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A Review of Digital Twin Technology Applications in Marine Engineering

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Abstract

The purpose of this review paper is to explore the application of digital twin technology in marine engineering. Firstly, the current status and outlook of marine engineering applications, and the definition and development status of digital twin technology are presented. Then the applications of digital twin technology in marine engineering are described in detail, including conceptual studies in ship design, structure and operation, specific cases in ship engine and sensor diagnostics, motion prediction, etc. Then, the advantages and challenges of digital twin technology in marine engineering are summarized, and future directions for development are proposed. This review paper aims to provide a valuable reference for practitioners and researchers in the field of marine engineering.

Keywords

Digital Twins; Marine Engineering; Development History; Application.

1. Introduction

With the rapid development of modern science and technology, digital twin (DT) technology as a new type of technology is widely used in different fields, including manufacturing, transportation, medical and military. In the field of marine engineering, DT technology is also widely explored and applied, and it can provide efficient and accurate data support for the design, construction, operation and maintenance of marine engineering.

This paper will introduce the application of DT technology in marine engineering. Chapter 2 will briefly introduce the current status and future development trend of marine engineering to provide background and foundation for the subsequent application of DT technology. Chapter 3 will introduce the development history and definition of DT technology to provide readers with the basic knowledge to understand DT technology. Chapter 4 will focus on the application of DT technology in marine engineering, including the design, construction, operation and maintenance of marine engineering, and discuss the advantages and application effects of DT technology in these aspects. Chapter 5 will provide an in-depth discussion on the advantages and challenges of applying DT technology in marine engineering, with a view to providing readers with a more comprehensive and in-depth understanding.

The main purpose of this paper is to provide readers with case studies and analysis of the application of DT technology in marine engineering in order to help readers better understand the application and effects of DT technology in practice, and to explore the development direction and challenges of DT technology in the future.

2. Current Status and Prospect of Application in Marine Engineering

Marine engineering is the application of engineering and marine science knowledge for engineering projects in marine resource development, marine environmental protection, maritime transportation

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and military defense. Its significance is to develop and utilize marine resources to solve the problems of energy, food, material and environment faced by human development and survival.

Marine engineering faces many application dilemmas status quo, such as the complexity and variability of marine environment, the contradiction between marine resources development and environmental protection, and the limitation of marine engineering technology. These dilemmas have a profound impact on the feasibility, sustainability, safety, efficiency and market demand of marine engineering.

The size, direction and frequency of waves and currents can cause damage to marine engineering. The depth of the ocean can affect the construction and operation of marine engineering, and in deeper waters, the construction and maintenance of marine engineering requires higher technology and more expensive equipment. The salinity and temperature of the seawater can also affect the design and construction of marine engineering. High salinity seawater may cause corrosion and wear to the structures and materials of offshore engineering [1]. Changes in seawater temperature can also have an impact on marine engineering, for example, increased seawater temperature may lead to expansion and deformation of marine engineering structures.

The cost and risk of offshore engineering are also important factors limiting its development, especially in the fields of offshore wind power, offshore oil and gas exploration and development, etc. The construction and operation of these projects often require significant financial and technical investment [2]. Offshore projects are usually more expensive than onshore projects, mainly because of the need to face more complex marine environments and higher safety standards. For example, offshore wind power requires more corrosion-resistant materials, larger wind turbines and more expensive installation equipment, all of which contribute to the high costs. In addition, the operation and maintenance costs of offshore projects are also high because the equipment to be maintained is often in harsher marine environments [3].

Marine engineering is in turn exposed to natural and man-made risks. Natural risks include waves, currents, storms and marine life. For example, marine life may attach to the structures of marine engineering, causing corrosion and biological wear and tear. In addition, large marine organisms may also collide with marine engineering, causing structural damage. Man-made risks include technical problems, equipment failure and personnel safety, which can lead to serious accidents and losses [4]. Cost and risk have a profound impact on the development of marine engineering. First, high costs and risks can make the sustainability of marine engineering challenging. Therefore, more efficient technologies and strategies need to be sought to reduce costs and risks, and to improve the sustainability of offshore engineering. Second, cost and risk are also important drivers of technological advances and market demand for offshore engineering. Technological advances can help reduce costs and risks, and improve the efficiency and safety of marine engineering [5]. Market demand, in turn, can promote the development of offshore engineering and drive more investment and development of offshore engineering.

