrix MT on both sides of the equation at the same time, and define the square matrix N as N=M^TM. In order to determine the Bezier curve expression f(x). Get the control point matrix C expression:

$$\mathrm{C} = \mathrm{N}^{-1} \cdot \mathrm{M}^{T} \cdot \mathrm{B} \tag{3}$$

The quotient of the two-norm of the difference between the fitted continuous function *f*(x) and the discrete point $\|f(x) - Q\|_2$ and the square root of the scanning point cloud is defined as the reconstruction error coefficient λ, as follows:

$$\lambda = \sqrt{\frac{\sum_{j=1}^{n}[f(x_j) - z_i]^2}{\sum_{j=1}^{n} {z_i}^2}} \tag{4}$$

It characterizes the degree of conformity between the fitted continuous function *f*(x) and the discrete points, which is used as a fitting error evaluation method. When the size of λ is 0, the fitting effect is the best, and the function *f*(x) passes through all discrete points.

3.1.2 The pose constraint layer modeling of the digital twin model of the part

Parts are generally composed of multiple features, of which only one or a few features will interact with other parts, and the matching relationship between features is determined by feature registration elements, so these registration elements are accurately identified and matched with corresponding elements Matching is a prerequisite for the successful assembly of parts.

Part features are divided into assembly features and other features according to whether they will have a mating relationship with other parts. Assembly features mainly include plane features, surface features, shaft features, hole features, pin features, and groove features. The assembly feature is decomposed into a variety of element structures, including three types of feature registration elements: point, line, and surface. Through the matching between feature registration elements, the part to be assembled and the reference part have a constraint relationship, and the relative degree of freedom is zero. The state, that is, the two are fixed together to complete the part assembly process.

In addition, the geometrically stable assembly form does not match the actual assembly situation. In order to ensure physical stability, it is also necessary to consider the influence of the position of the center of mass on the assembly attitude. So as to realize the modeling of the physical state layer of the part digital twin model.

3.2 Assembly execution process control based on digital twin

Engine assembly has undergone repeated execution of the process of "assembly-test run-decomposition-fault inspection-assembly-test run". It has the characteristics of multiple installations and multiple trials and complex processes, which is significantly affected by the state of assembly technology. The digital control method of the assembly execution process based on the fixed process sets few variables, and it is difficult to adjust the workflow adaptively. As shown in Figure 2, the digital twin-driven engine assembly execution process control method first establishes a process template covering all nodes of engine assembly such as assembly, commissioning, decomposition, fault inspection and reassembly, and instantiates the digital twin model for a single engine. Using workflow technology to drive the execution and computer control of the process, realize the computer control of the workflow execution of a single engine assembly, and set the right time at the right time.

Push the task package to the appropriate station to effectively handle the task’s recall, waiting, suspension, restart and other conditions. Define variables and branches in the workflow model, and realize the closed-loop and active control of the technical status and the assembly process control through the active identification and process trigger mechanism of the faulty inspection status, the transfer status, the through-change status, the out-of-tolerance status, and the zero status. Integration with technological status control. Real-time tracking of production progress, material status, equipment status, and quality information, and obtain quality status judgment and evaluation results through real-time perception and fusion calculations, and truly and real-time reflect the abnormalities, alarms, production progress and key indicators of the assembly line in the virtual space.

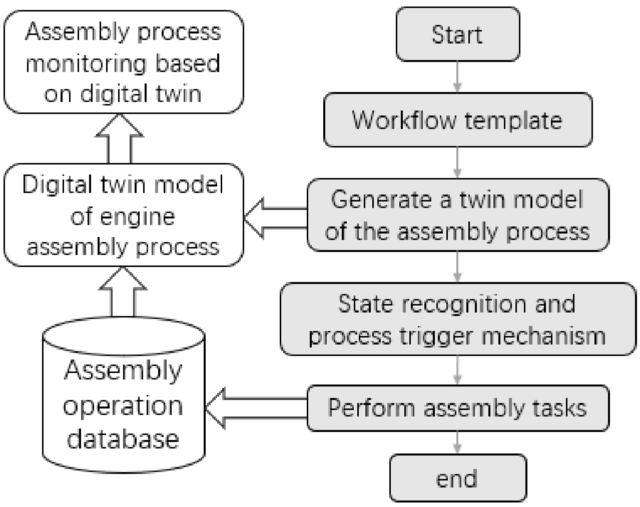

Figure 2. Assembly execution process control based on digital twin

3.3 Rotor stator assembly clearance control based on digital twin

The rotor stator radial clearance is one of the key factors that determine the performance and safety of the engine. The smaller the radial clearance, the higher the work efficiency and performance, but the greater the potential safety hazards of scratching and rubbing. The larger the radial clearance, the higher the safety, but the lower the working efficiency and performance, which may cause turbulence and increased vibration of the runner coating. However, the radial clearance of the rotor stator is "difficult to predict, control, and detect", which puts forward higher requirements on assembly technology.

