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Construction and Application of Digital Twin for Propulsion System in New Energy Ships

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Abstract. Digital Twin (DT) is considered to be the general purpose technology of the 4th industrial revolution, and realizing its engineering application universality is the common endeavor objective of both universities and companies. Based on the theoretical framework and technical route of DT, this paper focuses on its application exploration for new energy ships. Via blending technologies of cloud computing, open source software, the marine control system and characteristics of new energy, authors carry out a feasibility analysis from the shipboard and cloud architecture and implementation plan respectively. A DT of propulsion system is developed, deployed and operated online on a new energy ship (NES). Meanwhile, the DT data is used to correct the calculation deviation of the battery State of Charge (SOC) by the ship's physical system. The research in this paper will provide a decision-making platform for situations such as safe operation, fault diagnosis, and condition-based maintenance, and also provide an effective solution for future DT system design of new energy ships.

Keywords. Digital Twin, New Energy Ships, Propulsion System, Internet of things

1. Introduction

In recent years, new technologies, such as 4G/5G wireless communications, Internet of Things, Cloud Services and Artificial Intelligence, are undergoing rapid development. The physical entity world and the digital virtual world have formed two systems, which develop and interact in parallel. Digital virtual technology serves physical entities, which are more efficient and organized with the support of digital technology. In this context, the digital twin is born.

The earliest concept of the digital twin can be traced back to the "a virtual, digital equivalent to a physical product" proposed by Prof. Michael Grieves of the University of Michigan in 2003. He emphasized that digital representations of a physical product should be able to abstract itself, and the physical product can be tested under real or simulated conditions based on digital representations, which is to construct an equivalent virtual entity of the physical entity [1]. In 2009, the US Air Force Research

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Laboratory (AFRL) also proposed the concept of "Airframe Digital Twin", in which Digital Twin first appeared [2-3]. In 2011, Prof. Michael Grieves officially cited Digital Twin (DT) in his new book "Virtually Perfect: Driving Innovative and Lean Products through Product Lifecycle Management", which quoted the suggestion of John Vickers of NASA [4]. Then, Dr. Fei Tao of Beihang University extended the three-dimensional model of Digital Twin "physical entity-virtual mirror-connection" to five dimensions. The five-dimensional model uses the manufacturing workshop as a carrier, which is combined with the emerging hardware and communication technologies, increases the dimensions of data and services. That caused a sensation in academia [5-6]. Based on DT five-dimensional model, technologies of application and exploration of DT have been widely carried out subsequently. Academician Jianrong Tan of Zhejiang University presented an assembly precision analysis method based on a general part DT model, which would integrate multi-source heterogeneous geometric models and maps assembly information from assembly semantics to geometry elements, allowing automatic assembly positioning of parts and improving the efficiency of assembly simulation [7]. Academician Deren Li of Wuhan University discussed the relationship between DTs and smart cities, analyzed the characteristics of smart cities based on DTs, and focused on the five main applications of smart cities based on DTs [8]. Those scholars provide method reference for DT's landing application.

Because DT is being an effective way to realize the intelligent interconnection and interaction of the manufacturing physical world and the information world, it is also highly concerned by technology companies. Global industrial and software giants such as Siemens, Ansys, Microsoft, and GE have made great achievements in the fields of DT platform construction and engineering applications after years of intensive cultivation. DT is also considered to be the general purpose technology of the fourth industrial revolution [3], and it is being applied in the fields of manufacturing, service industry, urban development and military industry. However, the current application research in academia still focuses on the theory, methodology, feasibility of the application direction, and experiments on a single-point problem, which is difficult to be adopted by engineering projects for reference and implementation. Most engineering applications in enterprises build a full-featured service platform with huge economic and labor costs, while application users only use the platform in a black box way. It is difficult to accurately implement the functional modules of the platform on the application object, and it is impossible to focus on the object mechanism to construct an accurate description model, which causes a waste of resources, and the application effect is also relatively poor.

