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Digital Twin Technology for Smart Shipping: Applications, Challenges, and Future Directions

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Abstract. Maritime shipping business has been an important event in global trade, but it is still marred by serious challenges such as high prices, environmental effects, hazards on ships and port congestion. With the use of technologies like Internet of Things, cloud computing, and artificial intelligence gaining an ever-increasing significance in the Industry 4.0 epoch, smarter and more efficient shipping solutions are getting recognized as an issue of even greater importance. In that case, the digital twin technology that is the development of virtual depictions of physical systems in real-time opportunity presents great potential to overcome these difficulties. The review is a collection of research on the topic carried out during the last five years to explore how digital twins are applied to smart ships, ports, and logistics systems and determine the main trends in technologies, application patterns, and gaps in research. It also addresses the way, in which digital twins can influence the forthcoming alteration of the maritime industry. Thus, the study of the digital twin technology in marine shipping is both theoretical and practical.

Keywords: Digital Twin, Intelligent Shipping, Smart Ships, Smart Ports, Logistics Visualization.

1. Introduction

Shipping is a fundamental aspect of worldwide transportation that is increasing in pressures through its operations, environmental, and safety concerns. The cost of fuel, maintenance and labour is on the rise which drives up the financial strain on maritime activity whilst emissions, port pollution, accidents and congestion persist in sabotaging the sustainability and efficiency of the sector. Shipping contributes an estimated 3 percent of the total carbon emissions, which means that it should employ smarter and more sustainable management strategies [1]. Simultaneously, digital twin systems have become achievable in maritime environments due to the development of sensing, communication, and computing technologies. IoT sensor data, AIS, radar, and other surveillance devices can now be transmitted and processed in close real time, which offers a base on which more combined digital operations can be formed [2,3].

A digital twin, in this case, will be a virtual mirror of a physical system or asset that will be constantly connected with its physical equivalent in data and simulation graphs. This aids real-time observation, scenario examination, risk projection and optimization of the operations in the maritime sector. Due to this fact, digital twins are becoming increasingly popular to enhance the performance

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of vessels, port management, and the resilience of a system. According to recent research and practice in the industry, they still do not reach the maturity and adoption levels across regions [4]. It is in this context that the key characteristics, applications, merits, and shortcomings of digital twin technology in maritime management have been assessed in this review.

2. Digital twin technology

2.1. Definition and main traits

A digital twin is a digital model of a physical object or system that is updated continuously using real-time data, e.g. produced by a ship or a port infrastructure. Its central features are the data-driven structure, real-time synchronization and bi-directional interaction. Data related to the physical systems are collected by sensors, IoT devices among others and then mapped onto a virtual model to reflect the current state of the physical systems. Meanwhile, control commands or readjustments to operations may be transmitted back out to the physical system. This will enable operators to test and compare various strategies on a simulated environment and then implement them on field thus enhance decision making. Digital twins can be used at every stage of the lifecycle, such as designing, constructing, and using smart vessels, and help to sustain a high level of optimization by constantly updating the data stream and refining the model [5].

2.2. Important technological frameworks

Digital twin systems are implemented by means of multi-layered technological systems. On the ship and in the port facilities, huge sensor networks at the perception layer gather real-time data, such as temperature, pressure, vibration, navigational, and environmental data on AIS, radar, and visual monitoring systems [2]. These are streams of data where they are the core inputs to the virtual model. The data transmission layer will rely on the high-bandwidth and low-latency communication systems like 5G networks and satellite systems in the sea [2]. Cloud and edge computing platforms are applied in the processing of data at the data modeling layer and storage tier. CAD models and GIS-based spatial data could be used to develop digital models of physical objects, and machine learning algorithms could be used to adjust model parameters in real time, so that the virtual model of the system was as close as possible to the real-world system. Technologies like virtual reality, augmented reality, and three-dimensional visualization engines are present in the interaction and visualization layer and make the interaction with the digital twin more intuitive. Operators and decision-makers can use these interfaces to monitor and control the movement of ships over virtual bridge systems or coordinate the activity of the terminals by digital port control towers. Through this, physical operations may be connected to simulation analysis very closely.

All of these layers make up a unified structure where data acquisition, transmission, modeling, and interaction are all unified. In addition to this basic architecture, one more significant developing trend is the introduction of digital twins into hydrogen energy the systems and blockchain technologies.