Therefore, the limitations of the dilemma of marine engineering applications need to be continuously broken through technological innovation and equipment upgrade, etc. to improve the efficiency, safety, reliability and maintainability of the project. And DT technology can precisely solve these dilemmas.

3. What is DT

3.1 Concept and Characteristics of DT Technology.

DT technology is a technology based on digital modeling, simulation and data analysis for creating virtual replicas in the physical world. It provides insight into the operation of physical systems and optimization solutions by digitally representing information about the geometry, material properties, kinematics and dynamics of physical systems and simulating and predicting them using computer simulation and analysis techniques.

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The core of DT technology is the mapping relationship between the physical system and the virtual system, i.e., mapping all the information and behaviors of the physical system into the virtual system and maintaining the consistency between the two in terms of operation and behavior. DT technology enables real-time monitoring, fault diagnosis, performance optimization and predictive analysis of the physical system, thus improving its operational efficiency and reliability. With the following features:

(1) Physical entities can be simulated in a digital environment: DT technology can collect and build digital models of the operational status, behavior and performance of physical entities, and then simulate them in a digital environment to predict their future behavior and performance, as well as optimize their design and operation.

(2) Enables real-time monitoring and control: DT technology enables real-time monitoring of physical entities through sensors and other devices in order to quickly identify and resolve any potential problems and to be able to control the operation of physical entities.

(3) Enables optimal decision making and resource management: DT technology can provide enterprises and organizations with real-time decision support and resource management tools that enable them to better understand the performance of their products, services and processes and enable timely improvements and optimizations.

(4) Accelerate product and service development: DT technologies can help enterprises and organizations test and verify the performance of their products and services in a digital environment, thereby accelerating their development speed and reducing development costs.

(5) Improve the quality and reliability of products and services: DT technology can help companies and organizations better understand the performance of their products and services, thereby improving their quality and reliability while reducing production and maintenance costs.

3.2 History and Status of DT Technology Development

The idea of using twin models dates back to the 1960s, when NASA began using computers to model spacecraft for flight simulation and monitoring in the Apollo program [6]. But the DT model was first introduced by Grieves in 2002 in his "Product Lifecycle Management (PLM)" course. It is defined as "a set of virtual information structures, ranging from the micro-atomic level to the macro-geometric level, that comprehensively describe a potential or actual physically manufactured product. In the best case, any information that can be obtained by examining a physically manufactured product can be obtained from its DT". At this point, the basic elements of DT technology are already in place, see Fig. 1: real space, virtual space, and a mechanism for linking data/information flow between the two [7]. After the initial Mirror Space Model (MSM) and Information Mirror Model (IMM) names, the model was finally dubbed "DT" by NASA in 2010 and defines DT for space vehicles as "DT is an integrated multi-physics field, multi-scale, probabilistic simulation process that reflects the state of the corresponding twin in time based on historical vehicle or system data, real-time sensor data, and physical models."[8].In 2014, Grieves published a white paper on DT, which speculates that the basic DT model consists of three main components: (1) physical entities in real space, (2) virtual products in virtual space, and (3) the connections of data and information that link the two together [9]. In 2016, Siemens released its DT platform "Product Lifecycle Management Software" and announced that DT will be the core of the company's future strategy. In 2017, Tao Feiyi proposed the concept of DT workshop and discussed the characteristics, composition and operation mechanism of DT workshop and key technologies, which provided theoretical support for the application of DT in manufacturing industry.In 2017 and 2018, Gartner listed DT as one of the ten most promising technology trends for the next decade [10].Later, Tao Fei et al. extended the original three-dimensional DT model by adding two dimensions (DT data and services) and proposed a five-dimensional DT model : physical entities, virtual entities, twin data, service systems and their connections in various aspects , which promoted further applications of DT in more fields.