As a general purpose technology of the fourth industrial revolution, DT's engineering application should be more universal. The achievements of the previous industrial revolutions such as steam engines, electricity/lights, and computers have proven this. Only when DT is conveniently, economically and accurately applied can it create real value for industrial progress and social development. Thus, the paper is based on the DT theoretical framework and the technical route, focusing on the analysis of its application technology in the systematic design and engineering implementation. We take a new energy ship as the object of implementation, which is with many monitoring points, large data volume, high stability requirements, lack of industry standards and implementation plans. Through the study of cloud computing, open source software, marine control system and characteristics of new energy, we carry out feasibility analysis from the shipboard and cloud system architecture and implementation plan respectively, and completed the development, deployment and online operation on the new energy ship. Finally, the DT data is used to correct the calculation deviation of the battery SOC (State of Charge) by the ship's physical system.

2. An overall architecture of DT engineering application

There are two main development directions for enterprise-led DT engineering applications. One is the development of infrastructure and software platforms, in which companies that own physical assets develop twins on their infrastructure and platforms, such as Siemens and Microsoft. The other is a physical asset-oriented design model, in which DT of specific asset objects is realized through data collection and model construction on the basis of existing software functions, such as Ansys. Also, some choose to develop in both directions, such as GE.

With the continuous upgrading of technologies, the theoretical and application requirements are constantly expanding and upgrading. The development and application of DT presents new requirements, including: (i) application field expansion, (ii) deep integration with New IT technology, (iii) data fusion with CPS, (iv) intelligent services, (v) universal industrial interconnection, (vi) model of dynamic multidimensional and multispacetime scale [6]. Combining these development requirements and the status of enterprise applications, an overall architecture of DT engineering application is shown in Fig 1.

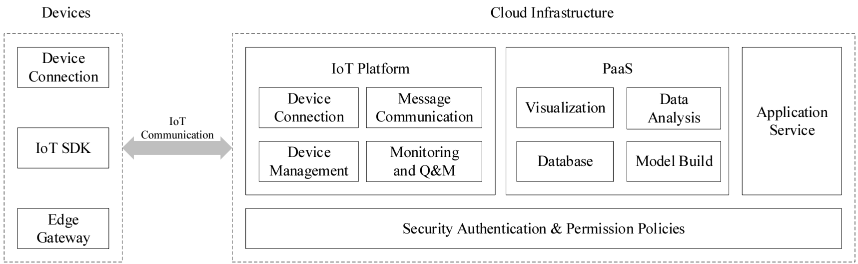

Figure 1. An overall architecture of DT engineering application

3. DT construction for propulsion system in new energy ships

So far, DT application technologies and engineering implementation for ships are still in their infancy, and there are very few cases and schemes that can be used for reference. China has vigorously promoted the development of new energy ships (NESs) from the perspective of energy security and ecological environmental protection, such as the "Guiding Opinions on Promoting the Development of Green Shipping in the Yangtze River Economic Belt" issued by the Ministry of Transport of the P.R.China [9], Ministry of Ecology and Environment of the P.R.China issued "Limits and Measurement Methods of Ship Engine Exhaust Pollutant Emissions" [10], "Inland Green Ship Regulations" issued by China Classification Society (CCS) [11], etc. The International Maritime Organization (IMO) also mandates a ship energy efficiency design index. The essence of inland green shipping is to change the form of propulsion from traditional diesel engine drive to electric propulsion or pure battery power, especially the pure battery power, it is the main development direction of the industry, due to its advantages of economy, safety and convenience. Since the propulsion, control and sensing of pure battery-powered ships are driven by current and voltage, while the collection, transmission and storage of current and voltage data have higher accuracy, precision and real-time, it is natural to build a DT system. The DT systematic design for new energy ships is mainly for a pure electric system. The system consists of four major parts: (1) battery pack, (2) DCDC power supply, (3) DC power distribution system, (4) propulsion motor, which is shown in Fig 2.

