The Application of Digital Twin Technology in Maritime Vessel Safety Regulation

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Abstract. The potential for the development of digital twin technology is enormous, gradually finding applications in the field of maritime vessel safety regulation. In response to the current issue of poor coordination between physical information and simulation model information during ship navigation, a design proposal combining digital twin technology with maritime safety regulation is put forward. The application of digital twin technology in the field of maritime vessel safety regulation is analyzed, and an architecture for a ship navigation environment monitoring system based on digital twin is constructed. The operational mechanism and key functional components of this system are demonstrated. A digital twin system for the ship navigation environment is built using Unity 3D and C# programming. Finally, the feasibility of applying digital twin technology in the field of maritime vessel safety regulation is verified through experiments.

Keywords: Digital Twin; Virtual Simulation; Navigational Environment; Maritime Safety.

1. Introduction

In the real operational environment of ships, there are many complex and unpredictable conditions [1]. These conditions are influenced by both natural environmental factors and the ship's own environmental conditions. When the navigational environment of a ship deviates from normal states, timely adjustments and corrections to the ship's navigation status can ensure its safe passage and reduce the occurrence of accidents. Having a timely understanding of the ship's navigational environment is a fundamental prerequisite for ensuring safe ship operations. Additionally, the structure of the ship itself is relatively complex, and its size is relatively large, making precise detection challenging. This is particularly true for maritime navigation, where factors like changing sea conditions and random variability pose even greater difficulties for real-time and precise detection [2].

Digital twin technology is an integrated, multidisciplinary coupling technique [3], characterized by Multi-dimensional, multi-scale, and high reliability [4]. It achieves information exchange and data fusion between physical space, information space, and service systems through bi-directional mapping and real-time interaction between the physical and information spaces [5]. It can create a virtual simulation environment based on the real physical world for users. This virtual simulation environment not only plays a role in monitoring and managing the ship environment but also proves effective in crew education and training. Tao Fei [6] proposed model construction criteria, Zhang Chenyuan [7] established an evaluation index system for the model, and Zhao Yan [8] put forward an evaluation system for the digital twin system of ships and offshore facilities. The application of digital twin technology not only enables intelligent operation and maintenance of ships but also facilitates holistic life-cycle health management of vessels [9].

2. The Application of Digital Twin in Maritime Safety Supervision

2.1 Preview Construction Achievements

A digital twin for ships can be applied to various stages in the life-cycle of a vessel, including product design, manufacturing, service, and operation [10]. The construction cost of ships is relatively high, and in the event of a safety incident, the losses can be enormous. For example, the Tian Jing Hao self-propelled cutter suction dredger cost 20 billion yuan to build, and the Tian Kun

Hao heavy-duty self-propelled cutter suction dredger cost 1.5 billion yuan. By utilizing digital twin technology to construct a digital twin, design flaws can be detected in advance, reducing design and manufacturing costs, and eliminating safety hazards caused by design defects.

2.2 Optimizing Safety Debugging

The approach of switching between virtual scenarios built with digital twin technology and physical entity operations enables rapid identification of safety hazards in ships. Through extensive data testing, it is possible to optimize ship operation processes, reduce the frequency of unplanned downtime due to malfunctions, lower maintenance costs, and extend the lifespan of the vessels.

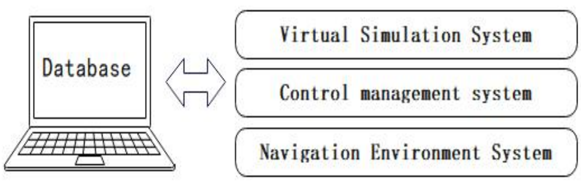
2.3 Analysis and Warning

By installing sensors, environmental information during ship navigation can be transmitted to the digital twin. The digital twin incorporates analytical algorithm logic to collect and analyze data from external natural environments and the ship's internal environment. It provides early warnings for potential malfunctions and offers feasible solutions to mitigate potential safety accidents in the future, thereby reducing accidents at their source.

3. The architecture of a ship's navigation environment monitoring system based on digital twin

3.1 The structure of the digital twin-based ship navigation environmental monitoring system

The structure of the ship's navigation environment system based on digital twinning is shown in Figure 1. The ship's navigation environment system includes the ship itself, the aquatic environment, wind force, temperature, etc. Through various on-site sensors, real-time monitoring of the parameters of the ship's navigation environment is achieved. The virtual simulation system is based on the parameters of the ship's navigation environment and related operational parameters, allowing for a digital mirror of the entire ship's navigation environment. The control management system is a comprehensive system that includes functions such as real-time control, risk assessment, abnormal alarm, and historical query. It achieves precise control between the real navigation environment and the virtual navigation environment. The twinning database of the ship's navigation environment is the core of the entire digital twinning system, including real-time data of the navigation environment entity, initial configuration of the navigation environment, virtual simulation data, and system iteration data, etc.



