Chapter 7

Digital Twin Technology

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Additional information is available at the end of the chapter

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Abstract

Digital twin technology is considered to be the core technology of realizing Cyber-Physical System (CPS). It is the simulation technology that integrates multidisciplinary, multiphysical quantity, multiscale and multi probability by making full use of physical model, sensor update, operation history and other data. It is the mapping technology for the whole lifecycle process of physical equipment in virtual space. It is the basic technology of Industrial 4.0. This chapter mainly introduces: (1) the generation of digital twin technology; (2) the definition and characteristics of digital twin technology; (3) the relationship between digital twin and digital thread; (4) the implementation of the product digital twin model; and (5) the research progress and application of digital twin research.

Keywords: digital twin, digital twin models, digital twin workshops, digital twin applications, Cyber-Physical System (CPS), virtual reality fusion, intelligent manufacturing, products lifecycle management, modeling and simulation

1. The generation of digital twin technology

The use of the "twin/twins" concept in the manufacturing can be traced back to NASA's Apollo program [1]. In the project, NASA needs to make two identical spacecraft. The aircraft left on earth is called a twin and is used to reflect the status/condition of the space vehicle in action. During the flight preparation, the space vehicle known as the twins is widely used in training. During the mission, the twins were used to simulate the space model on the ground, and it can accurately reflect and predict the status of the space vehicle in operation as much as possible, so as to assist the astronauts in orbit to make the most correct decision in emergencies. From this perspective, it can be seen that the twins are actually a prototype or model that reflects the real operation situation in real time through simulation. It has two significant characteristics: (1) the twins with the objects to be reflected are almost exactly the same as the appearance (the geometry and size of the product), content (the structure of the product and its macro- and microphysical properties) and properties (the function and performance of the product); and (2) it allows you to mirror/reflect real operation/state by means of simulation, etc. It needs to be pointed out that the twin at this time is still physical.

In 2003, professor Michael Grieves proposed the concept of virtual digital representations equivalent to physical products in a product lifecycle management (PLM) course at the University of Michigan and gives it a definition: which is a digital copy of one or a set of specific devices that can abstractly represent a real device and can be used as a basis for testing under real or simulated conditions [2]. The concept stems from the expectation of a clearer expression of the information and data of the device, hoping to put all the information together for a higher level of analysis. Although this concept was not called at the time as digital twin model (from 2003 to 2005, known as the "mirrored spaced model" [3], and during 2006–2010, known as "information mirror model" [4]), but its conceptual model had all the elements of the digital twin model, namely the physical space and virtual space and the relation or interface between them, therefore, it was regarded as the embryonic form of digital twin.

In 2006, the US National Science Foundation (NSF) first proposed the concept of the information physics system Cyber-Physical Systems (CPS), and could also be translated into a network entity system, or an information physical integration system [5]. The information physics system is defined as a network composed of physical input and output and interactive components. It is neither different from the independent equipment that is not connected to the network, nor it is different from the pure network without physical input and output.

In 2011, professor Michael Grieves, in his book "Virtually perfect: driving innovative and lean products through product lifecycle management" [6], cited the conceptual model of the noun digital twin model (digital twin), which is described by his co-author John Vickers, and it is still in use today. Its conceptual model is shown in **Figure 1**, including three main parts: (1) real space entity products; (2) virtual space virtual products; and (3) data and information interface between real space and virtual space.

This conceptual model greatly expands the "twins" in the Apollo program: (1) it digitizes the twin model and use digital expression to build a virtual product with the same content and nature as the product entity in appearance; (2) it introduces virtual space and establishes the association between virtual space and real space, so that data and information can be

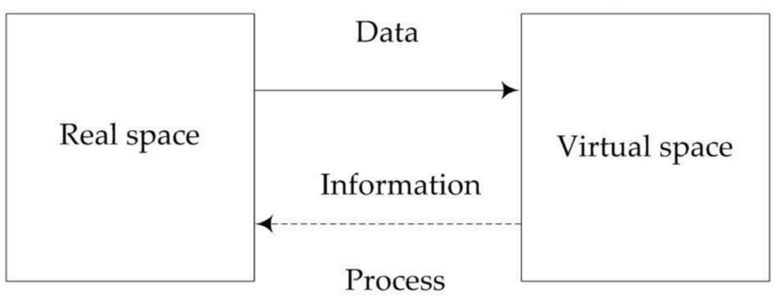

Figure 1. Conceptual model of digital twin.

exchanged between each other; (3) it visually reflects the concept of integrating the real with the imaginary, and controlling the real with the imaginary; and (4) extension of the concept and extension, in addition to products, factory, workshop, production lines, manufacturing resources (work position, equipment, personnel, materials, etc.), in the virtual space corresponding digital twin model can be set up.

However, it did not attract much attention from scholars when the concept and model were proposed in 2003. The main reasons are: (1) there were limited technical means to collect product-related information in the production process at that time, most of which were based on manual methods and paper documents; in particular, it is difficult to realize the on-line real-time collection of production data; (2) the digital description of physical products is not yet mature, and relevant software and hardware cannot support the precise definition and description of related properties and behaviors of physical products in virtual space; and (3) at that time, it was difficult to realize real-time processing of big data with computer performance and algorithm, and mobile communication technology was not mature enough, and real-time data transmission between virtual and real data was difficult to achieve.

