

Review

Research and Development of Inland Green and Smart Ship Technologies in China

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Abstract: Nowadays, the development of green and smart ships has become a trend in the global shipping industry. Some countries such as Japan and Korea, as well as several European countries, have already made some progress and advantages. In recent years, China has issued a series of policies to encourage and support the development of green and smart ships. Beyond that, the demonstration of green and smart ships has been promoted along with the trend of larger-sized and standardized inland vessels. The Chinese status and plans of green technologies are summarized including air layer drag reduction, efficient propulsion, DC networking, and clean energy. Some smart technologies have also been illustrated, for instance, intelligent driving, intelligent engine rooms, energy efficiency, hulls, cargo control, and information integration. Smart ship technologies need to be fully validated in order to improve industrialization applications. In the shipping industry, the development and application of smart ship technology need international and inter-regional cooperation, so as to achieve much higher energy savings, ensure environmental protection, achieve collaborative intelligence, and ensure safety and reliability. In turn, this will aid economic advances worldwide.

Keywords: inland ship; green ship technology; smart ship technology



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1. Introduction

In June 2013, while in Yangluo New Port in Wuhan, General Secretary Xi Jinping pointed out that “The Yangtze River Basin must strengthen cooperation, play the role of inland waterway shipping, and turn the entire basin into a golden waterway [1].” In April 2018, General Secretary Xi Jinping inspected the Yangtze River again and presided over a symposium in Wuhan on the comprehensive promotion of the development of the Yangtze River Economic Belt. In 2020, the freight volume on the Yangtze River exceeded three billion tons, and the total economic volume of the Yangtze River Basin accounted for more than 46% of the total for the whole country. The Yangtze River Basin has become a new growth belt for China’s economy [2].

To effectively undertake the strategic transfer of industries from the eastern coastal regions to the central and western regions, and to further achieve the Yangtze River Golden Waterway, it is necessary to promote the transformation, updating, and upgrading of ships on the Yangtze River and to develop large-scale, green, smart, and standardized technology. In recent years, China has successively issued a series of policies to encourage and support the development of green and smart ships and to coordinate the promotion of pilot projects of various green smart ships [3]. Green and smart ships have become a general trend in the global shipping industry as Japan, South Korea, and European countries have begun taking action and have achieved certain first-mover advantages [4].

Japan has brought together more than 40 local companies in shipping, shipbuilding, and ship equipment manufacturing to jointly launch smart ship projects, including large ferries, container ships, passenger ships, and other ship types. By seizing this cooperative opportunity and using the capabilities of the whole country, the All Japan cooperation plan aims for half of ships to be autonomous by 2040 [5]. The South Korean government created the Smart Ship x.0 plan [6]. In April 2020, Hyundai Heavy Industries of South Korea installed a modern smart navigation assistance system on a 250,000 ton bulk carrier to autonomously identify surrounding ships and use augmented reality for collision avoidance warning.

European countries are actively developing test smart ships. In December 2018, Rolls-Royce and Finferries put into operation the world's first smart ferry, Falco, as shown in Figure 1, which operates in the archipelago in the southern part of Turku, Finland. The ship has a certain autonomous navigation capability and can autonomously avoid collisions [7]. In May 2018, the 42 m-long carbon fiber all-electric catamaran “Future of The Fjords” began sailing, and is the first vessel of its kind to offer completely emissions-free transport through the Western Norwegian landscape [8]. In February 2020, the Kongsberg Group conducted adaptive transit on the ferry Basto Fosen VI, which has functions such as enhanced intelligent perception, autonomous docking and undocking, hazard warning, and route planning, and the equipment at the ship's ends can be fully operated automatically [9].



Figure 1. The autonomous ferry “Falco”.

China is also actively researching and developing smart ship technology. In December 2017, the world's first smart ship, Dazhi, as shown in Figure 2, was put into operation; it was independently developed by the China State Shipbuilding Corporation. Since then, this company has successively developed and built ships with smart navigation functions, such as the 400,000 ton super-large ore ship Mingyuan and the super-large oil tanker Kaizheng. Wuhan University of Technology has undertaken the inland waterway green and smart ship project to promote the green and smart development of inland ships.



Figure 2. “Dazhi” smart bulk carrier.

