A DT-RSDM Model

Linxi Li*
Nanjing Glarun Defense System Co., Ltd, Nanjing, China
*Corresponding author: tombrain@163.com

Abstract—With rapid development of Digital Twin (DT), it seems that DT is vital to realize Cyber-Physical System (CPS) with the aid of dynamic interaction between digital twin and physical counterpart. In radar applications, digital twin can solve inherent shortfalls in radar structure design including ideal design description, poor dynamic interaction and limited implementation extension. Thus, a new DT-driven 5S Radar Structure Design Model (DT-RSDM) is proposed in this paper, focusing on improving radar structure design effectiveness and efficiency by employing iterative design optimization, design knowledge management.

1. INTRODUCTION
With continuous advance of new emerging techniques, like cloud computing and AI, many countries have presented smart manufacturing strategies including Industry 4.0, Made in China 2025 to promote the industry transformation. To realize smart manufacturing, so-called Cyber Physical System (CPS) is proposed to create inter-connection and real-time integration between physical entities and virtual entities [1], while Digital Twin (DT) seems to be the vital to realize CPS.

Digital Twin concept can be traced to Apollo program in 1969, while the formal Digital Twin concept is widely considered to be first introduced by Prof. Michael Grieve in 2002 [2].

In 2012, AFRL and NASA jointly proposed the concept of “Aircraft Digital Twin” for the first time [3-7]. After then, many world-first-class companies have proposed or implemented various DT-driven smart manufacturing solutions, such as Siemens, PTC, Dassault, Lockheed Martin, Raytheon, Thales, etc. Among them, Siemens focuses on the digital twin of manufacturing system, PTC uses digital twin to establish closed-loop product development process. Raytheon Co. creates Advanced Radars Enterprise Sustainment Model (ARESM) to design more supportable and reliable radar architectures [8]. Dassault verifies the interactive integration of airborne radar products and digital twin based on 3DExperience platform [9]. Taking two AESA radars including Sea Fire and Ground Fire as example, Thales Group built a mechanical-electrical-thermal digital twin model, which is proven to be able to significantly enhance collaborative design capability in means of model transfer throughout the whole development process, from initial radar requirement development, radar architecture design, telecommunication design, structure design and design support [10].

Based on previous literatures [11-13], this paper describes Digital Twin as a multi-disciplinary, multi-physical-quantity, multi-time-scale, multi-probability simulation model, which combines historical data and real-time data, and creates digital mapping of physical entities in virtual world, so as to simulate, monitor, diagnose, predict and control the physical entities in the whole lifetime.
2. PROBLEM ANALYSIS
With rapid development of Digital Twin concept, its application fields have been extended to many fields, such as smart city, smart energy, smart healthcare, smart workshop, smart manufacturing and so on [18-19].

As high-end electronic equipment with complexity, radar is widely used in defense, earth observation, ATC, navigation, public security. Many modeling tools like ANSYS, CAE, FEA are adopted to realize mapping of physical radar structure and then digital structure design of radar products.

But, there exist several problems in digital radar structure design, including ideal design, bad real-time performance and insufficient digitalization.

In order to address the above-mentioned problems in digital radar structure design activities, this paper proposes a new DT-driven DT-RSDM radar structure design model, which can effectively fuse and manage the dynamic data from multiple sources in the whole radar lifecycle, iteratively optimize the radar structure design, implement multi-source knowledge mining towards radar structure design knowledge engineering.

3. DT-RSDM COMPONENT
In order to meet the requirements of radar structure design in Digital Twin environment, DT-RSDM radar structure design model driven by digital twin concept is proposed in this paper, whose components consist of Physical Radar Structure (PRS), Virtual Radar Structure (VRS), Structure Design Services (SDS), Radar System Structure Cloud (RSSC) and Structure Design Model Support (SDMS).

![Figure 1. DT-RSDM Radar Structure Design Model](image)

Physical Radar Structure (PRS) is serving as the basis of DT-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, DT-RSDM can be constructed hierarchically. For example, for radar units, an unit-structure-level DT-RSDM is constructed to carry out unit performance monitoring, unit fault prediction, unit maintenance & repair. While for the radar system, a radar-system-level DT-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 behavior response of PRS through physical models, geometric models, behavior 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 DT-RSDM operation, such as model simulation & verification service, data mining integration & analysis service, model interconnection service, fault prediction service and risk assessment service etc. DRS services are generated by all kinds of data, models, algorithms and simulations generated in the process of DT-RSDM operation.

Radar System Structure Cloud (RSSC) is the driving engine of DT-RSDM. It interacts with PRS, VRS, SDS and DMS components in real time to obtain physical data, running data of radar antenna. 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.

Structure Design Model Support (SDMS) is the operation support and application extension of DT-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 DT-RSDM applications beyond structural design, such as digital radar life cycle management, cooperative design running through full industry chain and full value chain.

Thus, DT-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 [14].

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

4. RSSC AS THE DRIVING ENGINE

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 [15].

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 (Hadoop etc.) 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 [16].

5. DESIGN OPTIMIZATION BASED ON DT-RSDM

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 modeling methods are insufficient to create an accurate servo model.

Using DT-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 DT-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 fed back based on DT-RSDM model, leading to closed-loop optimization. Finally, an iteratively optimized radar structure design scheme will be generated.

6. RADAR STRUCTURE FAULT PREDICTION & MAINTENANCE

At the early stage of digital twin concept development, digital twin was focusing on aircraft airframe fault diagnosis and further maintenance. As a complex product, radar is designed with multiple subsystems, hundreds of units, thousands or ten thousand of modules, leading to an extremely complex structure [26-28].

Thus, radar structure fault prediction and safe manipulation with high-fidelity, dynamically-updated models are vital to radar equipment. While, lack of real-time data becomes the Achilles heel in radar structure fault prediction.
By creating multiple three-dimension radar electro-mechanical models and establishing typical radar fault libraries based on historical statistics data and field test data, DT-RSDM can create a multi-physics and multi-stress simulation model in radar system level, whose key physical parameters, stress models, assembly relationship are capable of being corrected based on various field test results. Finally, a Reference Fault Prediction Model (RFPM) of radar structure is formed.

In radar manipulation phases, continuous physical-virtual data exchange is helpful for iterative RFPM correction, leading to more and more precise description of the physical radar structure. At the same time, un-interruptedly updated radar structure manipulation data, fault data, maintenance data are also able to be used for calculating radar structure fatigue, predicting radar structure lifetime and presenting maintenance decision instructions.

7. KNOWLEDGE MANAGEMENT BASED ON DT-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 [17].

DT-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 DT-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.

8. CONCLUSION

As an emerging and promising technology helpful for smart manufacturing, Digital Twin can deeply integrate physical space and virtual space to realize full-product-chain integration, full-lifetime-management and full-value-chain cooperation.

DT-driven DT-RSDM proposed in this paper aims at solving several pain points encountered in radar structure design. DT-RSDM model composition is introduced and its driving engine RSSC is especially discussed. This model is helpful for radar product innovation with iterative 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.

Although a new model framework for implementing radar structure design in DT environment, it is just a concept model to describe the architecture of radar structure design system with digital twin engine, while related model implementations like modeling language, model develop tools are not discussed in this paper.

Thus, further research on DT-RSDM, especially concept engineering, multi-model fusion and control, model security protection and, AR/VR/MR-based physical-virtual interaction approaches, model implementations are necessary and highly recommended for realizing a pragmatic Cyber-Physical System.
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