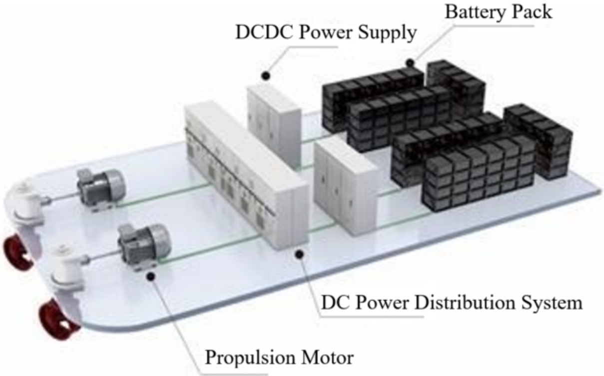

Figure 2. Major parts for pure electric system

A NES integrates with a high-safety lithium battery system, a high-efficiency variable frequency drive system, a high-mobility pod propeller, an intelligent ship handling and operation and maintenance system, and the mute effect reaches the luxury car level standard. The main design parameters are shown in Table 1 [12-13].

Table 1. Main design parameters of a NES

Design Parameters	Value
Total Length	53.20 Meters
Waterline Length	≈ 49.96 Meters
Total Width	13.40 Meters
Type Width	10.80 Meters
Type Depth	2.7 Meters
Design Draft	1.55 Meters
Displacement	410 Tons
Top Speed	10±0.2kn(6m Water Depth)
Endurance	8 Hours(10 Knots Speed)
Passenger	300P
Propulsion Power	2×200kW
Battery Capacity	2.24MWh

The NES is equipped with a 2240kWh LiFePO4 battery. After DC conversion, it outputs a stable DC voltage, and then the DC power distribution system outputs 380V power AC power and 220V daily AC power, which are used for propulsion system and shipboard equipment respectively. The ship's control system and data acquisition system are implemented by a variety of combined PLCs and supporting communication modules. The communication protocol mainly uses CANopen and Modbus TCP. The collected data is aggregated to the bridge industrial computer for local monitoring management. The monitoring system is shown in Fig 3.

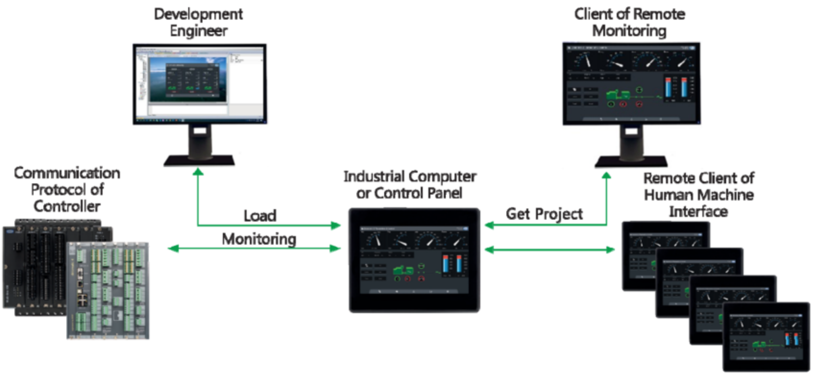

Figure 3. The monitoring system for a NES

Due to the fact that the capability of computing power, storage capacity, and application service of the shipboard industrial computer is not able to directly build a DT system, the cloud services must be used for core computing and storage. For the shipboard terminal, the client application developed must achieve both local monitoring and data upload to the cloud. Therefore, we believe that the most appropriate solution is based on Node.js development. Node.js is an open source and cross-platform JavaScript runtime environment, the software type is open source with cross-platform capabilities, the license agreement is a friendly MIT agreement. It runs the V8 JavaScript engine of the Google Chrome kernel outside the browser, and its application runs in a single process without the need to create a new thread for each program request. Node.js standard library provides a set of asynchronous I/O native functions to prevent JavaScript code from being blocked, and is written in a non-blocking paradigm, so that blocking behavior becomes an exception rather than a norm. When Node.js performs I/O operations, such as: reading data from the network, accessing the database or file system, the program will resume the operation when the response returns, instead of blocking the thread and wasting the CPU loop waiting, which makes Node.js handle thousands of concurrent connections on one computer without the burden of managing thread concurrency [14], this feature is very good at solving the blocking problem of shipboard industrial computer when processing with high concurrent connections.