2. The Current State of China's Inland Waterways and Ships

There are seven major waterway systems in China. From north to south, they are the Songhua River System, the Liao River System, the Haihe River System, the Yellow River System, the Huai River System, the Yangtze River System, and the Pearl River System. At present, the construction of the Han River and the Jiang-Han Canal, the Jining-Hangzhou section of the Beijing-Hangzhou Canal, the Jiang-Huai Canal, the Zhe-Gan Canal, and the

Yu-Qian-Gui Canal has mostly been completed. The Beijing-Jining section of the Beijing-Hangzhou Canal, the Xiang-Gui Canal, the Gan-Yue Canal, and the Pinglu Canal are under construction or under planning. These form a layout with four horizontal and four vertical waterways with a two-network transportation system [10], as shown in Figure 3. “Four horizontal waterways” refers to the Yangtze River, Xijiang, Huai River and Heilong River waterway. “Four vertical waterways” refers to the Beijing-Hangzhou Canal, the Jiang-Huai Canal, the Zhejiang-Gan-Yue Canal and the Han-Xiang-Gui Canal. “Two networks” refers to the high-grade waterway networks of the Yangtze River Delta and the Pearl River Delta.

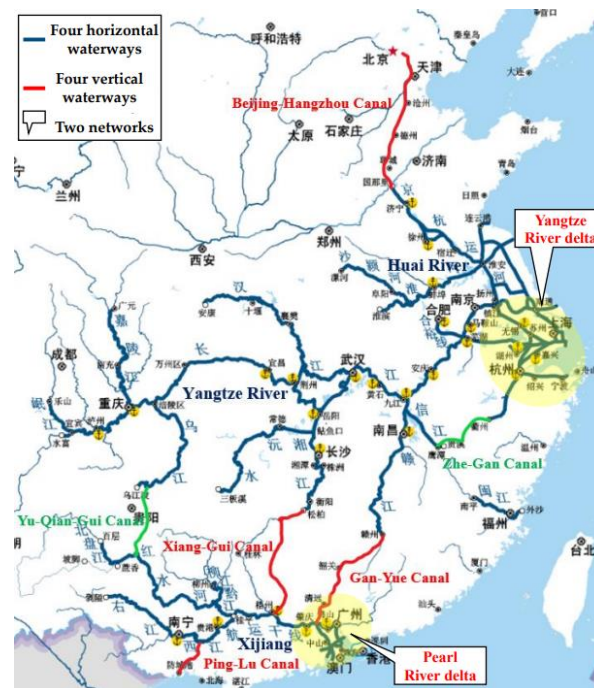


Figure 3. Map of inland waterway in China.

The Yangtze River has the longest navigable major routes, with more than 100,000 existing ships, and thus, it is the most representative. Due to the lack of overall planning, the ships navigating the Yangtze River compete with each other, and most of them are old ships. These factors significantly affect the capacity, structure, and functions of the golden waterway [11–14]. These ships are mainly characterized as follows:

1. Ships generally have small tonnage, high emissions, and low efficiency.
2. There is a lack of smart technology, excessive reliance on the crew, occurrence of many accidents, and poor safety records.
3. There is insufficient application of energy-saving and environmental-protection technology, resulting in high energy consumption and poor economic performance.
4. Ship technology is old and unable to fully adapt to the current states and development of various aspects of the infrastructure, such as waterways and ports.

The ships on the Yangtze River can no longer meet the needs of current economic and social development [15] and urgently need to be updated, transformed, and replaced. The Yangtze River is a natural waterway, which restricts the lengths of ships, and the clearance of the bridges restricts the heights of ships. Therefore, the shipping market's demand for large-capacity ships can only be met by adjusting the ship width to develop wide and flat ships.

After nearly two decades of joint research [16] and with the support of the European Union (EU) Asian-Link project (which is established to promote regional and multi-lateral exchange and cooperation between EU member states and higher education institutions in South Asia, Southeast Asia, and China) as well as national, provincial, and municipal

projects, our research team has achieved a series of innovative results in wide, flat, and green ship technology for application on the Yangtze River. Now, our team is undertaking research, development, and a pilot application of smart ship technology. In 2018, the 1140 Twenty-foot Equivalent Unit (TEU) river-sea-going container ships Hanhai 1, Hanhai 2, Hanhai 3, Hanhai 5, and Hanhai 7, which we developed, were successively placed into operation. Compared with the best ships on the market at the time (700 TEU), the transportation efficiency of these ships was increased by 50%, fuel consumption was reduced by 30%, and emissions were reduced by 40%. Known by the industry and the media as the “Renaissance on the Yangtze River” [17], the operation of these ships is referred to as a disruptive revolution in Yangtze River shipping. We have enabled large ships to reach the sea and solved the problems of sea ships being unable to enter the river or river ships being unable to go out to sea. This revolution initiated the Thousand Container Era of shipping in the midstream of the Yangtze River [18]. Hanhai 1 was selected as the 2018 Global Star Ship, and the development of wide and flat river-sea-going ships won first prize at the Hubei Province Technology Invention Awards in 2019. The 1140 TEU river-sea-going container ship Hanhai 1 with a wide, flat, and large ship shape is 129.8 m long, 23.9 m wide, and 11 m deep, which has a reference load capacity of 13,500 tons. It is the largest ship type navigating both the Yangtze River and the open sea in China.

