A Hierarchical Digital Twin Model Framework for Dynamic Cyber-Physical System Design

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ABSTRACT
Cyber-physical system (CPS) is a new trend in the complex system related research works, where network connectivity enhances computing power and systemic behavior emerges through the competition, interaction, collaboration and integration among individual interweaving, which consists of real-time monitoring, data management, physical feedback control. From this perspective, CPS is a dynamic entity with rich functions. However, designers may encounter a difficult situation, in which subsequent dynamic changes of the system are discussed and appropriate functionalities are added in the early design phase. Since the digital twin is the digital duplicate of the physical entity, it can dynamically evolve following the product life cycle. In this paper, we propose a hierarchical digital twin model framework for CPS design. In the light of digital twin concept, the hierarchical high-level models facilitate storage of information from the entire product life cycle. Finally, an industrial robot application is presented to demonstrate the efficacy of the model framework.

CCS Concepts
• **Computer systems organization → Embedded and cyber-physical systems** • **Computing methodologies → Modeling and simulation.**

Keywords
CPS; Complex System; Digital Twin; Modeling&Simulation; Industrial Robot

1. INTRODUCTION
In the last decade, the new generation of mechatronic systems is functionally extended to cyber-physical system can be found in complex system such as power grid, aerospace, automotive, healthcare, manufacturing, traffic control, etc. As widely believed, CPS is the synergy between the pair of physical world and cyber world on the basis of the embedded systems, sensor technology, and networking technology, which enables the complex system to have the capabilities of self-aware, self-compare and self-adaption [1]. In the physical world, distributed and interconnected heterogeneous components or subsystems over the network combine to perform specific functionalities and performances, which can be captured by sensors and controlled by actuators. In the cyber world, the physical data and even information coming from sensors and networked components, correspondingly, is properly processed and analyzed to achieve real-time monitoring, precise control and prediction. Thus, CPS is becoming a dynamic entity that evolves with the product life cycle. Traditionally, the design of complex systems is completed in the early stages of the life cycle. Designers always seek to centrally define all the behaviors and work processes of the system, which is impossible for dynamic CPS and makes the system relatively isolated, mutational and unpredictable on the contrary. In the light of the CPS design, it calls for a new framework that can deal with the complexities of interwoven heterogeneous systems as well as utilize dynamically growing data, in order to achieve the fusion of the virtual world and the physical world and establish dependable CPSs.

Recently, a new technology named digital twin to implement CPS has emerged. The digital twin expects to have the capability to integrate all the valuable information throughout the product lifecycle and create a virtual image of the physical entity. The relatively formal definition of digital twin is released by NASA in 2012: “A Digital Twin is an integrated multiphysics, multiscale simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin [2].” The concept is quickly introduced to a complex system, consisting of physical entities, virtual models and the linkage data [3]. The most important innovation of digital twin for CPS is that it realizes two-way interaction between physical world and cyber world. On the one hand, changes in the behavior and state of physical entities can be dynamically reflected in the virtual model in real time. On the other hand, digital twin model can make intelligent analysis and decision-making and control the status and behavior of product in real time based on all available data from system status, environmental perception, experience and knowledge data, etc. It is well to be reminded that the digital twin is a set of models describing physical entities, rather than a fixed and unchanging single model.

Digital twin has been applied to almost all stages of the life cycle of complex systems, which particularly places emphasis the operation and maintenance phase of the system monitoring,

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forecasting, control and fault diagnosis. To date, the capability of digital twin for the design of complex systems is seldom studied that how and in what ways the interaction, collaboration and integration between the physical world and the cyber world is realized in the product design stage.

The core topic of this paper is the presentation of the hierarchical digital twin model (HDTM) framework for CPS, which can guide designers to create a digital twin, and use information from the digital twin to support the design of the complex system. The hierarchical digital twins can not only handle heterogeneous CPS, but also take advantage of CPS's growing data. More importantly, the digital twins established during the design phase can evolve dynamically with CPS and continue to function in the later stages of the life cycle. The rest of the paper is structure as follows. the following section covers the introduction to the background knowledge and related work. Section 3 introduces the general framework of digital twin. Section 4 presents the details of the hierarchical digital twin model framework and the digital twin-driven CPS design process. Section 5 showcases a case study of the industrial robot design under this framework. Finally, Section 5 gives the conclusions and future work.

