A novel smart model for high-end equipment structure design

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Abstract. Cyber-Physical System (CPS) serves the key to realize smart manufacturing, while Digital Twin (DT) acts as the key to realize CPS. The evolving and maturing Digital Twin concept has several inherent shortfalls. In this paper, a new RSDM model enabled by Digital Twin is proposed to address these problems with iterative design optimization and efficient design knowledge management. The results show that RSDM model is helpful for enhancing radar structure design efficiency and design optimization, and is a promising framework for implementing smart design.

1. Introduction

With emergence of artificial intelligence, cloud computing, Internet of Things (IoT), several nations are looking forward to moving to smart manufacturing by initiating Industrial Internet, Made in China 2025 and other strategies [1-3]. For realizing smart manufacturing, a Cyber Physical System (CPS) shall be created to build the inter-connection and real-time integration between physical entities and virtual entities [4]. Digital Twin (DT) is acting as the key to realize CPS by implementing virtual-physical integration.

Digital Twin concept is generally believed to be introduced by Michael Grieve in 2002 for the first time, who defined DT as the conceptual model underlying product lifecycle management (PLM). However, this concept did have all the elements of DT, including physical products in physical space, virtual products in virtual space, the link for data flow and information flow between them [5].

Many famous companies have proposed or implemented smart manufacturing solutions based on DT, like Siemens, PTC, Lockheed Martin, GE, Dassault, Raytheon and Thales. For example, Siemens focuses on the digital twin of manufacturing system [6-10], GE uses Predix digital twin platform to realize monitoring and maintenance [11]. Raytheon Advanced Radars Enterprise Sustainment Model (ARESM) is established to enhance more reliable radar architecture design [12]. Dassault verifies the interactive integration of airborne radar products and digital twin based on 3DExperience platform [13]. Thales has initiated a TroUE strategy. Taking Sea Fire and Ground Fire multifunctional phased array radar as example, Thales built a radar mechanical-electrical-thermal digital twin model, which greatly improves the collaborative radar design capability by running the model through the whole development process including radar demand design, electronic design, structural design and design support [14].

2. Demand Development

Now, Digital Twin concept is widely used in aerospace, ship building, disaster prediction, smart manufacturing and smart workshop [15-19].
Radar, as a complex electronic system, gets its application in many fields including defence, earth observation, resource exploration, navigation, health care etc. For creating three-dimensional physical models, geometric models, assembly models on radar products, many modelling tools are employed like CAE, CAD, ANSYS to realize multi-element mapping of physical radar structure and then digital structure design of radar products.

However, there are still many problems encountered in radar structure design, including ideal design, poor real-time interaction and insufficient digital design application.

For example, current radar structure design system can describe ideal radar definition from radar designers, giving accurate simulation value assignment, but in the real world, all product parameters will be affected by several factors including process, assembly or manipulation, resulting in inconsistency. Thus, it is difficult to accurately reflect the actual state of the real radar product.

Moreover, all existing radar structure design systems can produce static structure scheme with no dynamic real-time response to complex process environment, manufacturing environment and operation environment.

Thus, a new RSDM radar structure design model is proposed to address above-mentioned problems.

3. RSDM Model
In order to meet the requirements of radar structure design in Digital Twin environment, a Radar Structure Design Model (RSDM) is proposed in this paper. This model consists of Physical Radar Structure (PRS), Virtual Radar Structure (VRS), Structure Design Services (SDS), Radar System Structure Cloud (RSSC) and Design Model Support (DMS).

![Figure 1. RSM Model](image)

Physical Radar Structure (PRS) is serving as the basis of RSDM. According to radar functions and structures, PRS is generally divided into three levels: Radar Unit Level, Radar Subsystem Level and Radar System Level. In accordance with different requirements and management fineness, RSDM can be constructed hierarchically. For example, for radar units, unit-structure-level RSDM is constructed to carry out unit performance monitoring, unit fault prediction, unit maintenance & repair. While for the radar system, a radar-system-level RSDM is constructed to carry out radar performance monitoring, running diagnosis, fault prediction, design optimization decision with the aid of interaction/coupling relationship description among radar units and radar subsystems.
Virtual Radar Structure (VRS) is designed to comprehensively describe the geometric parameters, assembly relationship, physical properties, and behaviour response of PRS through physical models, geometric models, behaviour models and other models, thus creating a digital description of PRS with multiple spaces and multiple time scales. At the same time, VRS-PRS consistency, accuracy and sensitivity are also verified by various models, so as to ensure real-time or near real-time mapping between VRS and PRS.

Structure Design Services (SDS) is a set of various services supporting RSDM operation, including model simulation & verification service, data mining integration & analysis service, model interconnection service, fault prediction service and risk assessment service. DRS services are generated by all kinds of data, models, algorithms and simulations generated in the process of RSDM operation.

Radar System Structure Cloud (RSSC) is the driving engine of RSDM. It interacts with PRS, VRS, SDS and DMS components in real time to obtain physical data, running data of radar equipment. Combined with historical statistics data and expert knowledge, RSSC carries out correlation, conversion, integration and fusion to become Enterprise-level Radar Structure Design Cloud efficiently enabling the current radar structure design.

Design Model Support (DMS) is the operation support and application extension of RSDM. On the one hand, it inputs various design reference data from Product Chain, Value Chain and Asset Chain. On the other hand, it extends RSDM applications beyond structural design, such as digital radar life cycle management, cooperative design running through full industry chain and full value chain.