After 2011, the digital twin ushered in a new development opportunity. The digital twin was proposed and further developed by the US Air Force Research Laboratory in 2011; the aim is to solve the maintenance and life prediction of aircraft in the future complex service environment [7]. In 2025, they plan to deliver a new type of space vehicle and digital model that corresponds to the physical product. The digital twin has super realism in two aspects: (1) it includes all geometric data, such as machining error and (2) includes all material data, such as material microstructure data. In 2012, the US Air Force Research Laboratory proposed the concept of Airframe Digital Twin" as the hyper-realistic model of the airframe being manufactured and maintained. The Airframe Digital Twin can be used to simulate and judge whether the airframe meets the task condition. It is an integrated model composed of many sub-models [8].

The Airframe Digital Twin is a consistent model and computational model of a single airframe in the whole product lifecycle. It is associated with the materials, manufacturing specifications and processes used to manufacture and maintain aircraft. It is also a sub-model of aircraft digital twin, which is an integrated model including electronic system model, flight control system model, propulsion system model and other subsystem models. At this time, digital twin enters the initial planning and implementation stage from the conceptual model stage, and its connotation and nature are further described and studied.

Specifically, (1) it highlights the hierarchical and integrated nature of digital twin, for example, the aircraft digital twin, the airframe digital twin, airframe structure model, material state evolution model and so on, and is beneficial to the gradual implementation and final realization of digital twin; (2) it highlights the hyperrealism of digital twin, including geometric model, physical model, material evolution model, etc.; (3) it highlights the universality of digital twin, that is, it includes the whole product life cycle and extends from the design stage to the subsequent product manufacturing stage and product service stage; (4) it highlights the consistency of digital twin in the whole life cycle of products, which reflects the idea of a single data source; and (5) it highlights the computability of digital twin, and the real state of corresponding product entity can be reflected in real time through simulation and analysis.

In 2012, in the face of future aircraft light quality, high load and the demand of the longer service time under more extreme environment, NASA and the US Air Force Research Laboratory in cooperation put forward the common digital twin example of future aircraft. For aircraft, flight systems or launch vehicles, they define digital twin as an integrated multi-physical, multi-scale, probabilistic simulation model for aircraft or system, which uses the best available physical models, updated sensor data, and historical data to reflect the state of the flying entity corresponding to the model [9]. In the same year, digital twin were formally introduced into the public view in the roadmap of modeling, simulation, information technology and processing released by NASA [10]. The definition can be considered as a periodic summary of previous research by the US Air Force Research Laboratory and NASA, especially it emphasizes the integration, multiphysical, multiscale, probabilistic characteristics of digital twin, and its main function is to be able to reflect the state of corresponding flight products in real time (continuing the function of the twins of the early Apollo project); the data used includes the current best available product physical models, updated sensor data, and historical data for product groups.

In 2013, Germany proposed the "Industry 4.0," whose core technology is Cyber-Physical System (CPS). CPS is a multidimensional complex system which is integrated with computing, communication, control, network and the physical environment [11]. Based on the big data network and mass computing and through the organic integration and deep cooperation of 3C (computing, communication, control) technology, the real-time perception, dynamic control and information service of large-scale engineering systems can be realized. CPS from physical space, environment, activities, large data collection, storage, modeling, analysis, mining, evaluation, prediction, optimization and coordination combine with design of the object, testing, and performance characterization to realize the depth fusion of network space (cyberspace) and physical space, real-time interaction and mutual coupling and update on each other; Furthermore, it promotes the comprehensive intelligence of industrial assets through self-perception, self-memory, self-cognition, self-decision-making, self-reconstruction and intelligent support. CPS connects people, machines and things. The virtual and real bidirectional dynamic connection in CPS connotation has two steps: (1) virtual entity such as the design of a product is simulated first and then manufactured and (2) entity virtualization. In the process of manufacturing, using and running, entities reflect their status to the virtual end and conduct monitoring, judgment, analysis, prediction and optimization through the virtual mode.

By constructing a closed loop channel for data interaction between information space and physical space, CPS can realize the interaction between information virtual model and physical entity. The emergence of digital twin provides a clear idea, method and implementation way for CPS. On the basis of the physical entity modeling the static model, through the real-time data acquisition, data integration and monitoring, dynamic tracking of physical entity working status and progress measurement result (such as acquisition, traceability information, etc.), the physical entities in the physical space are reconstructed in the information space, forming digital twin with the ability of perception analysis and decision execution. Therefore, from this perspective, digital twin is the core technology of CPS.

In 2014, Professor Michael Grieves elaborated digital twin in detail in his white paper "Digital Twin: Manufacturing Excellence through Virtual Factory Replication" [2]. In the same year, the U.S. defense department, PTC, Siemens and Assaults accepted the term "digital twin" and began to use it in marketing campaigns. It needs to be pointed out that they all use "digital twin" instead of "digital twins".

In 2015, General Electric Company planned to implement real-time monitoring, timely inspection and predictive maintenance of engines based on digital hygiene and through its own cloud service platform—Predix, using advanced technologies such as big data and Internet of Things [12]. In Made in China 2025, CPS is considered to be an integrated technical system that supports the deep integration of industrialization and informatization, and is an important starting point for promoting the integration of manufacturing and Internet.

In 2017, in order to realize the interactive fusion of the physical world and the information world of the manufacturing workshop, Tao Fei puts forward the realization mode of the digital twin workshop, and made clear its system composition, operation mechanism, characteristics and key technology, which provided the theory and method reference for the realization of the information physical system of the manufacturing workshop [13]. For two consecutive years (2016 and 2017), Gartner, the world's most authoritative IT research and consulting firm, listed digital twin as one of the top 10 strategic technology trends of the year. The world's largest weapons manufacturer Lockheed Martin in November 2017 ranked digital twin as the top of the six leading technology in the future defense and aerospace industries. In December 2017, the China Association for Science and Technology (CAST) Intelligent Manufacturing Academic Union (CIMA) listed digital twin as one of the top 10 technological advances in intelligent manufacturing at the World Intelligent Manufacturing Conference [14].