2. RELATED WORKS

In this section, we will introduce the background knowledge and related work related to complex system design and CPS architecture.

2.1 Design Methodology for Complex Systems

With the development of information technology and hardware technology, traditional industrial systems have become complex systems. The behavior of complex systems is the result of a collaboration group, which shows a higher hierarchy, a more complex and more collaborative function. The design method of complex system has always been the focus of research.

Umeda et al. proposed the Function–Behavior–Structure (FBS) framework which modularizes a complex system and analyzes it hierarchically [4]. The complex system is decomposed into multiple modules that are interconnected and functionally independent, and can be progressively layered for each module to achieve the desired design. FBS framework gives the direction of the design of complex systems.

On the basis of the original FBS, Gero and Kannengiesser place the functions, behaviors and structures in the expected world, the interpreted world and the external world, and realize the contextual design process through the interaction of three worlds[5]. Traditionally, the interpreted world is the designer's subjective understanding and experience description of the external world. Therefore, it is difficult for the interpreted world to connect with the expected world and the external world, and the external world cannot be objectively and accurately reflected.

Christophe considers requirement analysis as an important design concept in the conceptual design stage, and built the RFBS(Requirement-Function-Behavior-Structure) model [6]. The International Council on Systems Engineering (INCOSE) presented the concept of MBSE at the International Symposium in 2007, and further extended the RFBS, which began in the conceptual design phase, through the subsequent R&D lifecycle phase, supporting system requirements, design, analysis, verification and validation [7]. In addition, however, MBSE is a method of product optimization through iterative closed loop. It fails to make full use of the value of real-time data and cannot follow the dynamic changes of the system in time.

Traditional design methods rely on the knowledge or experience of the designer to identify high-value data and not respond to real-time data in a timely manner. But this does not mean abandoning existing design theories and methods. Rather, this article continues to adopt these design approaches and considers the dynamics of the system.

2.2 CPS Architecture

CPS is the operation and implementation form of complex system under industry 4.0 architecture[8]. However, the complexity of physical heterogeneous system and virtual abstract calculation makes the design of CPS difficult. A general or unified architecture plays an important role in the CPS design process.

According to the definition of CPS, the typical architecture of CPS can be composed of three layers: physical layer, network layer and application layer[9]. Such definition is still abstract and lack of pertinence and guidance in the implementation process.

In regard to factory automation, BC Pirvu et al. put forward the anthropocentric cyber-physical system（ACPS） reference model, which Integrates the physical component (PC), the computation-al/cyber component (CC) and the human component (HC) [10]. ACPS achieves adaptive and dynamic division of the system through interactions among components. The ACPS reference model materializes the typical architecture of CPS.

Lee establishes CPS 5C (Connection, conversion, cyber, cognition, configure) architecture for industrial 4.0 manufacturing system[11]. The CPS 5C-level architecture is applicable to different layers in the industrial system, namely component layer, machine layer, workshop layer and enterprise layer.

However, there are still many areas of research for CPS to be improved. The previous architectures do not fully consider the interface components of connections within the system, especially between the physical world and the virtual world, when building the intelligent system of industry 4.0.

3. BASIC CONCEPT OF DIGITAL TWIN

Digital twin technology can not only use the existing theories and knowledge of human to establish virtual models, but also use the simulation technology of virtual models to explore and predict the unknown world, so as to find and find better methods and approaches, constantly stimulate human innovative thinking, and constantly pursue optimization and progress. Therefore, the digital twin technology provides new ideas and tools for the realization and development of the current CPS concept.