The NES has about 2,000 collection points on the whole ship, and the relevant data of ship communication and navigation equipment such as depth sounder, ship automatic identification system (AIS), GPS is also connected to the industrial computer through the serial port (DB9), so that its concurrent connections present a larger magnitude. In addition, as the requirements for battery safety monitoring are further improved, battery monitoring point data will increase exponentially, and the stability and performance requirements for concurrent connections will also be higher, while Node.js has solved this problem in the framework design. The development tool uses Node-RED, which is an application developed on the basis of Node.js, it is an open source, dataflow-based visual programming tool and has been widely used in IIoT and control systems. It connects hardware devices, application interfaces, and online services together, provides a browser-based programming environment and rich node types, makes it very easy to create a process, and also provides a running environment for the operation of the process, has the one-click deployment capability. The shipboard terminal program developed under the Node.js framework using the Node-RED development tool contains two main modules, of which the module pushing to the cloud is connected to the IoT platform through the MQTT protocol.

Table 2. Program module function on shipboard

Module Function	Function Description
■ Collect Data ■ Storage Data	To collect system equipment point data such as EMS, BMS, propulsion system, monitoring alarm system, pod device steering gear side control box, GPS, AIS and other system equipment points and store local database
■ Update Local Library ■ Push to Cloud	To collect system equipment point data such as EMS, BMS, propulsion system, monitoring alarm system, pod device steering gear side control box, GPS, AIS, etc. and push it to the cloud database

When data is connected to the Alibaba Cloud IoT platform, the most important indicator for product and parameter selection is system throughput, which is: TPS (Transactions per Second). The calculation formula is as follows:

$$tps = n_d \times q_u + n_d \times q_d \tag{1}$$

Where n_d is the number of access devices, q_u is the amount of messages reported by a single device per second, and q_d is the amount of messages sent by a single device per second. Consider that the NES is encapsulated and reported according to different message types, there are at least 4 types, and 1 report every 2 seconds, the uplink for 30 ships to connect at the same time is: $tps = 30 \times 4 \div 2 = 60$; consider the difference between ships, the initial configuration of the IoT platform is at least: the message downlink TPS is 100 messages/sec; the rule engine TPS is 100 messages/sec; the time sequence data written into the TPS is 5,000 messages/sec.

The choice of the database should fully consider the performance and stability under high throughput when the query and analysis business is paralleled with the exponential growth of the data volume. The storage space consumed by the average daily data volume of a single ship is as follows:

$$C = n \times b \times f \times t \div p \tag{2}$$

Where C is the storage space capacity, unit is byte (Byte); n is the number of acquisition points; b is the storage space required for a single point, and the ship data is mainly switching value and power electronic parameters; f is the sampling frequency, it is usually 1 time per second; t is the sampling time, unit is second (s); p is the reporting cycle, that is, the data uploaded to the cloud has undergone a certain down sampled. A high-performance database must be selected to support the normal throughput of twin data. We chose the Alibaba Cloud Hologres database, which belongs to the enterprise analytical data warehouse and has the ability to analyze and query massive big data in seconds. Hologres integrates real-time services and big data analysis scenarios, it is fully compatible with the PostgreSQL protocol and seamlessly connects with the big data ecology, it can use the same data architecture to support real-time write real-time query and real-time offline federated analysis. Its execution engine is a general architecture that supports complex queries and high-performance real-time service queries, it has the following characteristics: (1) distributed execution model, (2) fully asynchronous execution, (3) vectorization and column processing, (4) adaptive incremental processing, (5) deep optimization of specific queries [15]. According to the design and implementation of this plan, DT data is stably collected, transmitted and stored. Also, a visual service is provided to remotely monitor real-time operating status as shown in Fig 4.

Figure 4. A visualization service from DT

4. DT applicaton exploration for new energy ships

In the NES, the most critical changes compared to diesel main engine-driven and diesel-electric ships are power batteries and BMS (Battery Management System). BMS is responsible for detecting battery working conditions, estimating battery SOC and battery health, completing the functions such as thermal management, charge and discharge control, data communication, balance detection, fault diagnosis and liquid crystal display. Among them, SOC is the most important parameter, it is the basis of everything else, if there is no accurate SOC, the battery will always be in a protected state, and no amount of protection functions can make the BMS work normally, nor can it prolong the service life of the battery. In addition, high-precision SOC estimation can effectively reduce the required battery cost.

