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Digital Twin Technology in Marine Power System Operation and Maintenance

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Abstract. The marine power system is the core for propulsion, generating electricity and supporting operation of main equipment. Its operation and maintenance is therefore particularly important. However, traditional operation and maintenance approaches have certain deficiencies in equipment condition monitoring, anomaly detection, and maintenance decision-making, and remain reactive rather than proactive. Digital twin technology applied to intelligent operation and maintenance of the marine power system can identify faults in advance and suggest maintenance decisions. This paper adopts the methods of literature review and case analysis to summarise the applications of digital twin technology in the monitoring of marine power system operations, fault diagnosis and predictive maintenance. Digital twin technology connects physical devices with virtual models and plays a key role in monitoring, analysing and predicting the operating status of equipment as well as providing intelligent maintenance decisions. However, the current application still faces issues such as difficulties in data acquisition and sharing, single models and insufficient engineering verification. The future will require progress in areas such as standardising data formats, uploading to globally shared cloud platforms, upgrading hybrid virtual models, and conducting long-term experimental verification.

Keywords: marine power system, digital twin, status monitoring, fault diagnosis, predictive maintenance

1. Introduction

The marine power system is the core for propulsion, generating electricity and supporting operation of main equipment. Its operating status directly affects the safety of vessel navigation, equipment reliability and energy utilisation efficiency. Currently, the operation and maintenance of the marine power system still rely heavily on regular inspections, human experience-based judgements and post-fault repairs. In complex operating environments, there may be issues such as insufficient perception of equipment status, untimely fault detection and delayed maintenance decisions. However, digital twin technology can connect physical devices with virtual models, through real-time data to achieve equipment status synchronisation, analysis and dynamic evaluation. It allows operators to access a digital replica of the vessel to monitor the vessel and its machinery in real time. It also provides new technical support for the intelligent operation and maintenance of the marine power system [1].

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Current research has applied digital twin to the status monitoring, fault diagnosis and predictive maintenance of the marine power system [2]. In terms of status monitoring, research usually uses sensor data like temperature, pressure, rotational speed, vibration and torque to update virtual models. This enables the model to reflect changes in operational status of the power equipment. In terms of fault diagnosis, digital twin can compare the actual monitoring data with the model calculation and identify abnormal status based on key parameters and deviations. Some research has also combined mechanism models with data-driven methods to improve the models' adaptive capacity to complex operating status and changes in equipment status [3, 4]. In addition, existing research has attempted to use digital twin to analyse the dynamic responses and status changes of the propulsion system in order to provide foundations for equipment health and predictive maintenance [5, 6]. However, related research still faces issues such as insufficient long-term operational data and fault samples, difficulties in dynamically updating models and the evaluation methods lack unified standards. Part of the research carries out verifications in experimental platforms or simulation environments. The long-term applicability still needs further research under the actual operating conditions like changes in sea conditions, the ageing of equipment and load fluctuations.

This paper adopts the methods of literature review and case analysis to analyse digital twin applications in marine power system operation and maintenance. The focus is on discussing the fundamental technical principles and processes of digital twin, and it illustrates applications in operational status monitoring, fault diagnosis and predictive maintenance with typical research. On this basis, this paper further analyses the issues of marine power system digital twins in operational data, model construction and engineering verification, and then discusses the corresponding development direction.

2. The technical foundation of digital twin for marine power systems

2.1. The basic concept of digital twins

Digital twins establish a connection between physical entities and virtual models that correspond through operational data, enabling the virtual models to reflect the actual operational status of the physical equipment [7]. Digital twin systems generally consist of physical equipment, data collection and transmission, virtual models and application services. The physical equipment is responsible for generating actual operational data, and the equipment status is transferred to the digital end in the data collection and transmission processes. Then the virtual model updates the operational status according to the received data and further provides a foundation for subsequent analysis. For marine power systems, diesel engines, propulsion units, generator sets, and other auxiliary equipment continuously generate status information such as temperature, pressure, rotational speed, and vibration during operation. This data is collected by sensors and transmitted to the digital end. It enables the virtual model to update in accordance with changes in the equipment operational status. For marine power equipment, a digital twin is not a static 3D model or simulation model that is established separately, but requires maintaining the data connection between the physical equipment and the virtual model. When the operating status of the equipment changes, relevant data can be promptly input into the virtual system and then used to update the model's status or associated parameters. In this way, the virtual model can not only represent the operational status of the equipment at a specific moment but also record changes in status during different operational stages. It provides the basis for equipment status comparison and analysis of anomalies. When parameters like temperature, pressure, vibration and rotational speed exceed the thresholds, the