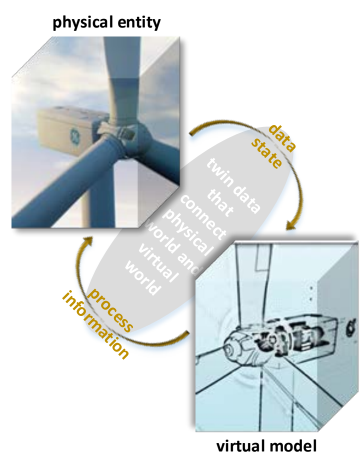

Figure 1 A General form of digital twin for complex systems

As shown in figure 1, the system models constructed in the digital virtual volume space has a precise mapping relationship with the functions, behaviors and states (FBS) corresponding to the physical entities in the physical entity space. Data or information, by means of data management and analysis tools, forms an effective correlation between the twins, which generates specific functions across the product lifecycle. Therefore, the digital twin is considered as the core key technology for implementing CPS realizes the integration of the physical world and the information world. The components are as follows：

- **Physical entity** is the carrier of digital twin. Whether the collaborative interaction of heterogeneous physical systems that make up CPS, or the simulation of virtual models, or data processing, is based on physical entities. The physical entity is the ontology of CPS external action.
- **Virtual model** is the real-time accurate depiction of physical entities in virtual space, which can be used as the computing engine of CPS. Based on the data from the entity, on the one hand, it can be used to verify and update the existing models; On the other hand, the updated model can monitor the system state and identify fault modes, and then realize the prediction and health management of system operating status.
- **Twin data** is the driver of digital twin. Data can be accumulated at different stages of the product life cycle (design, engineering, operation and service), and the potential value of data can be mined through processing and analysis. Dynamic real-time interactive data connects physical entities and virtual models into an organic whole, driving the operation of each part.

Therefore, the digital twin that is considered as the core key technology for implementing CPS realizes the integration of the physical world and the information world. Yun has created a digital twin platform for heterogeneous CPS to improve the reliability of the advanced driver assistance system[12]. Gabor et al. proposed a digital twin software architecture framework to optimize the behavior of complex systems[13].

The application of digital twin is generally focused on the operation and maintenance stage of the product, but it also has great value in the design stage. If the digital twin is built during the design phase and can be dynamically increased along with the CPS during the product life cycle, the digital twin can be a system that integrates the relevant knowledge (data and information) of the current phase, so that it can be useful in the following stages.

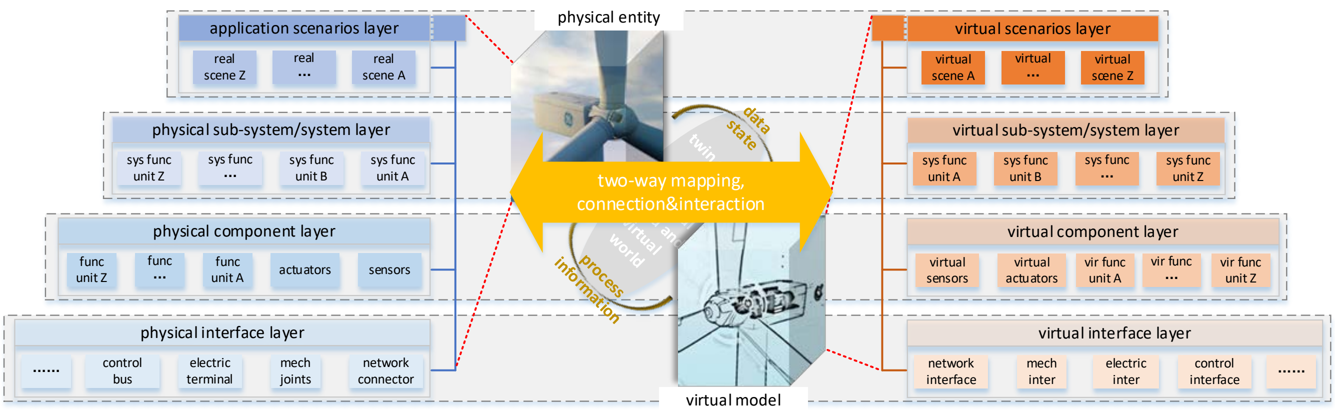

Figure 2 A hierarchical digital twin model framework for dynamic cyber-physical system design

4. DIGITAL TWIN-DRIVEN DYNAMIC CPS DESIGN METHODOLOGY

This section aims to contribute with a hierarchical digital twin model framework that allows designers can define the basic information of the subsequent changes of CPS at the early design stage, ensuring that the early design can follow the dynamic changes of the system and function in the later stage.