It can be seen that the digital twins have developed rapidly in both theoretical and application levels in recent years. At the same time, the application range has gradually shifted from the product design stage to the product manufacturing stage and operation and service stage, which has attracted wide attention of scholars and enterprises. The main reasons are the following aspects:

1. the rise and wide application of model digital expression technology such as model lightweight, MBD, physics-based modeling, etc., makes it possible to accurately describe physical products at various stages of the product life cycle using digital methods; and

2. the rapid popularization and application of the new generation of information and communication technologies such as large data, Internet of Things, mobile Internet, cloud computing, and the rapid development of computer science and technology such as large-scale computing, high-performance computing, distributed computing, as well as the emergence of intelligent optimization algorithms, such as machine learning and deep learning, make products reliable with real-time dynamic data collection and predict possible, such as fast transmission, storage, analysis and decision, and provide important technical support for real-time correlation and interaction between virtual space and physical space.

2. The definition and characteristics of digital twin technology

From the perspective of the origin and current development of digital twin, its applications mainly focus on product design and operation and maintenance stages, but with the rapid spread and application of new generation of information and communication technology such as big data, Internet of Things, mobile Internet, and cloud computing, digital twin have gone beyond the traditional product design and operation phases. To make it easier to understand the digital twin, this section gives a definition of the digital twin technology.

2.1. Definition of digital twin and digital twin model

Digital twin refers to the processes and methods for describing and modeling the characteristics, behavior, formation process, and performance of physical objects using digital technology, and can also be referred to as digital twin technology. The digital twin model refers to a virtual model that completely corresponds to and is consistent with the physical entities in the real world, and can simulate its behavior and performances in a real-time environment in real time. It can be said that digital twin is techniques, processes, and methods, and that digital twin models are objects, models, and data. Digital twin technology is not only using human theory and knowledge to build virtual models but also can use virtual model simulation technology to explore and predict the unknown world, to find better ways and means, and constantly inspire human innovative thinking. The pursuit of optimization and progress, therefore, in digital twin technology provides new ideas and tools for current manufacturing innovation and development.

In the future, there will be a digital twin model in the virtual space that is exactly the same as the entity in the physical space. For example, the physical factory has a corresponding factory digital twin model in the virtual space, and the physical workshop has a corresponding workshop digital twin model in the virtual space. Physical production lines in the virtual space have corresponding production line digital twin model and so on.

Digital twin is the foundation of the intelligent manufacturing system. The most important enlightening significance of digital twin is that it realizes the feedback from the physical system to the digital model of cyberspace [15].

This is a feat of reverse thinking in the industrial field. People try to plug everything that happens in the physical world back into digital space. Only full life tracking with loop feedback is the true full lifecycle concept. In this way, the digital and physical world can be truly harmonized throughout the entire lifecycle. Various types of simulation, analysis, data accumulation, and mining based on digital models, and even the application of artificial intelligence, can ensure its applicability to real-world physical systems. This is the significance of digital twin to intelligent manufacturing. The intelligence of an intelligent system must be first perceived, modeled, and then analyzed. Without digital twin' accurate modeling of a real production system, the so-called intelligent manufacturing system is passive water and cannot be implemented.

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2.2. Definition of product digital twin model

Considering the evolution process and related explanations of the existing product digital twin model, the author gives the definition of the product digital twin model: the product digital twin model refers to the full-element reconstruction and digitized mapping of the physical entity's working state and work progress in the information space, and is an integrated multiphysics, multiscale, hyperrealistic, dynamic probability simulation model that can be used for simulating, monitoring, diagnosing, predicting, and controlling the formation process, state, and behavior of physical entities in the real world. Product digital twin model generated by the product model based on the product design stage, and during the next product manufacturing and service stage, with the product data and information interaction between physical entities, constantly improves their integrity and accuracy, finishing a complete and accurate description of product physical entity. Some scholars have also interpreted the digital twin model as digital mirror, digital mapping, digital twins, etc.

It can be seen from the definition of the product digital twin model that: (1) the product digital twin model is a simulation model in which product physical entities are integrated in the information space, a digital file of the entire lifecycle of product physical entities, and the integrated management of the product lifecycle data and full value chain data; (2) the product digital twin model is perfected by continuous data and information interaction with the physical entity of the product; (3) the final representation of the product digital twin models is a complete and accurate digital description of the physical entity of the product; and (4) product digital twin model can be used to simulate, monitor, diagnose, predict, and control the formation process and status of physical entities in a physical environment.

The product digital twin model is far beyond the category of digital prototype (or virtual prototype) and digital product definition. The product digital twin model includes not only the description of the product geometry, function and performance, but also the description of the formation process and state of the whole life cycle, such as product manufacturing or maintenance process. Digital prototype, also called virtual prototype, is a digital description of a mechanical product or a subsystem with independent functions. It not only reflects the geometric properties of the product object, but also reflects the function and performance of the product object in at least one domain. Digital prototype is formed in the stage of product design and can be applied to the whole lifecycle of products, including engineering design, manufacturing, assembly, inspection, sales, use, after-sale, recovery and other links. The definition of digital product refers to the activities of digitizing the function, performance and physical properties of mechanical products. From the connotation of digital prototype (or virtual prototype) and digital product definition, they mainly focus on the description of the product geometry, function and performance in the product design stage, and does not involve the description of the formation process and state of other full life cycle stages such as product manufacturing or maintenance process.