The SOC estimation battery is based on the ampere-hour integration method, the algorithm and model are solidified in the BMS controller and calibrated in the factory state. Algorithms and models are related to many physical characteristics, such as: temperature, polarization effects, battery life, etc., and have non-linear characteristics, especially SOH (State of Health) will accumulate with the use of time, and eventually lead to the SOC error in the controller becomes bigger and bigger. Re-modeling calculations using twin data in the cloud, and iterative optimization using DT is an effective strategy to solve this problem. If the initial state of charge and discharge is recorded as SOC_0, then the SOC of the current state is calculated as:

$$SOC = SOC_0 - \frac{1}{Q_N}\int_0^t KId\tau \tag{3}$$

$$K = K_t \times \eta \tag{4}$$

Where Q_N is the rated capacity of the battery at standard temperature; I is the charge and discharge current; η is the charge and discharge efficiency, also known as the Coulomb efficiency; K is a temperature-related constant, and K_t is the correction coefficient, the calculation formula is:

$$K_t = 1 + 0.008(\mathrm{T}_a - \mathrm{T}) \tag{5}$$

Ta is the standard temperature at the rated capacity of the battery, and T is the real-time ambient temperature.

The output charge is calculated from 2021-07-24 19:27:36 to 2021-07-24 19:39:31, when the controller reports that SOC is 97.6%:

$$\Delta C = \int_0^t Id\tau \div 0.95 = 34800\,\mathrm{C} \tag{6}$$

The value of I used in the calculation here is the bus current of the battery system in the left compartment, that is, the real load current. Therefore, it needs to be divided by $\eta = 0.95$ to be equal to the discharge current of the battery system itself, and the total power of the battery system in the left compartment is:

$$Q_n \approx 1120kWh \times 97\% \times 60 \times 60 \div 640V \times 1000 \approx 6111000C \tag{7}$$

Where 97% is the DCDC conversion efficiency from the battery cluster to the left compartment battery system, and 640V is the bus voltage output by the left compartment battery system, the SOC change during this time period is:

$$\Delta SOC = 34800C \div 6111000C \approx 0.57\% \tag{8}$$

We use the DT system to calculate the SOC, where the current and voltage are the output data of the left compartment battery system, which represents the real load value, and the charging and discharging efficiency uses laboratory experience values, the results are shown in Fig 5.

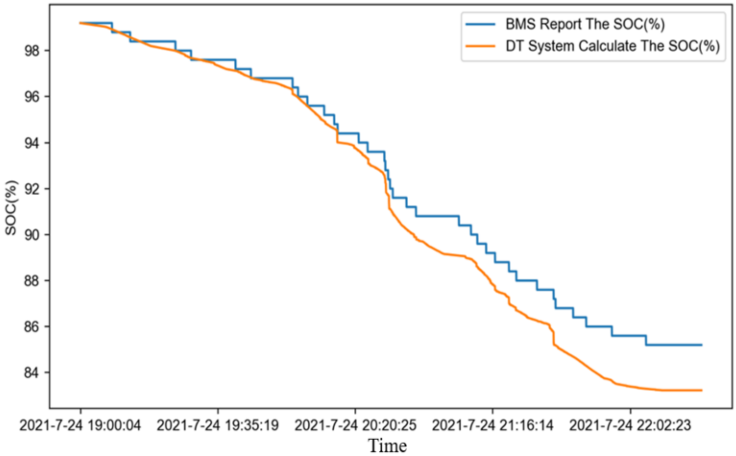

Figure 5. Comparison of SOC reported by BMS of the left compartment battery system and SOC of the DT system calculation

From the comparison of the calculation results, it can be seen that the calculated value of the DT system is continuously changing, which is basically consistent with the change of the battery's continuous output current, and conforms to the true physical characteristics of the battery. Meanwhile, it can be seen that as time increases and power consumption increases, the cumulative error of the SOC value reported by the BMS is gradually increasing.

5. Conclusion

In this paper, taking a new energy ship as the object, we summarize the definition, development status and engineering application of the DT technology, and present its overall architecture and key technical scheme. Based on this, an application exploration has been carried out in SOC estimation for BMS, and it is expected to perform a certain reference role in the design and development of new energy ships and inland green shipping.

Acknowledgments

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