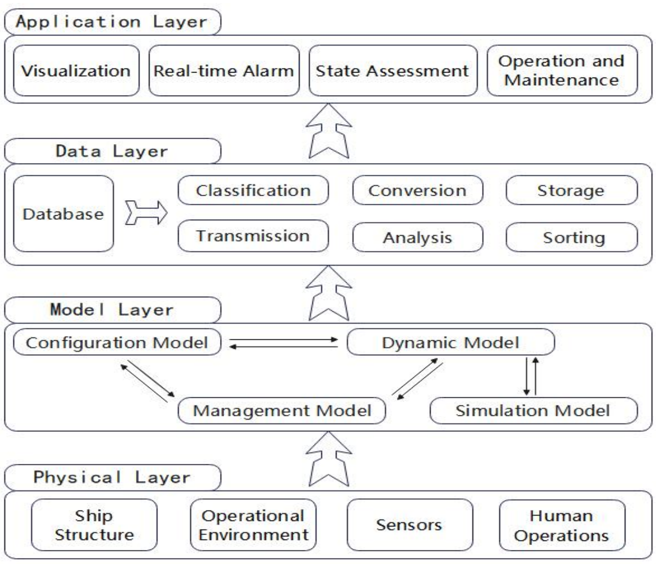


Fig. 1 The structure of the ship's navigation environment system based on digital twin(Left)
Fig. 2 The Architecture of Ship Navigation Environment System Based on Digital Twin(Light)

3.2 The structure of the digital twin-based ship navigation environmental monitoring system

The architecture of the ship's navigation environment system based on digital twin mainly consists of four parts, as shown in Figure 2.

(1) Physical Layer. This mainly includes the ship's body status, external environment, various sensors, personnel operations, and other physical entities. Its main function is to provide various parameters and information data of the ship's navigation environment.

(2) Model Layer. The model layer is the mapping and mirror of virtual environment to physical entities, including configuration models, dynamic models, simulation models, and management models.

Configuration model refers to the topological structure and static configuration of the ship's navigation environment, including the selection of sensors, spatial layout, and the relationships and constraints between relevant scenarios.

Dynamic model refers to the working mechanism of relevant systems on the ship during the navigation process. It mainly includes the different expressions of dynamic models and environmental models under different environmental conditions.

Simulation model refers to the synchronized mirror of the ship's actual navigation environment at the physical and geometric levels. This includes aspects such as virtual simulation environment, dynamic display of virtual scenes, and visual effects.

The management model is the structural framework for the operation and management of the system, including control network structure, data collection, transmission and processing, and the operational logic of control management.

(3) Data Layer. It mainly includes the twin database and data processing core of the ship's navigation environment system. Data and parameters transmitted from the model layer will be collected in the data layer.

(4) Application Layer. The main goal is to achieve digital monitoring and management of the ship's navigation environment. This includes visual monitoring, real-time alarms, and comprehensive operational maintenance of the ship's navigation environment.

4. Digital Twin-based Ship Navigation Environment Design

4.1 Construction of Ship Navigation Environment Digital Twin Model

In the construction of the virtual model of the ship's navigation environment, it is necessary to consider not only the geometric features of the real physical environment but also establish the physical characteristics of the real-world environment. To achieve the digital twinning of the ship's navigation environment, it is essential to ensure the synchronization between the virtual environment and the physical environment, as well as the coordination and unity of multi-dimensional models involving physical aspects, resources, rules, and actions. To ensure the accuracy of model construction, integration and fusion of multi-level models is required to form a complete and comprehensive virtual ship navigation environment model, as shown in Figure 3.