3. Current Inland Green and Smart Ship Technology in China

Inland ships generally have limited drafts, and they dock and undock frequently [19]. The applicable ship types are quite different from those of sea-going ships. This section will describe inland ship technology, green ship technology, and smart ship technology.

3.1. Inland Ship Technology

Due to the requirements of the large-scale shipping market, inland ships are characterized by being wide, shallow, and full form, with a large breadth draft ratio (B/T) and a large block coefficient (C_b), and generally navigating at low speeds. To achieve excellent performance of inland ships, it is necessary to develop a ship characterized by a large capacity, low fuel consumption, environmental-protection capabilities, and high efficiency. Such a ship should be developed from wide, flat, and large-capacity ship types. It should also be maneuverable in shallow water and structurally safe and reliable.

3.1.1. Research and Development of Flat Ship Type with Full Form

The depth of inland waterways is greatly affected by the season [20], so inland ships are generally designed to have variable draft. Based on the requirements of the cargo capacity, ships are generally wide and flat, with full bows and sterns, and relatively long parallel mid-hulls. Based on the most economical ship type parameters, the initial ship profile can be determined. The bow and stern profiles can then be optimized through numerical simulations and model tests to obtain a ship profile with minimal drag forces.

Bow type: A full-form ship with a shallow draft has a full-line shape, a large wet surface area, and a low Froude number [21]. The wave-making drag accounts for a small portion of the total drag such that the viscous drag accounts for the majority of the total [22]. Optimizing the bow line shape can effectively reduce the bow wave breaking drag and bilge-vortex drag. Bulbous, forward, watermelon, and vertical bows are the four bow types commonly used in inland ships, as shown in Figures 4–7. Commercial software FLUENT (2021 R2) was used to predict the drag at different speeds. The corresponding total drag coefficients are shown in Table 1. The bulbous and vertical bows exhibited similar drag performances. In areas with restricted dimensions, such as ship locks, the vertical bow has significant advantages and was therefore adopted in the inland ship types we developed.



Figure 4. Bulbous bow calculation model.



Figure 5. Rake forward calculation model.



Figure 6. Watermelon head calculation model.



Figure 7. Vertical head calculation model.

Table 1. Calculation results of the total drag coefficient of different bow types.

Vs (kn)	Bulbous Bow	Forward Bow	Watermelon Bow	Vertical Bow
9.0	3.139	3.214	3.342	3.139
10.0	3.156	3.260	3.363	3.125
10.5	3.190	3.268	3.400	3.221
11.0	3.256	3.339	3.517	3.322

Total drag coefficient (C_T) in Table 1 is a dimensionless coefficient that represents the characteristics of total drag, which is defined as follows

$$C_T = \frac{R_T}{\frac{1}{2}\rho V^2 S} \quad (1)$$

where R_T is the total drag; ρ is the density; V is the speed of ship; S is the wet surface area of hull.

Stern type: For wide, flat, and full-form ships navigating inland waterways, their sterns contract more drastically with a high longitudinal gradient. These shapes easily lead to bilge vortices at the tail [23], resulting in increases in energy dissipation and thus increases the drag on the ship. In addition, the large block coefficient of a stern body causes uneven wake at the surface of the propeller blades [23], which affects the propulsion efficiency. For the twin-skeg ship type, the twin stern fins act as a catamaran, thereby reducing the length-to-width ratio of the ship, and slowing the degree of stern hull contraction, thus resulting in superior performance. Twin-skeg ships use the deflection of the stern fins to pre-swirl the incoming flow, which can also improve the anti-rotating propulsion effect [24] of the propeller efficiency and demonstrate excellent maneuverability. The twin stern fins combine the excellent maneuverability of the twin-skeg ship type with good resistance to slamming, making it more suitable for river-sea-going vessels in both river and sea. Adopting an external rotating twin-skeg stern shape as shown in Figure 8, a pre-swirl is formed at the propeller disc during ship navigation to improve the propulsion efficiency of the propeller.

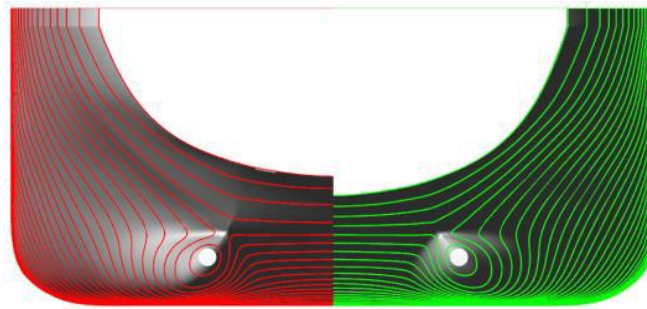


Figure 8. External rotating twin-skeg stern shape.