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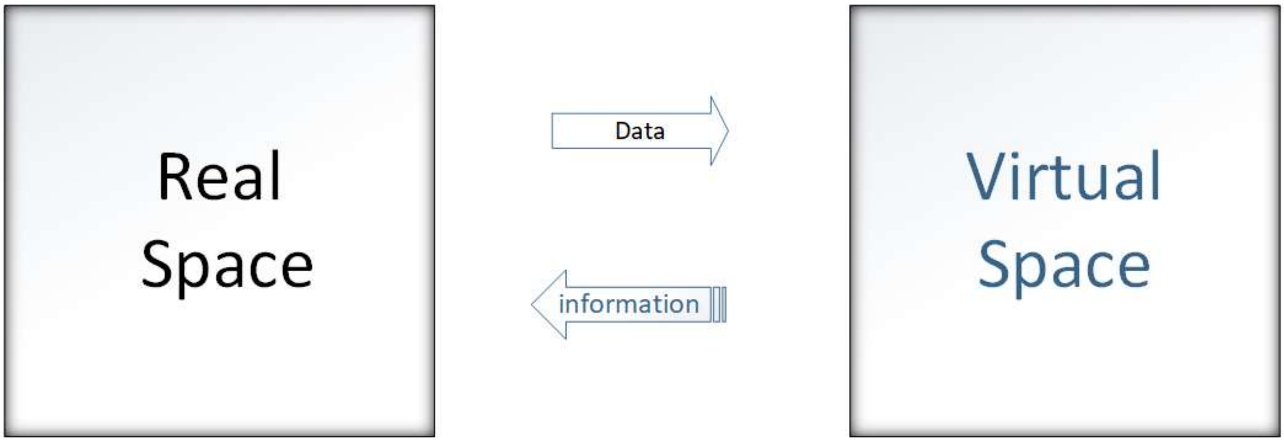

Fig. 1 Digital Twin Fundamentals

The development of computer technology and the expansion of application areas, including cloud computing, high-performance processors, the Internet of Things (IoT), Big Data Analytics (BDA), Artificial Intelligence (AI), Blockchain technology, etc., have facilitated the digital adoption of DT in ten major industrial sectors: (1) aerospace, (2) manufacturing, (3) healthcare, (4) energy, (5) automotive, (6) oil, (7) public sector, (8) mining, (9) agriculture, and (10) marine [11].

4. DT Applications in Marine Engineering

From 2017-2018, conceptual studies on the design , structure and operation of DT ships have been proposed by scholars [12,13,14]. And the subsequent studies cover the whole life cycle of a ship. For example, Kan Wang investigated the characteristic scenarios and key parameters of ship engine systems and ship cargo containers during operation by a DT-based approach [15]. D. Rogers et al. then developed a model of an engine control system for the measurement chain associated with a closed-loop engine combustion controller, which in combination with DT can lead to carbon emission reductions in marine engine systems [16]. Bin Huang proposed a DT-based 5G converged shipbuilding network, which effectively improves the efficiency of shipyard 5G converged networks through an efficient and reliable multi-mode terminal access and multi-service quality management method [17]. Andrea Coraddu et al. constructed a hybrid physical and data drive model for simulating the dynamic state of a four-stroke marine diesel engine , and demonstrated the feasibility of reducing emissions from marine dual-fuel engines based on a DT data-driven monitoring model [18,19].Lampros Nikolopoulos et al. successfully constructed a DT model that allows the user to simulate the response to changes in ship geometric design variables under uncertainty [20]. Qingcai Wu et al. proposed and implemented an innovative application framework for DT-based ship smart manufacturing system [21]. Eric VanDerHorn proposes a DT for monitoring and predicting ship-specific fatigue damage, improving ship reliability [22]. Fonseca et al. used existing data standards and web technologies to model and develop an open framework DT ships that can be linked to services such as visualization, simulation and remote control [23]. Sokratis Stoumpos et al. investigated a DT-based sensor diagnosis and health management for marine dual-fuel engines that can facilitate engine condition assessment and self-correction of engine sensor anomalies [24]. Matthew L. Schirmann et al. constructed a DT model for ship motion prediction based on machine learning methods, shipboard measurements, and widely available wave forecast and backcast data, with the aim of achieving safer and more efficient ship operations [25].