2.3. Basic features of the product digital twin model

The product digital twin model has many characteristics including: virtuality, uniqueness, multiphysical, multiscale, hierarchical, integrated, dynamic, super-realistic, computability, probability and multidisciplinary.

1. Virtuality: the product digital twin model is a physical product in digital mapping model, information space is a virtual model, belonging to the information space (or virtual space) and does not belong to the physical space.
2. Uniqueness: a physical product corresponds to a product digital twin model.
3. Multiphysical: the product digital twin model is based on the physical properties of physical product digital mapping model; It is not only necessary to describe the geometric properties of the physical product (such as shape, size, tolerance, etc.), but also to describe the various physical properties of the physical product, including structural dynamics models, thermodynamic models, stress analysis models, fatigue damage models, and material properties of product composition materials (such as stiffness, strength, hardness, and fatigue strength).
4. Multiscale: the product digital twin model not only describes the macroscopic properties of the physical product, such as geometric dimensions, but also the microscopic properties of the physical product, such as the microstructure of the material, the surface roughness and so on.
5. Hierarchical: the different components, parts, etc. that make up the final product can all have their corresponding digital twin models. For example, the aircraft digital twin model includes the rack digital twin model, the flight control system digital twin model, the propulsion control system digital twin model, etc., which is conducive to hierarchical and detailed management of product data and product models, and the progressive realization of the product digital twin model.
6. Integrated: the product digital twin model is a multiscale and multilevel integrated model of multiple physical structure models, geometric models, and material models, which is conducive to the rapid simulation and analysis of the product's structural and mechanical properties.
7. Dynamic: the product digital twin model will constantly change and improve through the continuous interaction with the product entity during various stages of the whole lifecycle; for example, product manufacturing data (such as test data, the progress data) will be reflected in the digital twin model of the virtual space, and at the same time, based on the digital twin model, can realize the real-time, dynamic and visual monitoring of the manufacturing state and process of the product.
8. Super-realistic: the product digital twin model and the physical product are basically identical in appearance, content, and nature, with high degree of actuality, and can accurately reflect the real state of the physical product.
9. Computability: based on the product digital twin model, simulations, calculations and analysis can be used to simulate and reflect the status and behavior of the corresponding physical product in real time.
10. Probability: the product digital twin model allows computation and simulation using probabilistic statistics.

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11. Multidisciplinary: the product digital twin model involves the intersection and fusion of multiple disciplines such as computational science, information science, mechanical engineering, electronic science, physics, etc., and has multidiscipline.

3. Relationship between digital twin and digital thread

Digital thread was first proposed by Lockheed Martin of the United States. In the production of F-35, they directly input MBD data into computer numerical control machine tools to process components, or complete the laying of composite materials through the programming system, and called this new working mode "digital thread." The "digital thread" saves 6000 sets of tooling for the three configurations of the F-35. It also eliminates the time required for the management of these tooling and the configuration of the parts, as well as the time it takes to distribute the tooling and load it onto the machine.

The US Department of Defense uses digital thread as the most important basic technology for digital manufacturing. Boeing has already been pushing forward the digital mainline technology of single data source product to interact. The National Center for Manufacturing Sciences NCMS (the National Center for Manufacturing Sciences) has confirmed that digital manufacturing as "one of America's largest and most potential competitive assets" and as a key strategy for the future. The digital main line, as its name suggests, is the main theme of digital manufacturing undoubtedly. The Industrial Internet Alliance does not hesitate to use the digital thread as key technology that the Industrial Internet Alliance needs to focus on. It is no exaggeration to say that the digital thread is the key to the revitalization of the US manufacturing industry. The digital thread is a strong connection between OEMs (manufacturers), operation and maintenance service providers, suppliers and end users. The background generated by the digital thread is based on the "model-centered," and the model here is provided with complete information rich, established in accordance with uniform open standards, norms and semantics of digital model, and it can be read steadily and unambiguously by the machine (or system). On this basis, the digital thread integrates and drives the modern product design, manufacture and guarantee process, allowing the models of each link to timely synchronize and communicate the key data bidirectionally. The principle is shown in **Figure 2**. It can be seen in the design and production process that the parameter simulation model is transmitted to the product definition of full three-dimensional geometric model and digital line processing into the real physical product, and then reflected in the product definition model by online digital detection/measurement system. Then, it is fed back to the simulation analysis model to realize a two-way data transmission process. The core of the digital line is how to build a collaborative environment that covers the entire process of product development, so that the unified model can realize bidirectional flow, reuse, and continuous enrichment of data during all phases of product development.

The "Industry 4.0" terminology team defines digital thread as: digital data stream of product design, manufacturing, and assurance, which is constructed with advanced modeling and simulation tools and cover the whole life cycle and value chain of product, and are integrated and driven by a unified model from all aspects of basic materials, design, process, manufacturing, and use and maintenance.