3.1.2. Maneuverability in Shallow Water

Inland ships must frequently dock and undock, and thus, high maneuverability is required. Further, the water depth of some voyages is shallow relative to the ship's draft. Previous research found that shallow water increases additional mass and hydrodynamic effects, reduces propeller efficiency due to vortices at the stern of the ship, and negatively impacts maneuverability [25]. Combining theoretical analysis, numerical simulations, and model tests, the motions of inland ships at different speeds and residual water depths was simulated. Through analysis of the flow field around the test hull of the virtual plane motion mechanism, changes in the ship attitude and motion characteristics with respect to the speed and residual water depth were obtained. Equations were developed to evaluate the maneuverability of inland ships in shallow water channels. Using turning and Z-shape model tests, the parameters that characterized the ship's maneuverability, such as the longitudinal distance, slewing diameter, and overtaking angle were studied. The results provide a basis for the navigation of ships in shallow water areas.

3.1.3. Lightweight Structure

To assess structural safety and reliability, a load–structure integrated analysis system was constructed [26]. General arrangement, structure, outfitting equipment, and other aspects were considered, and a comprehensive optimized design was conducted with structural weight as the objective function, resulting in a design plan that effectively reduced the ship weight. The objective function is described as

$$\text{Min } M(X) = \sum_1^n M(X_i) + M_0 \quad (2)$$

First, a rational arrangement to effectively reduce the hull load caused by the difference between gravity and buoyancy under various load conditions was researched. Using a structural design platform, parametric modeling of the plate thickness, frame size, and material properties of the typical hull cross-sectional structure was optimized under multiple ship constraints such as strength, rigidity, and stability. The optimization variables for the selected structural dimensions are shown in Figure 9.

The lightweight support structures for the outfitting equipment were designed through direct calculation. Next, the wave dispersion conditions of the operating route were used to conduct a long-term forecast of the wave loads acting on the hull from which the equivalent design wave heights and external forces acting on the hull were obtained for typical loading conditions at different times [27]. Based on the analysis of the nonlinear response of the structure, the durability of the hull structure was obtained to identify the ultimate sea condition that the ship could withstand or the structural safety margin under a specified sea condition. Finally, a three-dimensional finite-element model of the entire ship structure was built based on the requirements in the guidance for the direct calculation of hull structures. The deformation and corresponding stress distribution of each component, as well as the buckling strength, were analyzed by directly applying calculated loads under various load and sea conditions to this model. Based on the optimization mathematical model determined above, select the appropriate optimization algorithm and iteratively calculate

the optimal solution on the optimization platform [28]. For components with high stress or those prone to buckling, their structural forms and/or sizes were modified appropriately to obtain maximum safety with minimal weight.

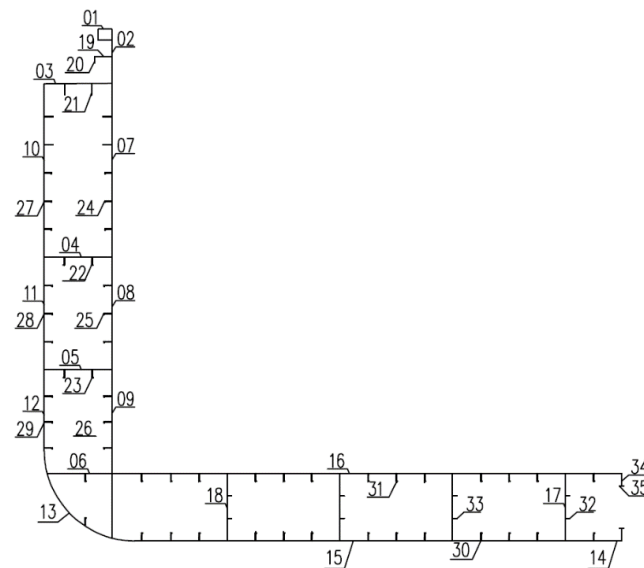


Figure 9. Optimization variables for structural dimensions.

3.1.4. Optimal Engine–Propeller Matching

Because the flow velocities of inland rivers are often high [29], the loads when the ship moves against and along the current are quite different. Using the characteristic curves of the main engines and the complex load characteristics of inland ships, multiple-operating-point propeller design was conducted to allow the propeller to work efficiently when the ship moved against and along the current. Highly efficient, wake-adapted propellers were developed based on circulation theory considering the stern circumferential and axial wake field conditions and a combination of related technologies, such as a large skew, blade tip unloading and an anti-cavitation profile. By thoroughly considering the comprehensive performance of propellers, such as the efficiency, cavitation, and vibration, and through model self-propelled tests, the propulsion performance of real ships with adapted propellers was predicted.