4.1 A Hierarchical Digital Twin Model (HDTM) Framework

The digital twin established in the early stage of product design, in parallel with the product engineering phase, operation phase and service phase, is a dynamic growth concept in the whole life cycle of the product. As shown in Figure 2, the fixed architecture ensures the uniformity of information sources, as well as the hierarchical structure can accommodate the constantly updated heterogeneous model and the growing multi-source data, thus realizing the fusion and construction of the physical world and the virtual world and building a digital twin that grows dynamically throughout the product life cycle.

The HDTM framework expands the traditional digital twin structure in Figure 1. On the left is the expanded topology of the physical entity of CPS. As is well known, CPS is an interdisciplinary field of engineering science that aims to integrate and interconnect mechanical, electrical, control, and computer networks that form the basis for product success. The more network connections that exist, the greater the integration requirements of the CPS, and the system becomes a dynamic entity. CPS acquires a layered structure or adds it as an "element" to larger systems (so-called “systems of systems”). In order to clearly define and verify requirements during the design phase, hierarchical system requirements need to be decomposed into criteria for design decisions. Referring to the design concept of MBSE, we define the physical entity as a hierarchical framework to realize the layer-by-layer decomposition of "application scenario - (sub) system - component - interface" from top to bottom.

In the middle part is the twin data, which consists of physical data and virtual data, as well as some "new data" obtained by integrating, merging and analyzing between them. After the two-way mapping between the physical entity and the virtual model is implemented, based on the principle of system operation consistency, the twin data covering the product life cycle is carried out for quasi-encapsulation, module to module accurate mapping, real-time interaction, operation prediction, etc., so as to truly depict and reflect the system operation state and explore the potential value of the system operation process. The twin data enables the integration and sharing of product lifecycle data and eliminates information silos. On the basis of the integration, the twin data continuously updates and expands its own data for deep data fusion, which is the drive to realize the connection and interaction between physical entities and virtual models.

Finally, the department on the right is the virtual model, which is the core of the digital twin. In the digital twin, the virtual model is the real mirror image of the physical entity. Correspondingly, the virtual model adopts the 4-layer framework consistent with the physical entity, from the bottom to the top:

- Virtual Interface layer: the starting point of the entire model architecture, including interfaces in various fields, such as network interface, mechanical interface, electric interface, control interface and so on.
- Virtual components layer: component models of various domains correspond to the components under the topology of real physical systems.
- Virtual (sub-)system layer: consisting of multiple interrelated component models that support the implementation of system-specific functions.
- Virtual scenarios layer: generated by the system model according to different application scenarios and tasks.

Compared with the traditional modeling methods, the hierarchical structure of the model achieves the consistency of the virtual model and physical entity topology very well, ensures the one-to-one correspondence of virtual model in all levels from system to component to interface, and forms the unique correspondence between virtual object. On this basis, the virtual model is calibrated with twin data so that it can accurately reflect the characteristics corresponding to the physical model.