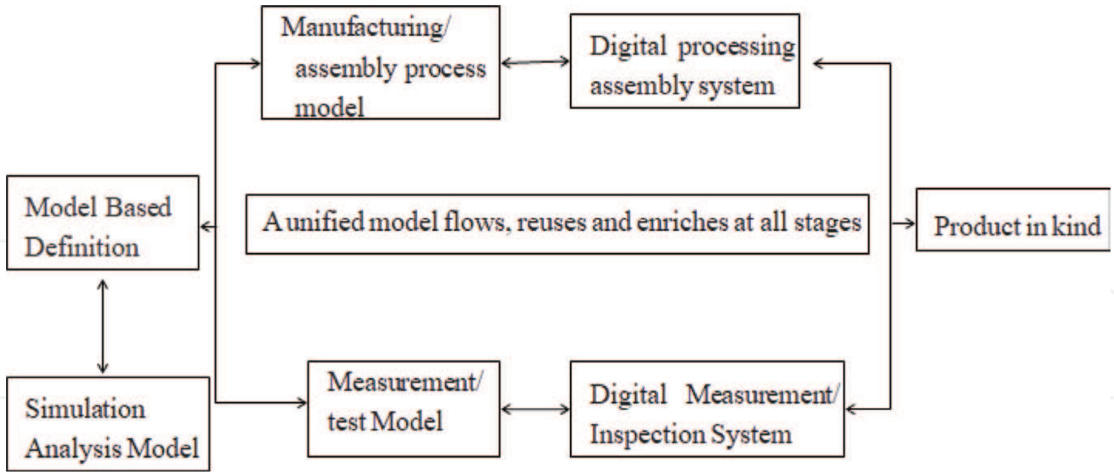

Figure 2. Principle of digital thread.

It can be found that digital twin is a concept that is related to and differentiated from digital thread. Digital twin is a digital representation of a physical product, so that we can see on this digital product what the actual physical product may be and related technology that includes augmented reality and virtual reality. Digital thread in the process of design and production, the parameters of the simulation analysis model can be passed to the product's full three-dimensional geometric model, and then transmitted to the digital production line to be processed into a real physical product, and then reflected in the product definition model through the online digital detection/measurement system, and it is fed back to the simulation analysis model, so that the current and future functions and performance of the dynamic and real-time evaluation system can be realized.

In short, digital thread runs through the entire product lifecycle, especially from the seamless integration of product design, production and operation, while digital twin, more like the concept of intelligent products, emphasizes feedback from product operation and maintenance to product design. It is the digital shadow of physical products. Through integration with external sensors, it reflects all the characteristics of objects from micro to macro and shows the evolution process of product life cycle. Of course, not only products but also production systems (production equipment and production lines) and systems in use and maintenance should be built as needed.

4. Implementation of digital twin technology

4.1. Product design stage

Product digital twin is a hyperrealistic dynamic model of physical products in virtual space. In order to achieve product digital twin, we must first have a natural (easy to understand), accurate, efficient digital expression method of data definition and transmission. The method supports all stages of product life cycle, including product design, process design, processing, assembly, use and maintenance. The model-based definition (MBD) technology that has emerged in recent years is an effective way to solve this problem, and therefore it has become

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one of the important means for achieving product digital twin. MBD refers to a digital definition method that attaches all relevant product design definitions, process descriptions, attributes, and management information to the product's three-dimensional model. MBD technology enables product definition data to drive all aspects of the entire manufacturing process, fully modeling the concept of parallel collaborative design of products and the idea of a single data source, which is also one of the essence of digital twin. The product definition model mainly includes two kinds of data: one is geometric information, that is, the product design model; and the other is nongeometric information, stored in the specification tree, and the PDM software supporting the 3D design software which is responsible for storing and managing the data [16].

Secondly, after the product definition based on the 3D model is realized, the process design, tooling design, production manufacturing process and even product function testing and verification process simulation and optimization need to be performed based on the model. In order to ensure the accuracy of simulation and optimization results, at least the following three points must be guaranteed:

1. High accuracy and hyperrealism of product virtual model: product modeling not only needs to pay attention to geometric feature information (shape, size and tolerance) but also the physical properties of the product model (such as stress analysis model, dynamic model, and thermodynamics model, and material stiffness, plasticity, flexibility, elasticity, fatigues strength, etc.). Through the use of artificial intelligence, machine learning and other methods, based on the historical data of similar product groups to achieve continuous optimization of existing models, the product virtual model is closer to the functions and characteristics of real-world physical products.

2. Accuracy and instantaneity of simulation: advanced simulation platform and simulation software can be used, such as commercial simulation software Ansys, Abaqus, etc.

3. Model light-weighting: model light-weighting is the key technology for achieving digital twin. First of all, the lightweight technology of the model greatly reduces the storage size of the model, so that the geometric information, feature information and attribute information needed for product process design and simulation can be directly extracted from the 3D model without any unnecessary redundant information. Second, the lightweight model makes it possible to visualize product simulations, simulate complex systems, simulate production lines, and simulate products based on instant data. Finally, the lightweight model reduces the time, cost, and speed of information transfer between systems, facilitates end-to-end integration of value chains, information sharing between upstream and downstream companies in supplies chains, business process integration, and collaborative product design and development.

4.2. Production stage

The evolution and improvement of product digital twin is through constant interaction with product entities. In the manufacturing phase, the physical real world delivers production test data (such as test data, schedule data, and logistics data) to virtual products in the virtual world and displays them instantly. Product's model-based production test data monitoring and production process monitoring are realized (including the comparison of the design value and the measured value, the comparison of the actual used material characteristics with the design material characteristics, the comparison of the planned completion schedule and the actual completion schedule, etc.). In addition, based on the production of measured data, through the intelligent forecasting and analysis of logistics and schedules, we can realize the prediction and analysis of quality, manufacturing resources, and production schedules. At the same time, the intelligent decision module formulates a corresponding solution to the entity product based on the results of the prediction and analysis, so as to achieve dynamic control and optimization of the entity product, and achieve the purpose of virtual integration and virtual control.