3.2. Green Ship Technology

Green ship technology refers to the ability to economically satisfy function and performance during the entire life cycle, while improving energy efficiency, reducing or eliminating environmental pollution, and providing good protection to operators and crews. Popular green ship technologies in China, such as surface drag reduction, direct current networking, clean energy and power, integration of energy-saving technologies, and cabin noise control, will be concisely introduced.

3.2.1. Surface Drag Reduction

By combining long-lasting antifouling and high-efficiency drag reduction coating technology with air layer drag reduction technology, drag reduction and a smart control system for inland ships was established to achieve minimal energy consumption. First, due to the introduction of new nanocoating materials [30], the dispersity and stability characteristics of the coatings were studied by testing the mechanical properties of the coating materials, such as the adhesion, hardness, flexibility, impact drag, and tensile properties. An oil-based nanocomposite coating technology with a cross-linking agent and encapsulated fibers in each functional paint layer was developed, resulting in a long-lasting antifouling, efficient drag reduction integrated ship coating technology [30]. Further, as

the viscosity of water is 1000 fold that of air, the introduction of an air layer between the bottom of the ship and the water can greatly reduce the frictional drag. Through the design of an air layer drag reduction system and the construction of an adaptive air flow smart control system, a real ship process implementation plan and an air layer drag reduction technology was created with adaptive control of the ship surface air flow [31].

3.2.2. Direct Current (DC) Networking

Inland ships generally have a short cruising range, which provides favorable conditions for electrification. Compared with the traditional alternating current (AC) networking electric propulsion system, direct current (DC) networking electric propulsion systems are an emerging electric propulsion technology that have significant advantages in terms of energy conservation, cost, weight, and system complexity [32]. First, a DC microgrid fault analysis model was established considering the active response and transient characteristics of the converter, and a fault location method of the DC microgrid was developed under the active response of the converter. The mechanism of the elastic recovery of the ship's DC grid voltage under large disturbances was revealed, and an optimized control method provided an effective solution for resolving DC network faults.

Next, targeting the assessment of electrical equipment reliability in the Yangtze River Green Smart Ship DC Network, and based on the operation and maintenance data accumulated during the operation, an electrical equipment condition monitoring database was constructed [33]. Through comprehensive data source acquisition, combined with high-performance data processing and analysis, multi-source information fusion technology was used to monitor the states of the electrical equipment and to diagnose fault states. A scientific decision-making and maintenance information reference was provided for the management and control of inland ship DC network electrical equipment and to reduce potential safety hazards. The assessment methods of electrical equipment were also studied to improve the safety and reliability of the DC network.

Further, the variable-frequency speed regulation characteristics of the generator sets in the DC grid system were studied to ensure that the oil/gas ran along the optimal consumption curves, thereby minimizing system energy consumption and emissions and maximizing operational efficiency. The use of battery energy storage was also assessed. Considering the speed regulation characteristics of the multi-source, multi-load, and multi-scenario generator set, the optimal configuration of the DC grid batteries was studied to improve overall efficiency and to propose battery capacity and configuration specifications. Reliable and efficient operation of the power converter for the DC system was evaluated and a smart charging control method was developed, resulting in improved efficiency of the smart charge/discharge controller to achieve further energy-savings [34]. A theoretical basis for calculating the efficiency of the DC network system of river and sea ships was established and guidance and specifications for the optimized design of the system were provided. Finally, using the hierarchical control strategy of the ship's DC network energy management system based on the droop characteristics, a stable control strategy for power interactive oscillations when multiple units are connected in parallel, and an active damping control strategy for improving the damping characteristics of constant-power loads, a DC network energy management system was developed and implemented for the ship. In practical engineering applications, the ships used in this system can adopt various forms such as diesel electric hybrid, gasoline electric hybrid, and pure electric.

3.2.3. Clean Energy and Power

Low-carbon power technologies, such as liquefied natural gas (LNG) and lithium batteries, were also evaluated as a source of stable power for inland ships. For LNG, the balance between the safe and efficient use of the gas supply system and commercial cargo was addressed, and the loss of cargo space was minimized, resulting in an optimal arrangement of the LNG fuel supply system. Simulation analysis was used to optimize the system process to ensure the safety and reliability of the system. Capturing gas that

evaporates naturally in the tank and the residual natural gas in the pipeline is critical to reducing overall gas loss, which would otherwise result in lower fuel efficiency and increased emissions. Process simulations were used to configure the system equipment to efficiently solve the problem of gas loss. Technology was developed for the gas supply volume, pressure, temperature, quality control, and security of the LNG supply system.