In marine energy, as wind turbines continue to grow in size, they are increasingly deployed offshore, which increases the challenges of operating and maintaining wind turbines (OWTs).DT technology has become a key technology for managing offshore wind farms to improve safety and reduce operation and maintenance costs. Researchers have proposed various DT-based applications to address the various challenges in offshore wind farm management. For example, the Unity3D-based

DT platform is used to predict potential failures of OWT components and present them in an augmented reality format [26]. A DT-based information update framework for offshore wind structure reliability analysis and remaining service life prediction [27]. and DT-based multi-degree-of-freedom torsion model for predicting the remaining service life of gearboxes in floating offshore wind turbine drive trains, etc [28]. In addition, DT can be applied to uncertain fatigue analysis of OWT structures, online load monitoring and remaining service life assessment, FOWT mooring cable tension monitoring, wind turbine blade structure damage source location and offshore wind turbine conduit frame structure health monitoring, etc [29,30,31,32,33]. In addition, DT-based wind turbine bearing fault diagnosis method is also proposed to improve the accuracy and stability of wind turbine bearing fault diagnosis.

DT technology also has great potential for maritime military applications. Autonomous maritime surface vessels developed with DT technology can meet the growing demands for water navigation and maritime security [34]. In addition, to counter the security threat of submarines, Peng Wang et al. proposed a digital twin and stochastic finite set based sensor control method for more effective anti-submarine warfare [35]. In the marine environment, Peishi Jiang et al. have developed a digital twin of the Earth's coastline that can be used for sea level measurements and risk avoidance [36]. Meanwhile, Henriksen et al. constructed hydrological information and predicted DT for climate change adaptation, water resources management and disaster risk reduction [37].

5. Advantages and Challenges of DT Technology in Offshore Engineering

5.1 Advantages.

Through the study of DT application in marine engineering, we found that DT has the following four advantages. These advantages make DT widely used and promoted, which is expected to further improve the efficiency and reliability of marine engineering and promote the sustainable development of marine economy.

(1) Cost and risk reduction: Traditional marine engineering testing and trials are costly and risky, while the use of DT technology allows testing and optimization in numerical models, predicting possible problems and making corrections, thus reducing the cost and risk of actual testing and trials. DT technology can also improve the design quality and efficiency of marine engineering, reduce construction and operation costs, and also reduce the actual testing and The risk of human casualties and environmental pollution caused by the tests.

(2) Improving efficiency and accuracy: The rapid simulation and optimization of digital models can predict the operation status and effect of the system, while comparing different solutions and selecting the optimal one. DT technology effectively shortens the R&D cycle, reduces trial and error costs, monitors the operation status of marine engineering in real time, and improves the efficiency and accuracy of operation and maintenance. In a comprehensive view, the application of DT technology in marine engineering can greatly improve the efficiency and accuracy, and provide powerful support for the R&D and operation and maintenance of marine engineering.

(3) Real-time monitoring and prediction: DT technology can realize real-time monitoring and prediction of the operation of marine platforms, ships, submarine pipelines, etc. Real-time data are collected using sensors and other devices, and processed and analyzed in digital models to quickly predict possible failures or abnormalities and provide targeted solutions to avoid unnecessary losses and risks caused by them. The digital model can also perform simulation experiments to predict the operational status and effect of the system, providing more accurate prediction and optimization solutions for marine engineering.