Therefore, how to achieve real-time accurate multisource heterogeneous data collection, effective information extraction, and reliable transmission in a complex and dynamic physical space are prerequisites for achieving digital twin. In recent years, the rapid development of technologies, such as Internet of Things, sensor networks, industrial Internet, and semantic analysis and identification, has provided a practical and feasible solution. In addition, artificial intelligence, machine learning, and data are used to demonstrate the role of digital twin in product data integration demonstration, product production progress monitoring, product quality monitoring, intelligent analysis and decision-making (such as product quality analysis and forecasting, dynamic scheduling and optimization). The rapid development of technology such as mining and high-performance computing has provided important technical support for this purpose. Since the assembly line is the carrier for product assembly, the architecture also considers digital hygienic production and assembly line digital twin. The framework mainly includes three parts:

1. Real-time collection of dynamic data in physical space: the dynamic data generated during the assembly process of the product can be divided into production personnel data, instrument and equipment data, tooling tool data, production logistics data, production progress data, production quality data, and actual work hour data. There are eight categories of data for reverse problems. First of all, for the manufacturing resources (production personnel, equipment, tooling, materials, AGV, pallets), combined with the characteristics and needs of the production site, the use of barcode technology, RFID, sensors and other Internet of Things technology, manufacturing resource information identification, the manufacturing process awareness information collection point is designed and a manufacturing object connection network is constructed in the production workshop to realize the real-time perception of manufacturing resources. The production personnel data, instrument and equipment data, tooling data, production logistics data and other manufacturing resources-related data are classified as real-time sensing data; the production progress data, actual work hour data, production quality data, and reverse problem data are classified as process data. Real-time sensing data collection will promote the production of process data. In addition, for the abovementioned large number of multisource, heterogeneous production data, on the basis of predefined manufacturing information processing and extraction rules, the multisource manufacturing information relationship is defined, data identification and cleaning are performed, and data is finally standardized and packaged and formed a unified data service and published it externally.

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2. The digital twin evolution of virtual space: by using the unified data service to drive the three-dimensional virtual model of assembly line and the three-dimensional model of product, the product digital twin instances and the assembly line digital twin instances are generated and updated continuously. Assembling line digital twin and product digital twin instances are associated with real-world assembly lines and physical products, and the data exchange between each other is achieved through a unified database in virtual space.

3. Status monitoring and process optimization feedback control based on digital twin: real-time monitoring, correction and optimization of product production process, assembly line and assembly station through historical data of assembly line, excavation of product history data, and assembly process evaluation technology through the comparison of real-time data and design data and planning data, the comparison of product technology status and quality characteristics, real-time monitoring, quality forecasting and analysis, advance warning, and production scheduling optimization are realized, so as to achieve closed loop feedback of product production process and bidirectional connection between control and virtual reality. Specific functions include real-time monitoring of product quality, product quality analysis and optimization, real-time monitoring of production lines, real-time monitoring of manufacturing resources, optimization of production scheduling, and optimization of material distribution.

4.3. Product service stage

During the product service (product use and maintenance) stage, the status of the product still needs to be tracked and monitored in real time, including the physical space location, external environment, quality status, usage status, technology, and functional status of the product. The actual status, real-time data, use and maintenance of recorded data predict and analyze the health, life, function and performance of the product, and provide early warning of product quality issues. At the same time, when the product fails and has quality problems, it can realize rapid positioning of product physical location, fault and quality problem records, parts replacement, product maintenance, product upgrade and even scrapping and decommissioning.

On the one hand, in the physical space, using the Internet of Things, sensor technology, mobile Internet technology, the measured data related to physical products (the latest sensor data, location data, external environment sensing data, etc.), product usage data and maintenance data are mapped to the product digital twin in the virtual space.

On the other hand, in the virtual space, the model visualization technology is used to realize the real-time monitoring of the physical product usage process; combining with historical data, historical maintenance data and related historical data of the same type of products, the continuous optimization of product model, structure analysis model, thermodynamic model, product failure and life prediction and analysis model is realized by using machine learning data mining methods and optimization algorithms; it makes the product digital twinning and prediction analysis model more accurate, and the simulation prediction results more in line with the actual situation. For physical products that have experienced faults and quality problems, traceability and simulation techniques are used to quickly locate quality problems, cause analysis, solution generation, and feasibility verification. Finally, the final results generated are fed back to the physical space to guide the product quality troubleshooting and tracing. Similar to the product manufacturing process, the implementation framework of digital twin in the process of product service mainly includes three parts: data collection in physical space, digital twin evolution in virtual space, and state monitoring and optimization control based on digital twin.

5. Research progress and application of digital twin technology

5.1. Research progress on digital twin

The concept of digital twin was first proposed by professor Grieve in 2003 at the University of Michigan's product lifecycle management course and was defined as a three-dimensional model including physical products and virtual products and the connection between the two. However, due to technical and cognitive limitations at that time, the concept of digital twin was not taken seriously. It was not until 2011 that the US Air Force Research Laboratory and NASA jointly proposed the construction of a digital twin for future aircrafts, and defined digital twin as a highly integrated multiphysical field, multiscale and multiprobability simulation model for aircrafts or systems. It was able to reflect the function, real-time state and evolution trend of the entities corresponding to the model by using physical model, sensor data and historical data, etc. Then, digital twin really attracted attention. Some scholars supplemented and perfected it on the basis of NASA's concept. For example, Gabor and others suggested that digital twin should also include expert knowledge to realize accurate simulation. Rios and others believed that digital twin was not only for aircrafts [17, 18].