Lithium battery power holds great potential as long as certain challenges are addressed [35]. First, battery life is greatly reduced due to the inherent inconsistency of battery cells in large-scale packs, a problem which is magnified by system temperature field differences and inconsistent current distribution [36]. Issues relevant to this problem include the field temperature distribution of marine lithium-ion battery systems, the heat generation process, heat dissipation flux demand, temperature field difference, and hot spot distribution in traditional marine battery systems under various working conditions [37]. To control battery temperature, immersion cooling technology, including the choice of the immersion media, flow channel design and optimization, and immersion convection heat exchanger [38], was evaluated. By circulating the protective liquid inside the battery system and exchanging heat with an external cooling medium, the maximum temperature rise and temperature range of the system were reduced to meet the temperature control characteristic demand during extended operation of the system.

We also evaluated active balance control technology of the new marine battery system to improve the consistency of the discharge depth of each cell in the battery system, thereby reducing the system life decay rate. This included the analysis of a battery system energy balance strategy and an active balance device, the determination of a reasonable discharge depth range suitable for long-lasting energy marine battery systems, and the establishment of a long-lasting battery system utilization strategy. Finally, the mechanical durability of the typical structures of battery systems and the compatibility of the typical materials of battery systems with an immersion protective fluid to ensure a long battery system service life were studied.

3.2.4. Integration of Energy-Saving Technologies

To achieve the best match of the ship, engine, propeller, and electricity generator for inland ships, an evaluation of the heat, machinery, electricity, and fluid, focusing on integrated energy management, and using energy efficiency design index (EEDI) minimization as the objective, was conducted. This resulted in an integrated design for energy savings and environmental protection, an integrated power plant design and optimized configuration, a pollution-free stern tube and low-noise shafting design, and a smart power station design [39].

First, an optimal arrangement of the exhaust system was designed by studying the characteristics of the exhaust noise of the main engine and comprehensively considering the exhaust volume and temperature. A new pollution-free stern tube and water lubrication system led to the design of a bilge water system that minimized waste oil discharge and achieved our environmental-protection goal. Next, an optimized propulsion system plan was designed based on comprehensive analysis of the characteristics of inland ship power plants, energy-saving and green design technical requirements, and LNG and lithium battery power characteristics [40]. An integrated design platform for inland ship power plants was built based upon power-integrated design methods and optimized configuration methods.

In addition, the torsional vibrations, cyclotron vibrations, alignment of the propulsion shafting, and the effect of external and system disturbances on the dynamic characteristics of the key shafting components were analyzed. Further, parametric mathematical and physical simulations of the shafting alignment were conducted, a shafting vibration calculation method and model under complex factors were constructed, and a low-noise shafting design analysis process and method was established for the system [41]. Finally, smart power station management systems, broadband shafting generator output frequency control, and the energy-saving efficiency were analyzed to build smart inland ship power

stations and provide support for energy savings and emission reduction in ships under complex working conditions.

3.2.5. Cabin Noise Control

Vibration and noise testing and data analysis were conducted to establish a vibration noise database and prediction platform for inland ships to guide the ship acoustic design and evaluation. Using numerical methods such as finite-element, boundary element, and a hybrid method, a vibration and noise value prediction platform and database were developed to provide technical support for cabin noise acoustic design and evaluation [42]. This included research on the evaluation of ship cabin acoustics and design according to the requirements of the acoustic control of inland ship cabins, establishing a set of rational scientific evaluation methods, and providing decision-making support for acoustic design and evaluation. We established inland water wave ship noise prediction and control technology and provided support for decision making in a soundscape design [43].

3.3. Smart Ship Technology

Smart ship technology refers to the using of information technology to automatically perceive and obtain information and data on the ship itself, marine environment, logistics, and ports so that intelligent operation can be realized in terms of navigation, management, maintenance, and cargo transportation [44]. Smart ship technology makes ships safer, more environmentally friendly, more economical and more reliable.

3.3.1. Smart Information Integration

Considering the battery modules, navigation data and environment, equipment state, and hull structure state and using advanced perception, heterogeneous network construction, data and digital twin modeling, virtual/augmented reality, and software service methods, a smart-integrated platform system for inland ships was designed and developed [45]. The smart information integration system is the “heart” of the green and smart ships for inland water, as shown in Figure 10, and it is responsible for the monitoring and management of the ship’s state. Through the unified digital description and dynamic description modeling methods for heterogeneous perception data of the ship’s operating state, the dynamic unified modeling of this data was achieved. Further, an efficient data retrieval and data access sharing mechanism allows for the integrated management of heterogeneous data of the ship operating state in the shipboard server.