3. How digital twin technology is utilized in the maritime sector

3.1. Smart ships

The applications of digital twins to smart vessels are used during the entire life cycle of a vessel such as design, construction, and operation of the vessel. CAD/CAE models and simulation tools are

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applied during design and construction phases in order to come up with the digital representation of hull structures [5]. After the ships become operational, digital twins based on navigation receive used sensor data on important elements, including main engines, auxiliary systems, and steering gears. These data have variables in terms of temperature, vibration, and fuel consumption. The data undergo preprocessing at the edge and then they are sent and aggregated as part of cloud platforms. Physics-based models are used there where they are combined with data-driven models to track equipment health and fault prediction. One such example is that Liu et al. acquired a model of a digital twin to predict the remaining useful life of marine engines, which minimizes unexpected shutdowns [6].

In addition to monitoring equipment, digital twins can be used to aid in navigation and energy optimization. They are able to simulate virtual environments with the aid of weather, sea-state and ocean current data testing a navigation strategy. Taghavi et al. introduced an energy consumption model on a digital twin, which evaluates the real-time fuel consumption at variable speeds with the help of multimodal adaptive filtering and Kalman filtering, to help in efficient route planning. Digital twins are being embedded in remote operation systems and autonomous navigation in more advanced applications. With the integration of digital twins and deep reinforcement learning and model predictive control, it is now possible to train control strategies in a simulation and ensure they remain synchronized to real-world systems. Berg et al. concluded that this is a better method of enhancing the reliability of autonomous navigational systems and remote monitoring and control [7]. In general, it is proposed that the digital twins applications in ships are developed the most in the predictive maintenance and energy optimization areas, whereas the task of the integration with the autonomous navigation is still at the initial phases.

3.2. Intelligent ports

Digital twin applications in smart port use cases are primarily concerned with emergency response planning, management of yard operations, terminal scheduling, and optimization of energy. Virtual port are used to maximize the coordination of quay cranes, yard cranes, and automated guided vehicles. Indicatively, the digital twin model proposed by Zhu et al. to bulk cargo ports implies settling on a loading plan and allocation of capacity through simulation-based optimization to minimize congestion and turnaround time [4]. In addition to scheduling, yard and container management is also carried out using digital twins. Wang et al. created a digital twin model that used both the physical yard layouts and agent-based models to mimic and optimize the processing of handling operations, showing improvements in both the yard utilization and operational efficiency [5].

Digital twins too are used more often in energy management within ports. They facilitate remote control and optimization of energy-housing systems like the infrastructure of power stations onshore and refrigerated containers. Port of Valencia introduced a Platform of digital twin which minimized the energy use by almost 80 percent, and its simulation-based optimization at Busan Port led to a reduction of carbon emissions by shore power by 75 percent and increased the prediction accuracy by 95 percent [1]. Besides the efficiency of operations and energy management, digital twins can also be used to conduct safety management and emergency response planning since they simulate accidents and can identify response plans. According to Liu et al., then emergency preparedness can be enhanced using intermittent training, which is based on simulation and reduces the preparation time [5]. In general, digital twins have been prospectively effective in enhancing operational efficiency and energy management at ports. Nonetheless, the performance is also largely reliant on interoperability of various data systems.

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3.3. Logistics at sea

Digital twins ensure a high degree of visibility and collaborate with optimization of maritime logistics and supply chains. With RFID, GPS, and environmental sensors, the conditions and location of cargo can be constantly tracked and reported to the cloud resources, which will enable stakeholders to monitor shipments in real time and react proactively to any possible delays [2]. Digital twin models in cold chain logistics are involved in the utilization of real-time sensor data to measure the consumption of energy and the probability of a cargo being damaged at a single logistic node. Digital twins are used together with the other forms of transport in multimodal transport where data obtained in one type of transport is combined with data of additional modes to create one platform, allowing algorithmic scheduling and optimization of the transport system [2]. Digital twins can also be used to replicate disruption scenarios, including port incidents or natural disasters, and assist the stakeholders in assessing responses to such situations when paired with artificial intelligence [2]. By and large, digital twins increase system-wide communication and visibility, in the logistics at sea. Nonetheless, their implementation is limited due to challenges in coordination and sharing of data between various modes of transport and stakeholders.

3.4. Examples of cases

To facilitate bulk cargo operations, Jurong port uses a digital twin platform which is a GIS-based platform named as JP Glass [8]. The system can help improve situational awareness, information sharing, and operational safety, by providing users with real-time weather and water information, monitoring the loading and unloading schedule, and yard conditions through a single visual interface [8].

The study conducted by Eom et al. has focused on implementation of a digital twin at Busan New Port in South Korea, at which they have modeled an interactive model of scheduling [9]. Users can also evaluate the carbon emissions and plan the emission reduction in real time with the use of the system. According to their study, digital twins can be applied to scheduling to minimize their delays and maximize energy use [9].