Thus, RSDM proposed here has several tenets, including physical-virtual integration, closed-loop product lifetime management and full-value-chain cooperation, and is valuable to transform radar structure design from digital design to higher-level smart design [20].

Next, this paper will focus on the application of RSDM in radar structure design optimization and structure design knowledge management.

4. RSSC Module
As the driving engine for integration of physical space and virtual space, RSSC uses multiple data processing algorithms, data analysis models, knowledge reasoning models to implement physical-virtual interaction and real-time synchronization.

In accordance with RSSC functions, RSSC engine can be divided into three components, including Data Layer, Computation & Analysis Layer, Interaction Layer.

4.1. Data Layer
Data Layer acts as the basis of RSSC, and consists of Data Warehouse Module and Data Pre-processing Module.

Data Warehouse Module is designed to store a large amount of data produced during radar structure design, process, manufacturing, and manipulation. Due to the diversity of data from different sources with different formats and different volumes, this module usually uses distributed database to meet data storage requirements, like HDFS, HBase and so on.

Data Pre-processing Module aims to address data-transfer error problem resulting from external environment factors or data loss during data transfer. Thus, this module can use algorithms like machine learning, rule constraint to solve data loss, data redundancy, data conflict, data mistake problems, so as to clean, convert and extract useable and structured data, so that these data can be used for further analysis directly.

4.2. Computation & Analysis Layer
Computation & Analysis Layer serves as the high-speed computation engine of RSSC. Based on various computation modules and intelligent algorithms, this layer can provide various support services for Interaction Layer.

According to the work flow, Computation & Analysis Layer is divided into three modules, including Data Analysis Module, Prediction Analysis Module and Knowledge Learning Module.
Data Analysis Module usually adopts multiple data analysis tools to analyze radar structure design data produced in different phases of radar structure design, process, production, and manipulation. This module is also useful for antenna design model training.

Prediction Analysis Module is used to diagnose and prediction radar structure design products. In combination with Data Analysis Module, this module can carry out antenna design fault prediction and antenna structure design optimization recommendation in real time, so as to provide antenna designer with re-design or design optimization decision support.

Knowledge Learning Module is designed to implement rapid radar structure design reasoning, learning and training with the aid of well-established radar antenna design knowledge base, and can improve radar antenna design capability in turn.

4.3. Interaction Layer
Interaction Layer is used to fuse physical radar antenna structure and virtual radar antenna structure for realizing final physical-virtual integration and bilateral control.

5. Radar structure design optimization based on RSDM

![Radar Structure Design Optimization Based on RSDM](image)

There are some problems in radar structure design optimization, such as high variable coupling, lack of parameter data and data access difficulty. For example, when radar is mechanically rotating, antenna array rotation is an important factor of structural fatigue of servo mechanism, which greatly affects the structural design of servo mechanism. However, there are many factors that influence the array rotation,
and these factors are coupled with each other and form a complex nonlinear function with the array rotation. Thus, traditional modelling methods are insufficient to create an accurate servo model.

Using RSDM model based on digital twin concept, physical data (including antenna mass, rotation speed, rotation direction, etc.) and virtual data (such as buffer pressure, efficiency coefficient, etc.) related to antenna rotation can be obtained, and physical-virtual data fusion can be carried out to accurately predict the transmission pressure load of antenna array, and then the structure optimization of servo mechanism can be calculated to achieve multiple benefits like reliability improvement, SWaP decrease.

In contrast, traditional radar structure design optimization needs a lot of manpower, resources and actually-measured data. Based on RSDM model, the structural design simulation can be carried out by combining the historical structure test cases and measured data, and the actual test environment parameters can be input into the radar structural design model, thus greatly simplifying the design optimization steps and improving the design accuracy and efficiency. After radar structure design optimization is completed, the design optimization can be evaluated and feedback based on RSDM model, leading to closed-loop optimization. Thus, an iteratively optimized radar structure design scheme will be generated.

6. Knowledge management based on RSDM
Radar structure design knowledge is usually implicit and hidden in a large number of data and facts, and rarely explicit. Professional knowledge mining systems and tools are needed for knowledge discovery. However, the current structural design knowledge mining is only limited to oral heritage or the structure design documentations accumulated in the enterprise for a long time. On the one hand, stored structure design data is mostly in discrete distribution, non-structural, in lack of integrity, knowledge mining methods are too obsolete with limited mining depth and narrow knowledge scope, leading to insufficient play to rich structure design knowledge wealth accumulated in long history of those world-leading enterprises. On the other hand, knowledge mining does not cover the data in full radar life cycle, especially the diversified data in stages of equipment manufacturing, quality inspection, equipment operation support, equipment disposal.

RSDM model can monitor and collect the radar data in full life cycle, so it is inherently advantageous in design knowledge mining.

With the help of RSDM model, data related to structure design in full radar lifetime can be fed to RSSC, and the hidden structure design knowledge can be mined by data mining tools. In combination with industry knowledge, various radar structure design knowledge libraries will be formed, and the running state, technical state, reliability and other data of the running radar equipment in physical space can be recorded, fed back and used in radar structure design in real time. Thus, currently-implemented structure design will be re-evaluated and refined, leading to optimum design ecology.

7. Conclusion
DT-driven RSDM proposed in this paper is aiming at solving several pain points encountered during radar structure design. This model is helpful for radar product innovation with continuous design optimization, efficient design knowledge management and radar R&D cost decrease by creating a digital radar structure twin with dynamic interaction with the physical radar structure counterpart.

Thus, further research and engineering implementation on RSDM are necessary and valuable for realizing a pragmatic Cyber-Physical System.

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