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digital end can use the results of models to estimate whether the equipment's status deviates from the normal operating range and subsequently provide a data foundation for fault identification and maintenance analysis.

The main difference between digital twins and traditional off-line simulations is also reflected in continuous data connection. Traditional simulation is usually based on preset parameters and boundary conditions to calculate and analyse the operational status of equipment under specific conditions. When the equipment ages, the load changes, or the external environment shifts, the original model parameters and input conditions typically need to be readjusted. However, digital twins can use the continuously acquired data during equipment operation to update the model status or related parameters, and then make the virtual model promptly reflect the actual changes of the physical equipment [8]. Therefore, compared with traditional off-line simulations that mainly focused on the analysis of specific conditions, digital twins more emphasise the continuous connection between the model and the actual equipment. It supports long-term status monitoring, fault diagnosis, and operational maintenance of marine power equipment.

2.2. The operation process of a marine power system digital twin

Firstly, the digital twin of the marine power system relies on the continuous acquisition of operational data. Diesel engines, gearboxes, propulsion units and other auxiliary equipment in the ship's engine room can be equipped with various types of sensors to collect operational parameters such as temperature, pressure, rotational speed, vibration and torque. After transmission and necessary preprocessing, this data enters the digital twin model, providing input for updating status of the virtual system and subsequent analysis.

During the model construction process, mechanism models, data-driven models, or a combination of both can be adopted according to the characteristics of the marine power equipment. Mechanism models are mainly used to describe the internal physical relationships and operational laws of the power system. In addition, data-driven models can utilise historical operational data to identify change features that are difficult to describe with explicit physical equations under complex conditions [3, 4]. Combining physical mechanisms with operational data, it is possible to maintain the physical meaning of the model while improving the adaptability of the model to changes in actual operational status [3]. When new sensor data are input into the system, the model status or related parameters can be corrected, and the virtual model can be updated in line with the operation of the physical equipment.

After completing the model update, the digital twin can compare the model's computational results with actual monitoring data to identify abnormal operational status. When abnormal changes occur in key parameters such as temperature, pressure, vibration and rotational speed, the model's results can be used to further analyse potential faults and their impacts. As the operational data keeps accumulating, the digital twin model can also be continuously calibrated to improve assessment of the status and fault diagnosis under different operational conditions. Finally, the relevant analysis results are fed back to marine operation and maintenance personnel to provide a basis for equipment status monitoring, fault diagnosis, and subsequent maintenance planning.

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3. Typical operation and maintenance applications and case analysis

3.1. Operational status monitoring

The marine power system continuously generates information on position, speed, vibration and other operational status during the operational process. A digital twin can use real-time collected data to update a virtual model. It also compares the model's calculated results with the actual operational status, thereby observing changes in the equipment and marine motion status. As for the propulsion system, the digital twin model usually maintains a relatively consistent trend of change with the actual system when critical components like the propeller operate normally. If an anomaly occurs in the propulsion system, the deviation between the model's estimated results and the actual operational status may change, so these differences of status can provide a reference for anomaly identification.

Hasan and other researchers focused on the ship propeller propulsion system, conducting digital twin simulations of the ship's path, position, and motion status during the operational process [5]. Figure 1 shows the experimental results under normal propeller operation. The left picture compares the ship motion path obtained from the digital twin model with the actual operational path. The right picture presents the position estimation errors in the x and y directions. The results indicate that the trajectory from the digital twin simulation generally maintains good consistency with the actual trajectory and the position errors remain within a relatively stable range under normal operating conditions [5]. This demonstrates that the digital twin model can continuously update the ship's motion status based on real-time operational data and thereby reflect the fundamental status characteristics during normal operation of the propulsion system.