Driven by the digital twin, the actual measured data such as the ellipticity, radial runout, eccentricity, flatness, parallelism, plane runout and angular position of the rotor and casing are input to establish the error transmission model of the rotor and stator assembly. The method of simulation is used to solve the axial deformation of the rotor, as well as the elastic support of the rotor, the amount of bending deformation, the amount of axis sinking, etc., with the minimum average clearance as the optimization objective, and the maximum clearance and minimum clearance meeting the requirements as constraints, establish an optimization model, and adopt The intelligent optimization algorithm finds the best rotor angular position, establishes the angular gap distribution diagram, and considers the vibration characteristic control requirements to obtain the best rotor stator coaxiality control value. In the assembly operation, install and debug the rotor based on the casing stop, measure and monitor the coaxiality of the rotor based on the axis of the stator casing, and use sensors to measure the radial clearance of each rotor to ensure the maximum The gap, minimum gap and average gap value meet the quality control requirements.

IV. Instance Verification

The digital twin-driven launch assembly technology covers a wide range and involves a lot of content, and its realization is an arduous project. To this end, an intelligent engine assembly platform is designed to support the realization of a digital twin model for engine assembly. The platform is divided into a basic resource layer, a perception execution layer, and an assembly business layer. Among them, the basic resource layer includes data resources, smart devices, and assembly production lines. It is not only the source of state perception, but also the executor of control instructions, and the carrier that realizes the two-way mapping and interaction between the physical world and the digital twin model. The perception execution layer is responsible for state perception and execution control. It is not only the medium of assembly business and basic resources, but also the center of virtual-real interaction and mapping. The assembly business layer is oriented to assembly process control, assembly operation guidance, process optimization control, technical status control, and data association analysis. It is the window through which humans interact with the digital twin system.

At present, digital twin-driven assembly execution process control and assembly technology state control subsystems have been applied in enterprises, digital twin-driven part selection and assembly operation guidance have completed technical research and development, and digital twin-driven stator assembly gap process control 、Association analysis of test data is in the research stage. Part of the implemented or applied subsystems have revolutionized the traditional engine assembly mode. Among them, the assembly execution process driven by digital twins adapts to the characteristics of multiple engine installations, multiple tests, and complex processes. Workflow technology is used to push the right task package to the right station at the right time, and it can actively identify fault inspections and transfer jobs. State variables such as, change, over-tolerance, zero-return, etc., trigger the corresponding process, realize closed-loop and active control of technical status, realize the integration of assembly process control and technical status control, real-time perception of production, materials, equipment, quality and other status, and truly reflect Abnormalities, alarms, production progress and key indicators in the assembly process.

In terms of assembly technology status control driven by digital twins, each engine has an assembly technology status model that completely corresponds to the physical status and covers the entire assembly process of the engine, which fully and truly reflects the material status and process of a single engine under installation. The evolution process of technical state, zero state, over-tolerance state, and through-change state supports the monitoring and traceability of process technology effectiveness control, material serial exchange, zero-return state, and over-tolerance state, as shown in Figure 3.

In terms of the selection and matching of digital twin-driven parts, taking a high-pressure turbine rotor balance assembly of an engine as an example, the key matching dimensions of the parts and the runout of the inner and outer spigot cylinders and end faces are measured, and the drum shaft and front face are controlled with the goal of controlling the coaxiality. The selection and optimal matching of sealing discs, turbine discs, and turbine rear axles, output parts matching list and circumferential installation angle, make the selected parts easier to assemble qualified, reduce parts replacement, and improve assembly efficiency and quality consistency.

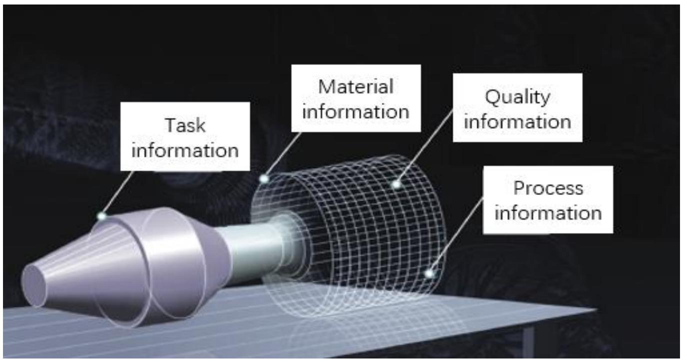

Figure 3. An example of assembly status tracking based on digital twins

V. Conclusion

This paper studies the engine assembly technology driven by the digital twin, and discusses its composition, function, process and key technologies in detail. Based on the interaction and integration of physical assembly and virtual models, it realizes assembly process control, parts selection, assembly operation guidance, assembly gap control, assembly technology status control, and assembly test data association analysis, which not only helps to improve assembly process and technology status control Intelligent, proactive, predictive, and can promote decision-making and optimization based on the physical state, improve the efficiency and standardization of assembly, improve the success rate and quality consistency of an assembly, thereby providing a feasible way to improve the technical level of engine assembly solution.

At present, the research on engine assembly technology driven by digital twins is in the development stage, and many problems need to be further studied and explored. It is hoped that this article can provide a certain theoretical and technical reference for the research and system development of engine assembly technology driven by digital twins.

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