It is worth noting that the digital twin model is a set of models that can be applied to different stages of product design. These design models have different goals at different stages. In the conceptual design phase, physical principles, functions, structures, etc. must be evaluated by executing models. These models consist of a set of parameters and a set of logical and quantitative relationships between these models. The number of parameters increases from the conceptual design stage to the preliminary design and detailed design. As the details of the design process increase, the physical entities become more and more complete, and accordingly, the granularity of the twin models under the hierarchical framework becomes more and more refined. In this process, the virtual model and the physical entity correspond to each other point-to-point, so the model can achieve the precise mapping of the physical entity to the greatest extent, and can reflect the influence of local details on the whole system. Furthermore, the hierarchical architecture provides a high degree of reusability and composition, allowing the model to continue to be continuously updated (not just parameters, but the model), which allows the twin model to adapt to different applications. In these scenarios, Normally, a single type of model is difficult to meet the analysis of various professional problems (heat, thermal, electromagnetic, mechanical vibration, etc.). In addition, the functional simulation interface (FMI)] achieves this requirement by providing a tool-independent standard for exchange of dynamic models and collaborative simulations [14], which is not explained in this paper.

With the advancement of product life cycle, digital twin enables designers to handle subsequent product changes early in the design process, which integrates dynamically updated models and ever-increasing data from physical entities. In Section 4.2, we will detail how designers use HDTM framework.

4.2 How Designers Use the HDTM Framework

Compared with the current development philosophy based on detailed engineering, the interrelationship between future system concepts and different stages of development will become more important. Digital twin will be an important approach throughout the life cycle. For designers, digital twin is a "smart tool" to recognize, transform and create physical products, which can provide designers with new ideas, methods and implementation approaches in the design process.

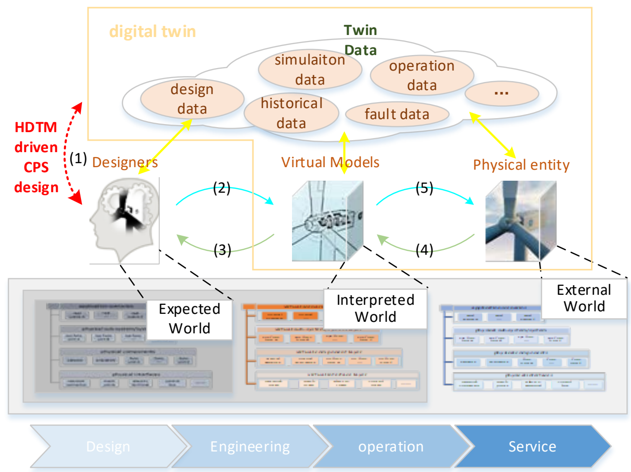

Figure 3 collaboration between designers and digital twin in HDTM framework

Figure 3 shows the collaborative process between the designer and the digital twin in HDTM framework. The design process of complex system is defined as the back-and-forth interaction between the expected world, the interpreted world and the external world [5]. Under the HDTM framework, the interaction and fusion of the interpreted world and the external world in the driving of twin data constitutes a digital twin. Among them, virtual model is the digital image of physical entity, which becomes the bridge between the expected world and the external world, and can be regarded as the overlapping expression of designer intention and real physics. In addition, existing information systems (e.g. PLM, PDM, ERP, etc.) store and provide a large amount of data information, such as historical data, design data, simulation data, operational data, and the like. This information is used by the digital twin and stored in the HDTM to provides a single source of information for designers, virtual models and physical entities.

Firstly, in the expected world, designers establish system requirements based on the historical data and the physical knowledge of historical models (Arrow 1 in Figure 3). Then, the requirements models, as well as the synchronous evolving functional models and product models (such as three-dimensional CAD model and EDA model used for integrated circuit manufacturing) as the design process advances, are established in the interpreted world, and the expected design requirements are verified and confirmed iteratively(Arrow 2 in Figure 3). In this process, digital twin integrates traditionally large and decentralized data (such as historical data, demand, feedback data, etc.) into HDTM. In turn, the designer can obtain the improvement measures and methods of the product through HDTM of a single information source (Arrow 3 in Figure 3). The final stage of product design is to integrate different components into a complete system for testing. In this case, the virtual model can be the real mapping of the historical product, and the real-time interaction between the virtual model and the previous physical entity can be comprehensively considered environmental factors and real-time factors to ensure the correctness of the design and help to reduce unnecessary physical testing.