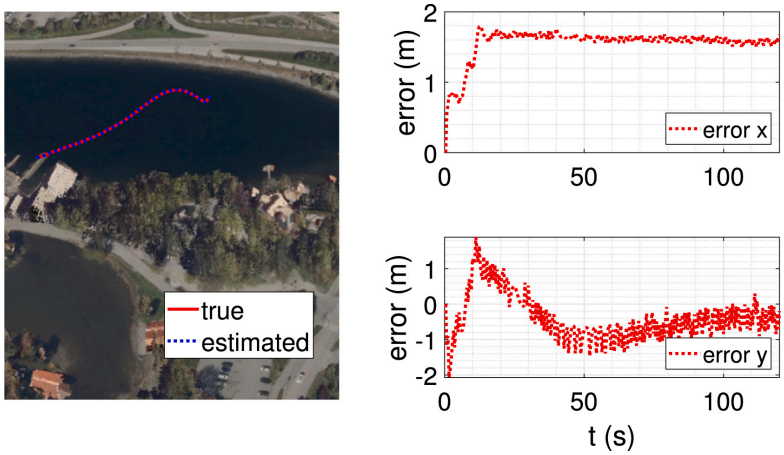

Figure 1. Comparison between the actual vessel trajectory and digital twin estimates under normal operation [5]

Figure 2 further illustrates the operational results after the propeller has malfunctioned. The figure indicates the moment when the fault occurred and shows the changes between the actual positions and the model-estimated positions before and after the fault. Compared with normal operational status, there is a more significant change in the position estimation error after the fault [5]. This deviation cannot be used alone to determine the specific type of fault, but it can serve as an indication of a change in the status of propulsion system. By continuously comparing actual operating data with estimated results of the digital twin model, it can spot changes that are different from the normal situation in time and then provide status information for subsequent fault diagnosis.

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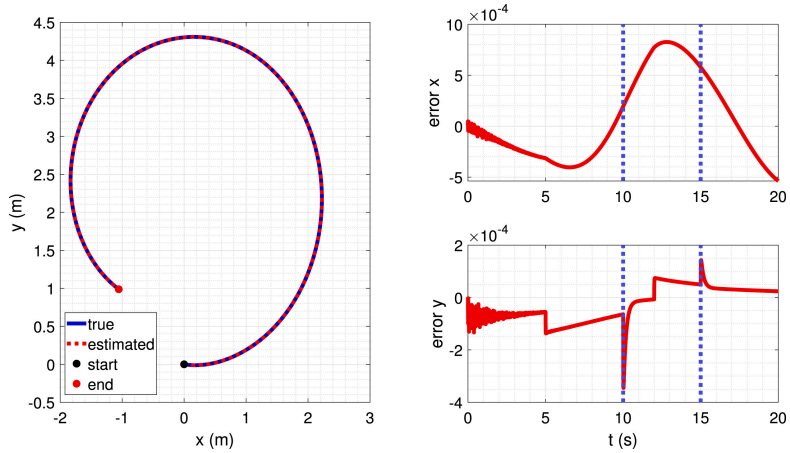

Figure 2. Comparison between the actual vessel trajectory and digital twin estimates under propeller fault conditions [5]

This case indicates that digital twins can not only be used to record the movement process of ships, but also reflect the operational status of the propulsion system through the difference between the actual status and the model-estimated status. However, there are still certain errors between the results of model estimation and actual measurements. In addition to sensor data noise, factors such as external environmental disturbances, model parameter settings and changes in actual operating conditions may also affect the results [5]. Therefore, in actual status monitoring, one cannot merely rely on a single error to determine whether the equipment has malfunctioned. Instead, a comprehensive analysis needs to be conducted by combining other operational parameters and subsequent diagnostic results.