Maritime and Port Authority in Singapore initiated the MPA Digital Twin the Singapore-based first country maritime digital twin in 2025 [10]. It is a virtual system, based on real-time information regarding vessel movements and weather conditions, including AIS, throughout the port demarcation. It assists in dynamic vessel monitoring and also underwater operations like hull cleaning [10].

The TwinShip project is an EU-financed industry project held under the leadership of such industry players as Wartsilas which attempts to devise a decision support system to ship design and retrofitting [11]. The system applies the AI to test data on the real world and forecast the cost and performance and emissions of various fuels and energy-saving technologies. The system will be tested in practice on four demonstration vessels and the project itself is projected to offer shipowners data based insights on the way to make their ships more energy efficient and minimize emissions.

These case studies indicate that digital twins can best be utilized with the help of real-time integration of data and decision-support systems. Scalability and standardization are however among the key barriers to large scale adoption.

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4. Problems and solutions for using digital twins in the maritime industry

Nevertheless, even though the digital twin technology has considerable potential, it still has a number of large obstacles preventing its implementation in the maritime sector. Among the most severe challenges, there are data silos and the lack of interoperability. Quite often, ship operators, port authorities, and cargo owners choose various standards and incompatible interfaces to gather the information; thus, this complicates the task of data sharing and integration. The completeness and accuracy of digital twin models may also be decreased because of the heterogeneity of information of several sources. Such issues are also highly motivated by the unavailability of standard data procedures and data control inequalities among stakeholders.

In addition to data related impediments, implementation is hampered by technical constraints. Digital twins of high fidelity demand processing of high amounts of real time data and the performance of complicated simulations. Nevertheless, maritime satellite communication systems continue to encumber the bandwidth and the latency, which complicates real-time transmission of data [1]. Moreover, such accuracy of modeling and simulation requires a huge amount of computing resources, and real-time coordination between the real and virtual system becomes a significant technical challenge. The process of model development is also associated with challenges because the maritime systems are very intricate and demand skills in numerous fields, such as fluid mechanics, mechanical design and control systems [5]. The higher the complexity of the system, the less it can be assured that any error in modelling and uncertainty will be managed and this will lead to a decrease in reliability of the virtual models and decision support quality.

Another significant obstacle is cost. The initial set up of digital twin systems involves a lot of costs in terms of sensors, communication encounters, software platforms, and staff training [3]. The small and medium-sized maritime business can hardly afford such investments in the short term, and such returns might not be felt at a short period of time. Meanwhile, there are threats associated with cybersecurity, information privacy, and data ownership due to the tight collaboration of the physical systems with their digital analogs. Bad users can also manipulate sensor information or try to hack control systems, and this limits virtual models and physical operations. Besides, the dissemination of sensitive information among various parties will create privacy, ownership, and intellectual property issues.

The outcome of this is the necessity to be more cooperative between technology developers, industry actors, governments and educational institutions in order to break these barriers. This should be in trying to enhance maritime communication infrastructure, adoption of standard data formats and interfaces and enhancement of collaboration among universities, companies and research centers in developing models. Governments may also make adoption stimulate: via pilot projects, financial gains, and common platforms that would reduce costs of implementation. Simultaneously, a more robust level of cybersecurity, such as encrypted data transfer and more transparent governance systems, is required to enhance the safety and dependability of digital twins.

5. Conclusions

The digital twin technology is increasingly becoming a pillar of change in the maritime industry as the technology can be used to provide a real-time image of the physical systems within a digital space. This feature aids in the monitoring, simulation, and prediction of the lifecycle of ships as well as the working mechanisms of ports, which enhances the safety and efficiency. In practice, there are examples that digital twins can save significant amounts of energy usage and emissions and that energy savings of up to 80 percent and carbon emissions reductions of approximately 75 percent

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have been observed. Though encouraging these results are followed by critical problems, especially the problem of data standardization, data security and lack of the interdisciplinary expertise. However, with the ongoing technology and the evolution of the bigger ecosystem, digital twins will have a growing impact on moving the maritime transformation.

Businesses, governments and academic institutions must invest more and work together more to achieve this potential. These synchronized activities will play a vital role in developing the shift to smart shipping and establishing a firmer base of the future development of the sector. Further studies need to be more concerned with enhancing data consistency and interoperability of systems in the maritime industry as well as integrating the digital twin technology with economic decision-making models that may be applied in domains like optimization of costs and dynamism in the shipping markets.

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