Second, after the product is designed, the virtual model is projected from the interpreted world to the external world, and the physical entity will be manufactured. In the operation phase, through the enabling technologies of the Internet of Things, sensors, etc., the operational data of the physical entities in the external world will be transmitted to the interpretation world to update the virtual model (Arrow 4 in Figure 3), and as part of the twin data that will be used to drive the digital twin in the CPS information space to make decisions and feed back to physical entities (Arrow 5 in Figure 3). At this point, the information created by the digital twin during product design and engineering can be used for evaluation during system operation. On the other hand, in the service phase, since digital twin provides an intelligent view of system information, users of different disciplines can also access the models and results of the early life cycle stages, which is the basis of a more flexible service plan.

In summary, the hierarchical digital twin established at the beginning of the design, with the development of the life cycle, the model and data in the framework are gradually increased, so as to follow the dynamic change of CPS and eventually become a part of the physical product.

5. AN INDUSTRIAL ROBOT CASE STUDY

As the core component of Industry 4.0, industrial robot consists of three basic parts: main body, drive system and control system, which can be regarded as a simple CPS system. In this section, we present a case study of the industrial robot HSR-JR605 to demonstrate the application of the HDTM framework in design practice and to illustrate the possibility for digital twin established during the design phase will continue to function in later stages of operation.

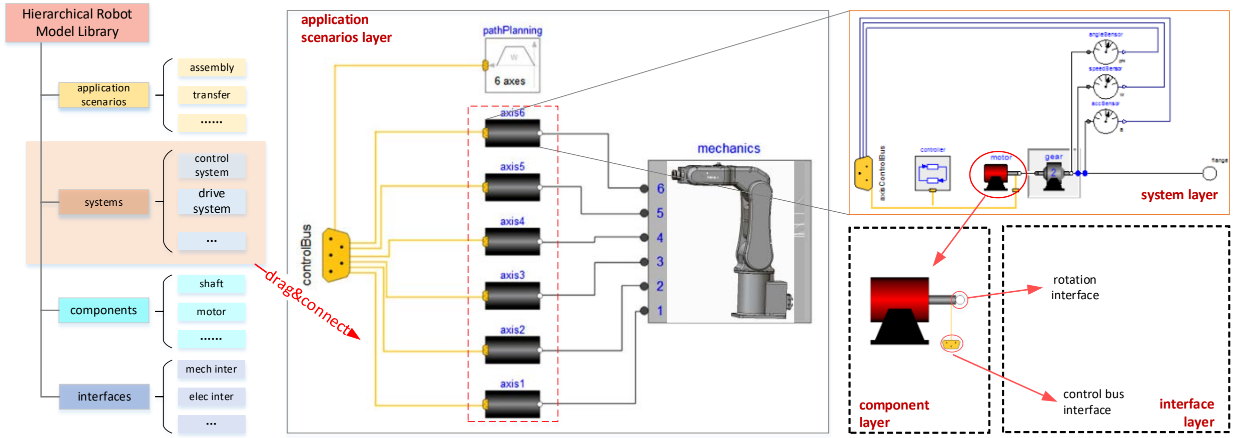

Figure 4 Hierarchical robot HSR-JR605 simulation model in MWorks

In the design phase, designers rely on the digital twin of previous generation devices to support new designs. The virtual model provided by Digital Twin under the solution environment MWorks software is represented as a hierarchical model library of the system described by the multi-domain modeling language Modelica [15]. As shown in Figure 4, the hierarchical model library covers all the professional domain knowledge of industrial robots. Designers can develop a new generation of industrial robot system models by dragging and dropping modular models, and verify and confirm each link of the design process. The simulation model is based on a hierarchical model that associates the simulation data with the display model. A hierarchical multi-granularity integrated modeling and presentation method that comprehensively presents the model structure and technical state of complex systems and provides decision support for different roles. The top-level model of industrial robot in Figure 4 contains multiple "system layer" models. The driving system model in "system layer" is composed of multiple "component layer" models, in which one key component contains the electrical interface and mechanical interface of "interface layer".