3.2. Fault diagnosis

In the long-term operation of marine power systems, components may experience wear, load variations, and external environmental influences, which then lead to performance reduction or localised faults. A digital twin can integrate sensor data with virtual models to compare the actual operational status of the equipment with the model's estimated status, as well as identify anomalies based on changes in key parameters. Compared with making judgments solely based on a single monitoring parameter, this approach can combine operational data with model analysis results to provide more information for fault identification and status evaluation.

Hasan and others studied ship propeller propulsion systems and used the digital twin model to estimate the parameters associated with propeller faults; changes in these parameters were then used to determine the system's operational status [5]. Under normal operating conditions, the estimated fault parameters should remain close to zero. When a propeller malfunctions, the estimated parameters gradually deviate from the normal status. Therefore, it serves as an important reference for identifying propulsion system faults.

Figure 3 shows the estimated results of fault parameters during normal propeller operation. The estimated value of the parameter generally remains around 0. It indicates that the digital twin model does not detect any significant faults under normal conditions. Figure 4 illustrates the changes in parameters after the propeller has malfunctioned. Following the fault, the relevant parameters gradually increase to approximately 0.1 and 0.5, showing a significant deviation compared to normal conditions [5]. This change indicates that the digital twin model can identify anomalies in

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the operation status of the propulsion system through variations in fault parameters and reflect the differences between different fault states.

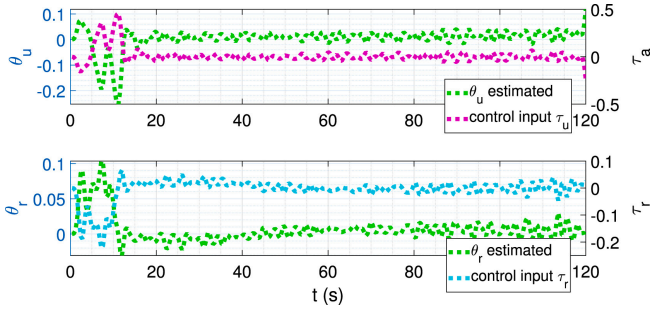

Figure 3. Estimated results of propeller fault parameters under normal operating status [5]

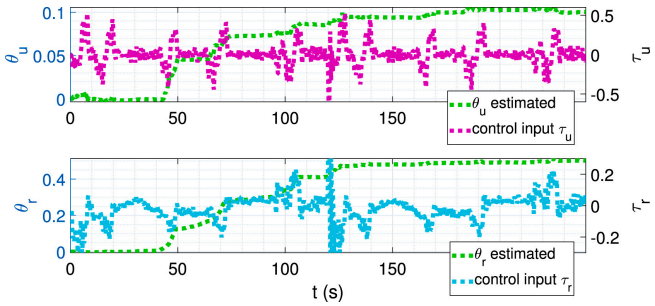

Figure 4. Estimated results of propeller fault parameters under fault status [5]

This case shows that the estimated model results and changes in fault-related parameters of a digital twin can be used to determine whether the propulsion system is abnormal. Most of the fault parameters are used to display changes in the system status. The actual fault diagnosis still requires comprehensive analysis in conjunction with fault types, equipment operating conditions and other monitoring parameters. For maintenance or shutdown decisions, it is also not advisable to rely solely on changes in a single parameter. The decisions should be made based on equipment safety requirements and actual operating status [5].

3.3. Predictive maintenance

Traditional marine maintenance is usually carried out according to a fixed schedule or conducting repairs after an equipment fault occurs. Although these methods are easy to implement, a fixed maintenance cycle cannot fully reflect the actual operating status of the equipment. However, repairs after a fault can easily affect the normal operation of the ship. Predictive maintenance focuses more on the changes in equipment status over time. It analyses current operational information and historical data to assess future operational trends and provides guidance for maintenance before significant faults occur. A digital twin can continuously receive operational data from actual equipment and use virtual models to analyse equipment condition. Thereby it can provide a technical foundation for predictive status and maintenance analysis of the marine power system.