In the process of continuous improvement and development of the concept of digital twin, academia has mainly carried out relevant research on modeling, information physics integration, interaction and collaboration, and service application of digital twin.

Some research has been carried out on the framework and modeling process of digital twin modeling in modeling, but there is still no consistent conclusion. Some progress has been made in modeling-related theories, including physical behavior research, nondestructive material measurement technology, quantitative error and confidence evaluation research. These auxiliary technologies will help to determine model parameters, construct behavior constraints, and verify model accuracy.

In the aspect of information physics fusion, there are only preliminary studies on the dimensionality reduction and integration of sensor data and manufacturing data in the aspect of digital twin information physics fusion, while the research on the theory and technology of digital twin information physics fusion is still blank. In order to solve this difficult problem, professor Tao Fei decomposed and refined the scientific problem of information physics fusion into four different dimensions of fusion: physical fusion, model fusion, data fusion, and service fusion in 2017, and designed the corresponding system implementation reference framework. Combined with the theory of digital twin technology and manufacturing service, this chapter systematically studies and discusses four key scientific issues of physical integration, model integration, data integration and service integration, and extracts and summarizes the corresponding basic theories and key technologies. His related work provides some theoretical and technical references for relevant scholars to carry out theoretical and technological research on the physical integration of digital twin information and for enterprises to build and practice the concept of digital twin.

The research on real-time acquisition theory of production data and man-machine interaction that has been carried out in the field of interaction and collaboration is helpful to realize the interaction and collaboration between the physical world and the virtual world. However, there are few related researches on interaction and collaboration between machines and services at present.

In service application, some research has been carried out on service application of digital twin in fatigue damage prediction, structural damage monitoring, real-time running states detection, faults location, etc.; however, there are still many problems to be solved in realizing service integration and coordination. From the above analysis, it can be seen that the research on the related theories of digital twin is still in its infancy. In order to promote the application of digital twin to the ground, it needs to be systematically and deeply studied in the aspects of digital twin modeling, information physics fusion, exchange and cooperation.

5.2. Application of digital twin technology

5.2.1. Product design based on digital twin

Product design refers to the work process of providing all the solutions needed for product production through research, analysis and design according to user requirements. The product design based on digital twin refers to the synergy of existing physical products and virtual products in the design driven by the digital data generated by the products, and continuously discovers new, unique and valuable product concepts and transforms them into detailed products. The design plan continuously reduces the inconsistency between the actual behavior of the product and the expected behavior of the design. The product design based on digital twin emphasizes the overall improvement of design quality and efficiency through the integration of virtual and real life cycles and the establishment of virtual simulation models with super reality.

5.2.2. Virtual prototype based on digital twin

Virtual prototype is a digital model built into the digital world that reflects the authenticity of a physical prototype, through multi-domain comprehensive simulation and equipment performance attenuation simulation, the performance of the equipment can be tested and evaluated before the physical prototype is manufactured, and the design defects can be improved to shorten the design improvement period. The virtual prototype based on digital twin is based on the comprehensive and realistic description of the mechanical system, electrical system and hydraulic multidomain system of the equipment. It has the ability to map the life cycle of the physical equipment, thus designing the equipment, and predictive maintenance provides powerful analytical decision support.

5.2.3. Workshop rapid design based on digital twin

The workshop rapid design based on digital twin adopts the idea of "information physics fusion," which completes the digitization of physical equipment, the scripting of motion process, the integration of the whole system, the synchronization of control commands, and the parallelization of on-site information to form a complete line of execution engine. Through the physical equipment and the corresponding virtual model for virtual and real interaction, instruction and information synchronization, a rapid design, planning, assembly and testing platform for the workshop supporting physical equipment connection is formed. The platform: (1) uses the 3D engine designs and builds a special model library, combining workshop area, capacity requirements, equipment selection, and construction of virtual 3D model of workshop, which can quickly complete the workshop layout design; (2) prepares action scripts for heterogeneous devices, develops response programs, builds virtual control networks, implements near-physical simulation of virtual full-line machining movements, and predicts, evaluates and optimizes based on actual data; and (3) can test the consistence of the distributed integration equipment and the whole line movement, the internal control logic, the instruction and information downlink channel, the job cycle synchronization and so on, and optimize the workshop design based on the virtual reality fusion data.

5.2.4. Process planning based on digital twin

Process planning is the technical document of the product manufacturing process and operation method; it is a disciplined document that all production personnel should strictly and conscientiously implement; and it is the basis for product production preparation, production scheduling, worker operation and quality inspection. Digital twin-driven process planning refers to the realization of process design and continuous optimization for production sites by establishing virtual simulation models such as products, resources and process flows with super reality, and virtual and real mapping of full factor and full process. In the process design mode of digital twin driving, the simulation model of virtual space and the entity of physical space are mapped to each other to form an iterative collaborative optimization mechanism of virtual and real symbiosis.

5.2.5. Workshop production scheduling optimization based on digital twin

Production scheduling is the nerve center of decision-making optimization, process control and performance improvement in the production workshop, and it is the operation pillar of orderly, stable, balanced economy, and is agile and efficient in the production workshop. The digital twin-driven scheduling mode is a new scheduling mechanism of virtual-real response, virtual-real interaction, virtual-control-real, iterative optimization, which is supported by the digital twin system, through the virtual-real mapping and interaction fusion of all elements, all data, all models and all spaces, and realizes cooperative matching and continuous optimization of the "workpiece-machine-constraint-goal" scheduling requirements. Under the digital twin-driven scheduling model, the scheduling elements are mapped to each other in the physical workshop and virtual workshop, forming the co-optimization network of virtual reality co-existence. Physical workshop actively perceives production status. Virtual workshop can analyze scheduling status, adjust scheduling scheme and evaluate scheduling decision through

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self-organization, self-learning and self-simulation. It can quickly determine abnormal range, respond quickly and make intelligent decision. It has better adaptability to change, disturbance response ability and abnormal resolution ability.