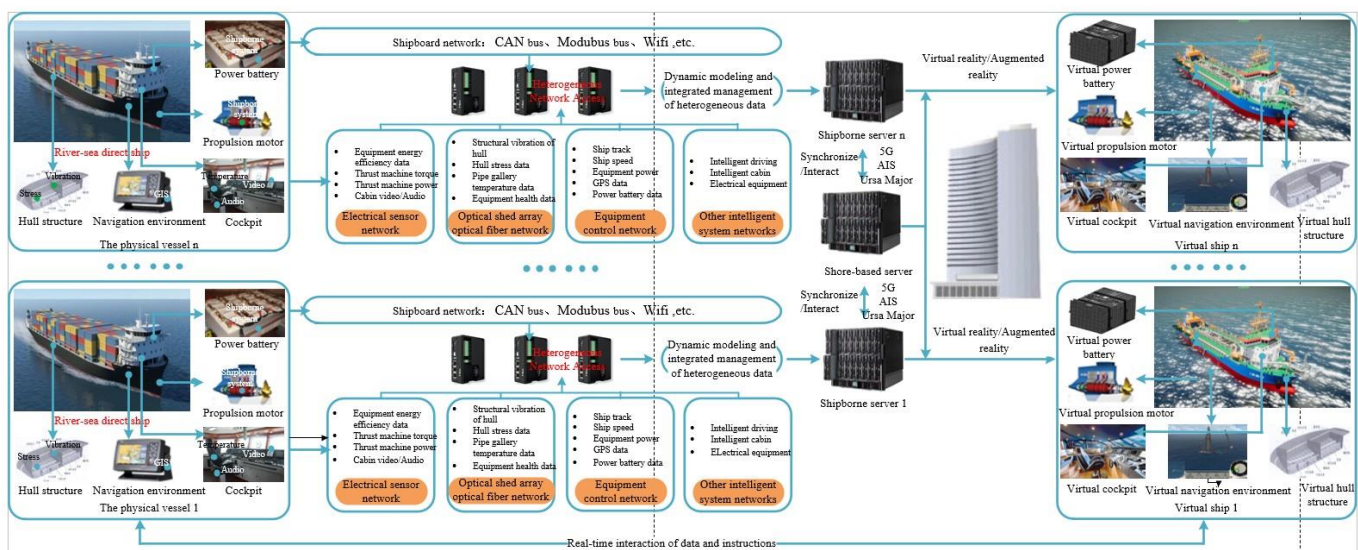


Figure 10. Structure diagram of intelligent information integration platform.

3.3.2. Smart Engine

Through sensing technology, it is possible to remotely control the operating state of the equipment in the engine room in real time and provide early warning information and maintenance plans in a timely manner, eliminating the need for crew members to monitor the equipment operation in the engine room. The horizontal, longitudinal, and torsional vibrations of propulsion shafting can directly reflect the health of the propulsion and transmission system. The system's shafting power can be used to monitor the transmission efficiency of the engine, gearbox, and shafting in real time. A multi-dimensional vibration and shafting power smart sensing system was established based on data mining to evaluate the operating state of the shafting [46].

It is also possible to evaluate the air compressor state based on the vibration method, the multi-parameter gearbox state, and the pump state based on vibration and thermal parameters. An evaluation method of the health of the ship's main engine, auxiliary engine, and main equipment was also established to ensure that the equipment in the engine room operates safely and reliably. The system includes smart decision-making methods for fault diagnosis of the engine room equipment, spare part trend analysis, and predictive evaluation methods based on spare part consumption statistics [47]. Dynamic inventory management software was developed based on handheld terminals and radio-frequency identification (RFID) electronic tags for spare part warehousing, storage, retrieval, early warning, and purchase reminders. Furthermore, spare part prediction and assessment methods were developed based on the analysis of engine room equipment health management data, as was a dynamic spare part management module based on intelligent data analysis. By studying the analysis of monitoring data and the prediction and evaluation of the main equipment in the engine room, basic parameters, such as the health state, fault diagnosis, and maintenance information for each piece of equipment can be assessed, allowing for a condition-based equipment maintenance strategy to achieve the dynamic management of spare parts, maintenance support, and efficient equipment operation.

3.3.3. Smart Navigation

Computer and control technology is used to analyze and process the acquired information to assist the captain in designing and optimizing the ship's route and speed. With the help of a shore-based support center, this technology informs the captain's decision making in open waters, narrow waterways, and complex environmental conditions [48]. Channel information and smart perception of the ship attitude in the complex navigation environment of inland waterways can provide dynamic, real-time, and reliable environment and ship navigation information for decision making. We mainly performed work on characterization technology of the navigation environment of inland ships, multi-source heterogeneous data fusion technology, and situational awareness-based smart navigation eye technology. Complex inland waterways make it necessary to also smartly analyze collision avoidance rules [49]. We conducted technical research on route/speed design and optimization based on multi-objective deep reinforcement learning to provide effective decision-making information and form a smart navigation assistance decision-making system. Figure 11 shows the block diagram of the navigation decision making for inland ships in a typical situation.