Existing research focused on propulsion systems under propeller-ice interaction conditions, where a digital twin simulation was conducted for the dynamic response of the shaft torque [6]. In this experiment, after the physical system is subjected to external excitation, the sensors record the corresponding torque response, while the digital twin model calculates the response of the power system based on the system input. Figure 5(c), (e), and (g) respectively show the excitation input in

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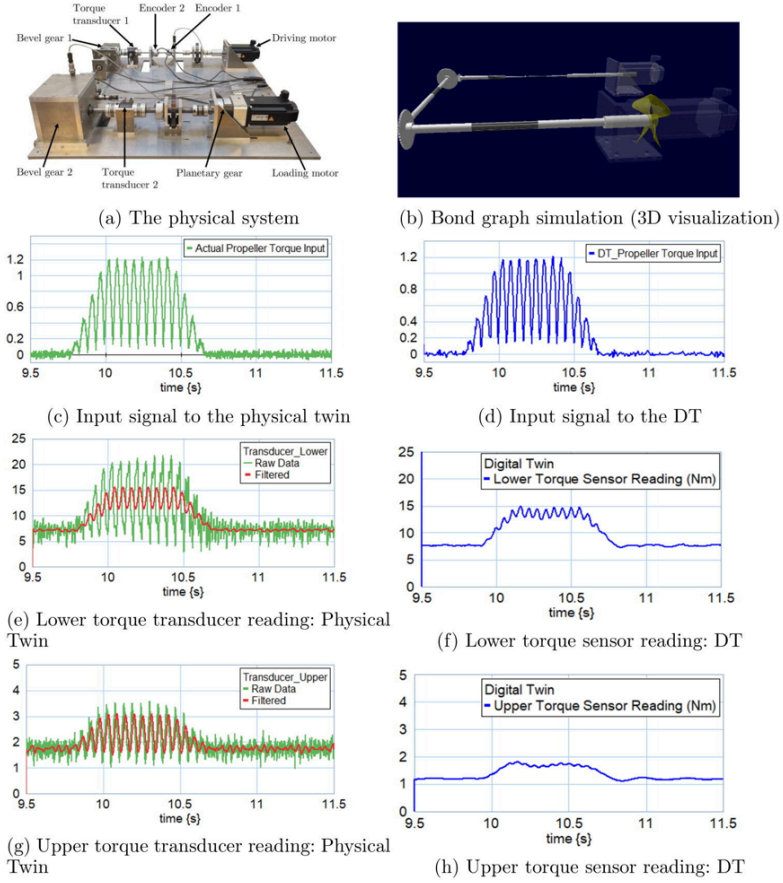
the experiment and the torsional responses obtained at different measurement positions. Figure 5(d), (f), and (h) present the corresponding results obtained from the digital twin model. From the results, under the experimental conditions studied, the digital twin simulation results exhibit a trend of variation that is largely consistent with the actual system response.

Prediction of the dynamic response shows how the power system will respond to different load conditions. When the marine propulsion system is exposed to ice load, load variation or other disturbances, the internal torque and other status parameters of the equipment will change accordingly. If the digital twin model can accurately reflect these changes, its predictions can be compared with the actual operating conditions. When persistent or significant deviations occur between the two, it is possible to further analyse whether the status of equipment has changed and then provide a basis for subsequent health assessment. Therefore, although this case mainly demonstrates the ability of a digital twin to simulate the dynamic response of a power system, this function also provides a foundation for status monitoring and predictive maintenance.



(a) The physical system (b) Bond graph simulation (3D visualization)

(c) Input signal to the physical twin (d) Input signal to the DT

(e) Lower torque transducer reading: Physical Twin (f) Lower torque sensor reading: DT

(g) Upper torque transducer reading: Physical Twin (h) Upper torque sensor reading: DT

Figure 5. Comparison of actual torque response and digital twin simulation results under propeller-ice interaction conditions [6]

However, only the short-term torque response cannot be used to determine when maintenance is needed directly. Predictive maintenance also requires a long-term operational record and data on equipment deterioration to determine whether a change in status is continuous and to distinguish between a normal fluctuation of operation and actual performance decline. Besides, model predictions can be influenced by parameter settings, operating conditions and data quality. Current studies also point out that the relevant digital twin models still require further error analysis,

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repeatability analysis, as well as uncertainty and sensitivity analysis, and a comparison with other modelling methods [6]. Therefore, using digital twins for predictive maintenance in the marine power system depends not only on whether the model can accurately replicate current operating status but also on verifying its ability to predict long-term status changes and equipment degradation.