(4) Optimize design and maintenance: The application of DT technology in marine engineering helps optimize design and maintenance, thus improving performance and lifetime. The digital model can compare different solutions in the design stage and determine the optimal design. At the same time, digital models can simulate the operating conditions in the actual environment and evaluate the

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reliability and lifetime of the system for better maintenance. the application of DT technology can also optimize the operating costs of marine engineering and improve efficiency and safety.

5.2 The Challenge.

However, we may face some challenges when implementing DT methods, e.g., with the continuous development of marine engineering, more and more DT techniques are applied in marine related fields. However, there are some challenges when implementing DT techniques, such as data acquisition and processing, model accuracy, computational resource requirements and data security:

(1) Data acquisition and processing: DT technology requires a large amount of data to build numerical models, but due to the complexity and uncertainty of the ocean environment, it is challenging to acquire accurate and complete data. In addition, data processing and analysis are time and resource consuming. To solve these problems, efficient data acquisition methods and advanced data processing techniques are needed to improve data quality and processing efficiency. At the same time, a perfect data management system needs to be established to ensure the integrity, accuracy and security of the data.

(2) Model accuracy: Marine engineering involves many different factors, such as ocean climate, waves, submarine topography and marine ecosystem, which have a great impact on the accuracy and reliability of the digital model. Also, the operational status and performance of the marine engineering equipment needs to be considered, which requires the collection and integration of a large amount of real-time data. In order to build accurate numerical models, accurate data and high-quality model construction methods need to be used. In addition, model validation and correction are needed to ensure the reliability and validity of the digital model.

(3) Computational resource requirements: DT technology requires a large amount of computational resources for the simulation and optimization of marine engineering. High-performance computers and large amount of storage space are required for the creation and simulation of digital models. For large marine engineering projects, this may require more advanced computational resources and more complex simulation algorithms. In addition, for DT applications of real-time monitoring and fault prediction, a large amount of real-time data needs to be processed, which also requires corresponding computational resources and storage space. Therefore, in order to effectively implement DT technology, it is necessary to invest in advanced computing resources and storage technologies to improve computational efficiency and processing speed.

(4) Data security: In the field of marine engineering, a large amount of sensitive data needs to be collected, processed and analyzed, such as the structure and operation of marine platforms, ships and submarine pipelines. However, the security and privacy protection of these data is an important challenge, because the leakage or improper use of these data may cause serious economic and reputational losses to enterprises and individuals. Data security includes data confidentiality, integrity and availability and needs to be ensured by using advanced security technologies. For example, use technologies such as encryption, access control and authentication, firewalls, intrusion detection and preventive measures to protect data security and privacy protection. Also, establishing transparent data use and sharing policies is an important means of ensuring data security.

6. Conclusion

This paper provides an in-depth discussion and analysis of the application of DT technology in marine engineering. Through the introduction of the current situation of marine engineering and the definition and development history of DT technology, this paper provides the readers with the foundation and background knowledge. By introducing and analyzing the application cases of DT technology in marine engineering, this paper shows the application scenarios and effects of DT technology in the field of marine engineering. Also, this paper discusses the advantages and challenges of applying DT technology in marine engineering.

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Overall, DT technology, as an emerging technical tool, has a broad application prospect in the field of marine engineering.DT technology can provide powerful support for the design, construction, operation and maintenance of marine engineering, improve engineering quality and efficiency, and reduce engineering risks and costs through digital simulation, intelligent analysis and other technical means. However, DT technology still faces some challenges in the field of marine engineering, such as difficulties in data acquisition and processing, insufficient algorithm research and application.

In response to these challenges, future research can be carried out in the following aspects: (a) further improve the theoretical basis and algorithm model of DT technology to improve its application effect and stability; (b) strengthen the combination of DT technology and traditional engineering technology to give full play to the advantages and value of DT technology; (c) strengthen the standardization and standardization of DT technology in the field of marine engineering to promote the application and promotion. Through these efforts, the application of DT technology in the field of marine engineering will usher in a broader development prospect.

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