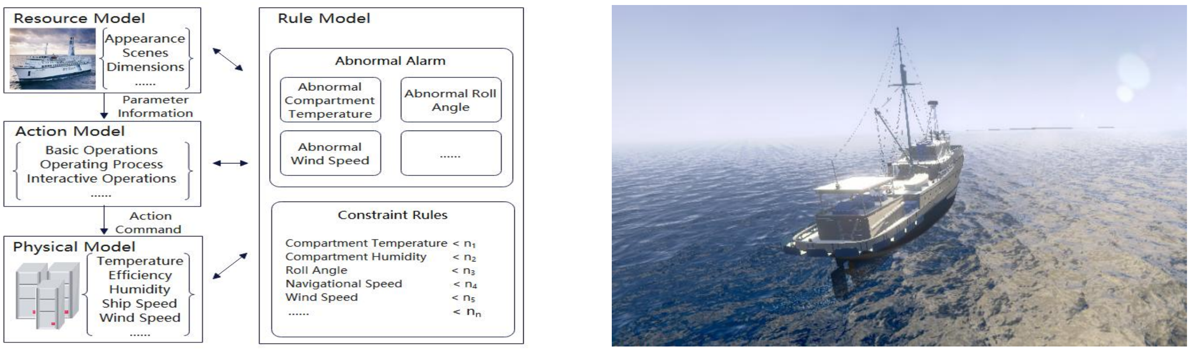


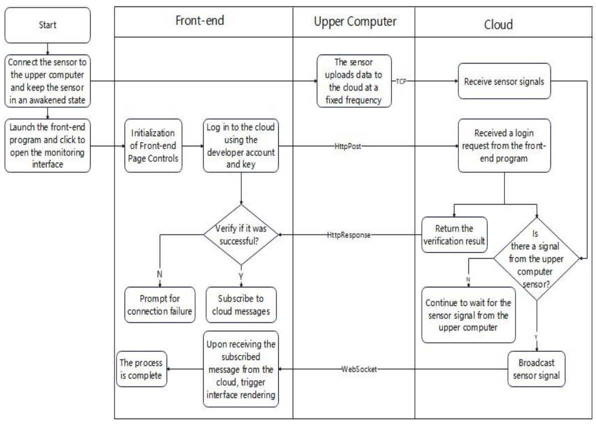
Fig. 3 Integration and Fusion of Multi-Level Models(Left)

Fig. 4 The Ship's Navigational Environment Model Based on Digital Twin(Right)

The resource model in the virtual environment primarily considers ship entities, environmental information parameters, visual effects, virtual scene simulations, sound and light simulations, etc. The physical model includes the physical characteristics of various parameters in the ship's navigation environment, such as wind speed, temperature, humidity, and velocity. The action model refers to the standardized actions and action sequences performed by interactive objects based on received real-time data. The rule model maps the relationships between various devices in the monitoring system in terms of operational mechanisms, actions, logic, and other aspects. Achieving a comprehensive mapping from the physical entity to virtual simulation in the ship's navigation environment requires consideration in multiple dimensions such as physics, resources, actions, and rules, in order to ensure the accuracy of the ship's navigation environment model system. Finally, the various system models are combined and linked together to achieve relevant digital simulations in the form of a three-dimensional visualization platform. Figure 4 shows the ship's navigation environment model based on digital twin built using the Unity3D engine.

4.2 Data Collection and Processing

The fundamental premise for achieving real interaction mapping between the physical environment and the virtual environment is the real-time collection, transmission, and storage of data. This requires using corresponding protocol conversions based on interfaces and communication protocols, and transmitting data information to the server through consistent interface standards, which are then uniformly stored in the database. Data collection includes multiple dimensions such as temperature, humidity, wind speed, ship speed, longitude, latitude, roll angle, pitch angle, and running time. The steps for sending and receiving sensor data information are shown in Figure 5.



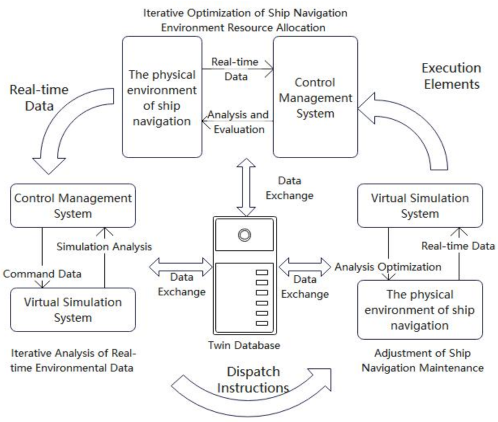


Fig. 5 Sending and Receiving Sensor Data Information(Left)
Fig. 6 The Operational Mechanism of Digital Twin Monitoring System(Right)

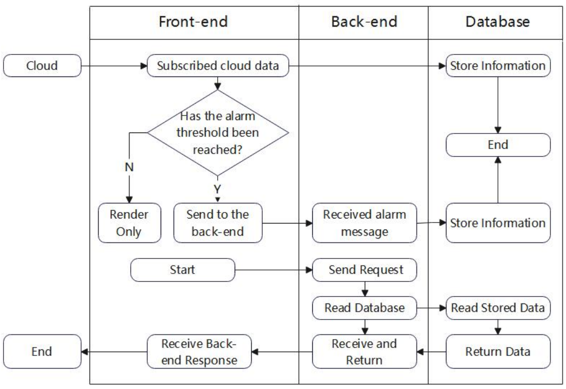
5. Operation Mechanism of Digital Twin Monitoring System

The operational mechanism of the digital twin monitoring system mainly includes three aspects: iterative optimization of ship's navigation environment resource allocation, iterative analysis of real-time environmental data, and adjustment of ship's navigation maintenance. The operational mechanism is shown in Figure 6. Through these three processes, the current navigation status of the ship's environment is assessed. Through iterative optimization of the system, real-time monitoring of the ship's navigation environment is achieved, while maintenance decisions are optimized.