4. Existing issues and development directions

Digital twins rely on a large amount of continuous and reliable equipment operation data, but the actual operational environment of ships is complex, with differences in the sources, formats and quality of data from different equipment. Additionally, some fault data are difficult to obtain, affecting model training, validation and application. For example, there is a scarcity of representative fault data in the marine environment, yet technologies like fault diagnosis and predictive maintenance require diverse and high-quality fault data as training samples to make accurate assessments [9]. To address issues related to data and information acquisition, data integration and quality improvement should be considered the development direction for digital twins in the operation and maintenance of marine power systems. Standardising data formats for different ship equipment, and establishing a global cloud for data collection, processing and storage, can be applied to digital twin model training.

The components of the marine power system are numerous, and their operation is complex and subject to changes in the sea and ship load. Building a digital twin model that can reflect the current conditions and predict the future state of the equipment is difficult. Many uncertainties occur in the operation of the marine power system, such as equipment wear and ageing, and therefore, it is difficult for mechanistic models with fixed parameters to reflect the actual condition of the equipment [10]. Data-driven models are highly dependent on the coverage of the historical training data. In bad weather, the power output may become too high to meet the demand for reduced power. To improve the continuous update and predictive ability of the model under various conditions, a single model needs to be upgraded to a mechanism-data-driven hybrid model that can offer predictive decisions for the operation and maintenance of marine power systems in the digital twin.

At present, the application of digital twins in the operation and maintenance of the marine power system is still mainly focused on experimental verification, simulation analysis and the study of individual equipment, and the verification cycles are generally short. Because actual ship operations are also influenced by various factors such as sea conditions, load variations and human operation, there is still a certain gap between existing research results and engineering applications under long-term and complex conditions. Experimental research on digital twins in operation and maintenance requires long-term validation, as short-term tests cannot prove that the model can accurately predict equipment ageing and environmental factors. Regarding safety, when digital twins participate in operation and maintenance decision-making, their output recommendations may contain errors, posing a safety risk. Procedures such as permission management, anomaly alerts and manual verification should be implemented to ensure that the digital twin can be manually operated and safely exited when it outputs erroneous decisions or lacks sufficient credibility.

5. Conclusion

Digital twins establish a dynamic connection between marine power equipment and virtual models through operational data, enabling the model to be updated in line with equipment status changes and providing technical support for status monitoring, fault diagnosis, and predictive maintenance of

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marine power systems. Existing research indicates that digital twins can utilise real-time monitoring data and model analysis results to reflect equipment operating status, identify abnormal changes, and further offer references for subsequent status assessments and maintenance planning. The case studies of ship propeller propulsion systems show that digital twin models can track vessel trajectories, estimate fault-related parameters and reproduce the shaft torque responses under propeller-ice interaction conditions, which demonstrates the feasibility of digital twins in typical operation and maintenance scenarios. These applications also indicate that the continuous data connection between physical equipment and virtual models is the foundation for digital twins to support the intelligent operation and maintenance of the marine power system. Meanwhile, their practical application is still affected by factors such as insufficient operational data and fault samples, limited model adaptability, and inadequate long-term engineering verification. In the future, further efforts are needed to improve the quality and sharing capabilities of multi-source operational data, to further enhance the integration of mechanism models with data-driven approaches and to verify the reliability and safety of models under more complex and long-term actual operating conditions. With the continuous improvement of data acquisition, model updating, and engineering verification capabilities, digital twins are expected to play a more stable role in the intelligent operation and maintenance of the marine power system.

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