5.2.6. Production logistics accurate distribution based on digital twin

Production logistics including enterprise internal logistics and enterprise external logistics between businesses are to guarantee the normal production and are the key of high production efficiency, and they reduce the product cost. Digital twin production logistics is under the twin data-driven, and through the actual physical entities and the virtual model mapping, real-time interaction and closed loop control, realize the task of production logistics combinatorial optimization, transportation route planning, transportation process control in the physical world and information world and overlapping generations between the top logistics services system, so as to achieve production logistics seamlessly and is an intelligent of a new kind of production logistics operation mode.

5.2.7. Intelligent control of workshop equipment based on digital twin

The control system of workshop equipment is the brain of workshop equipment. The correctness of its control function and control strategy directly affects the function and performance of workshop equipment. The control advantages of digital twin are as follows: (1) in the stage of equipment design, the design of the control system is matched based on the digital twin virtual reality synchronization, so that the control system and the physical equipment are fused earlier and match, and the burden of the real machine is lightening; (2) in the commissioning stage, the overall matching of control system and equipment is further promoted, the design defects are improved, and the design redundancy is reduced; and (3) in the running stage, the control feedback information is no longer a relative independent parameter, but the physical real time state of the digital twin, which can provide objective and effective data support for the autonomous decision of the algorithm.

5.2.8. Man-machine interaction based on digital twin

By human-computer interaction, the flexibility of the machine can be improved and the workload of manual work can be reduced. The workshop man-machine interaction based on digital twin refers to the construction of a digital twin virtual workshop which is fully mapped to the actual physical workshops. Through high speed and reliable communication technology, the robot can quickly adjust the work plan by identifying the workers' instructions through touch, gesture, or sound, so as to make it possible to cooperate with the workers. Industry action and update the manufacturing process of virtual workshop in real time.

5.2.9. Assembly based on digital twin

The assembly of complex products is the final stage and key link of the realization of product function and performance. It is an important factor affecting the quality and performance of complex products. The quality of assembly determines the final quality of complex products to a great extent. The assembly process of the digital twin drive will be based on the integration of the Internet of Things of all equipment, the integration of the physical world of the assembly process and the information world, and the precise control of the parts, equipment and assembly process through the intelligent software services platform and tools, and the unified and efficient control of the assembly process of complex products. The self-organization, adaptation and dynamic response of the product assembly system are realized.

5.2.10. Testing/detection based on digital twin

The digital twin drive test/detection is to build a high-fidelity test system and a virtual model of the measured object in the virtual space. With the help of test data real-time transmission and test instruction execution technology, the multi-discipline/multi-scale/multi-physical properties of the physical object under test and the virtual object under test are driven by historical data and real-time data to achieve high-fidelity simulation and interaction. It thus intuitively and comprehensively reflects the full life cycle state of the production process and effectively supports scientific decision-making based on data and knowledge. The digital twin-driven test/detection process includes knowledge modeling, system design, system construction, and full lifecycle management and autonomous decision-making of system, object, and process state data.

5.2.11. Manufacturing energy management based on digital twin

The management of manufacturing energy consumption refers to monitoring, analyzing, controlling and optimizing the energy consumption of water, electricity, gas, heat and raw materials in the manufacturing process, while ensuring the performance of the manufacturing system and the economic benefit of the enterprise, so as to realize the fine management of energy consumption, achieve energy saving and reduce the cost of the manufacturing enterprise, and maintain the enterprise, the purpose of the competitiveness of the industry.

5.2.12. Product quality analysis and traceability based on digital twin

Product quality analysis and tracing refers to the design of the correct and reasonable manufacturing process, at the same time, the processing precision, stress and other factors in the production process are comprehensively considered to realize the analysis of the quality of the product. In the case of quality problems, it can trace all the links in the processing and find out the reasons, thus improving the processing technology and control, processing quality.

5.2.13. Fault prediction and health management based on digital twin

Prognostics and Health Management (PHM) use various sensors and data processing methods to evaluate the health status of the equipment, and predict the equipment failure and residual life, so as to transform the traditional post maintenance into pre service maintenance.

5.2.14. Product-service system based on digital twin

Product-service system (PSS) is a value providing system that provides a combination of different "physical products and services" to consumers, including a product oriented PSS, a use oriented PSS, and a result oriented PSS. Under the support of digital twin, PSS is based on the digital twin, through the intelligent analysis and decision-making of different "physical products and service" combination, rapid personalized product service configuration and service process experience and rapid supply, and the use of the virtual and real synchronization among elements to realize the optimal allocation and integration of resources. The PSS based on the digital twin model makes full use of the digital and information system to effectively support the intelligent decision-making, rapid supply, intelligent service, value and environment analysis of the life cycle of complex products and services.

6. Conclusions

The digital twin technology can not only make use of the theories and knowledge of human beings to establish virtual models, but also make use of the simulation technology of virtual models to explore and predict the unknown world, and find better ways, constantly stimulate the creative thinking of human beings, and continue to pursue the optimization and progress, which are the innovation of the current manufacturing industry. This chapter mainly summarizes the definition, connotation and implementation methods of digital twin technology.

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