6. Key Functional Components

6.1 Alarm Function

The alarm function of the ship's navigation environment monitoring system is an important criterion for measuring the practicality of the monitoring system. During the ship's voyage, if there are issues such as abnormal increase in temperature in a compartment, excessive wind speed on the sea surface, or excessive roll angle, it is necessary to detect and resolve them promptly. The normal operation of the alarm function can help the crew quickly grasp the abnormal information of the ship. The alarm function of the monitoring system and the front-end initialization process are shown in Figure 7.



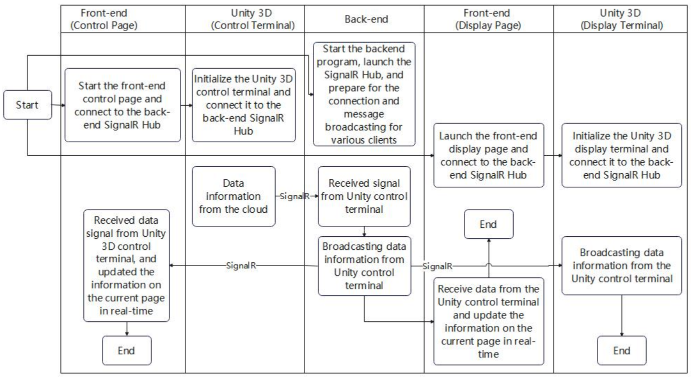


Fig. 7 Monitoring System Alarm Function and Front-end Initialization(Left)

Fig. 8 The interaction process of data information with Unity 3D(Right)

6.2 Data Information and Unity 3D Interaction Function

The digital twin of the ship's navigation environment is built based on Unity 3D software, enabling the interaction of information between data and Unity 3D. This forms the foundation for achieving a real mapping between the physical world and the virtual environment. The interaction process between information data and Unity 3D is shown in Figure 8.

7. System Display

This chapter presents the interface of the digital twin ship navigation environment monitoring system. By connecting and activating the sensors, the information of the ship's navigation environment is visualized from the physical world to the computer end. It also displays the ship's own navigation status and issues alerts for adverse navigation situations. The interface of the digital twin ship navigation environment monitoring system is shown in Figure 10.

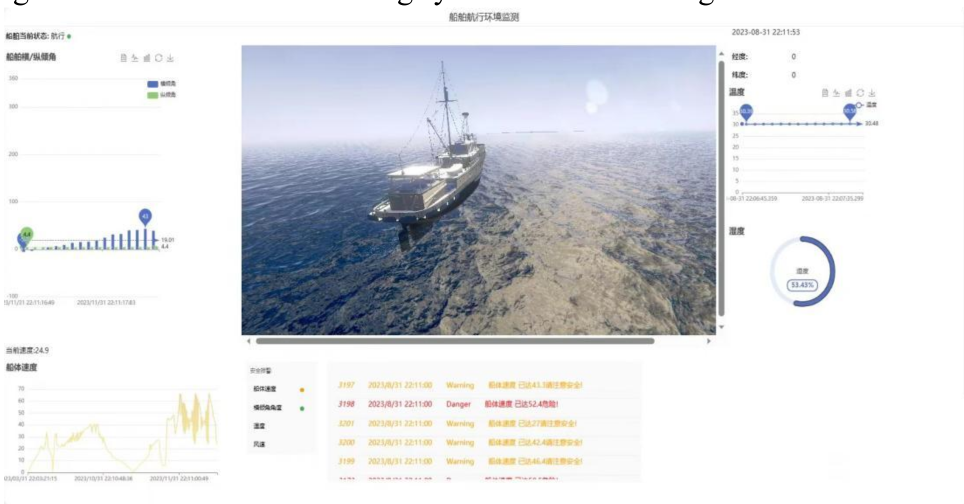


Fig. 9 Interface of Digital Twin Ship Navigation Environment Monitoring System

8. Summary

This paper establishes an architecture for a ship's navigation environment system based on digital twinning technology. It achieves the integration and interaction of the ship's navigation environment monitoring system in three dimensions: the physical world, real-time data, and simulation models. Finally, it showcases the interface of the digital twinning ship's navigation environment monitoring system. The research and development of digital twinning technology in the field of ships are still in their early stages, and there is room for further application, especially in the domain of ship safety supervision. Future research on digital twinning engine room systems will focus on addressing complex system modeling, improving modeling accuracy, and dynamic data-driven analysis.

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