As the design process advances, the complexity of design objects increases, and more and more professional designers participate, professional models for dealing with specific engineering problems will be created. The need for consistency between models increases. In the HDTM framework, all information is stored in a unified hierarchical architecture to provide a consistent source of data, and all models should use this data source to handle all inputs, which is also essential for the successful development of next-generation devices. As shown in figure 13, a specific simulation model is established for different field problems of the motor, taking the driving motor components of industrial robots as an example. Vibration modal analysis is used to calculate the deformation of the motor stator subjected to unbalanced magnetic pull. The electromagnetic finite element model is used to calculate the magnetic field and the generated force. The temperature rise model calculates the heat generated by electrical losses. In the unified HDTM framework, all these models can be integrated into the industrial robot system model through FMI to achieve a detailed analysis of system-specific functions.

Then, the virtual model provided by Digital Twin is re-used after some modifications according to the new design requirements. Designers can understand the improved information of the product from a single information source (Digital Twin), such as workspace, payload, motion accuracy, dynamic characteristics, and so on. With the refinement of the design, a test model associated with the historical physical entity is established to simulate real-time conditions and working environment. Digital twin-driven virtual verification can make full use of the data of the previous generation of equipment, environment and user information and historical data, identify design defects and find the causes, and predict the actual performance of physical products as accurately as possible, avoiding unnecessary physical tests in the later period.

In addition, the above process will continue during the subsequent stages of the life cycle. The HDTM framework has been established as a suitable interface for virtual models interacting with real data early. Therefore, during the operational phase, operational data is also collected as part of the twin data by digital generation, which can be used to validate and update the actual operating conditions of the existing model to support control decisions within the Cyber space.

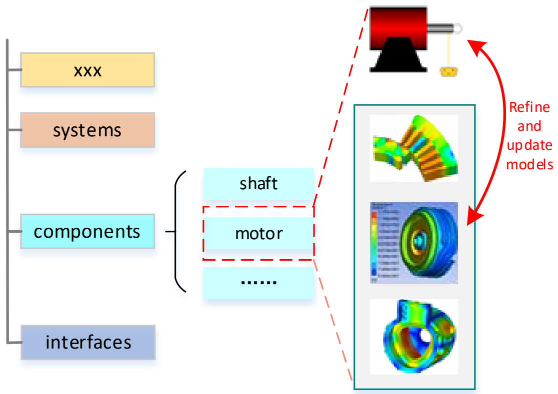

Figure 5 Refinement and update of motor model under HDTM framework

6. CONCLUSION AND FUTURE WORKS

As far as CPS is concerned, network connectivity enables the collaboration of heterogeneous systems and expands the functions of the system. The growing dynamic data among sub-systems becomes the computing engine of cyber part. Thus, CPS is a dynamic entity. Digital twin is a virtual image of a physical entity that can reflect CPS state changes in real time, providing solutions for different but specific goals and problems and achieving the integration of the physical world and the cyber world.

This paper presents the HDTM framework for implementing dynamic CPS design. The framework defines the architecture and interfaces of CPS with extensibility and reusability from the beginning, supporting the interweaving of virtual models and twin data at different levels of detail across the different disciplines and lifecycle phases involved. The benefits of the HDMT framework are improved consistency, seamless development processes, and information reuse in lifecycle phases. On the one hand, the twin data integration the model data and the physical data can be used to drive the update of the virtual model and the physical entity operation; On the other hand, the virtual model is a bridge to communicate designers and the physical world, and it can accurately reflect the changes of physical entities through continuous refinement and update of hierarchical model. In addition, an example of industrial robot design shows the possible form of application of the HDTM framework in the product design phase and subsequent operation phase.

In the future, we will focus on technologies related to the interactive fusion between twin data and virtual models, twin data and physical entities. The real-time, security and accuracy of data is a prerequisite for the operation of digital twins. A further challenge is how to extract visual information that can be used in designer decisions from large amounts of data. In addition, although we aim to provide a design paradigm, it is also necessary to practice the releted methods in a specific field.

7. ACKNOWLEDGMENTS

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