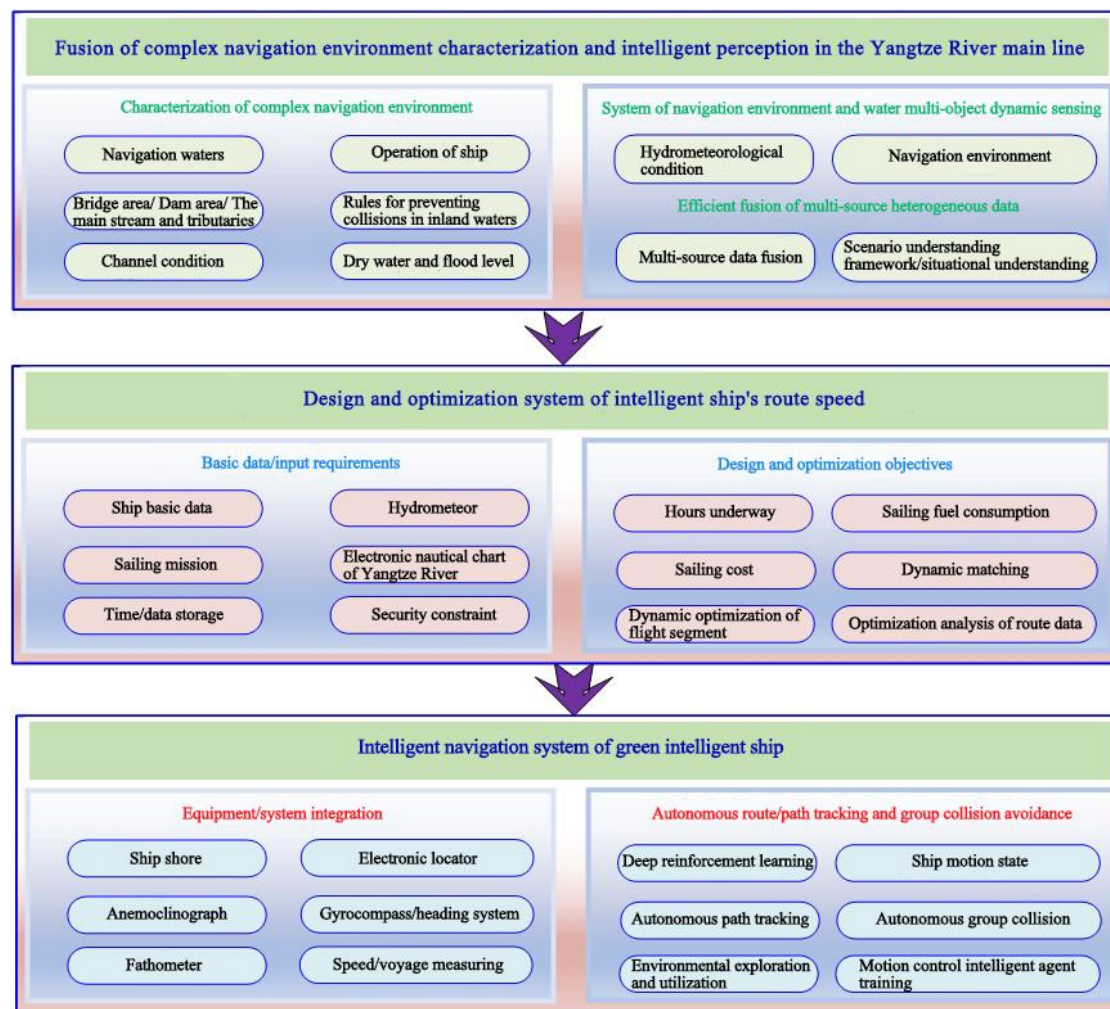


Figure 11. Green intelligent navigation decision block diagram of inland rivers.

3.3.4. Smart Energy Efficiency

Through the smart energy efficiency system, energy savings and emissions reduction were effectively achieved, laying the foundation for Yangtze River green and smart port shipping. Methods for collecting the key parameters, fuel consumption, and oil volume of the energy-consuming equipment, such as green smart ship main and auxiliary engines, and data collection devices, such as anemometers, global position system (GPS) devices, inclinometers, and ship draft sensors, were developed [50]. Using the equipment energy consumption and navigation state parameters of the whole ship, a data collection technology and system was developed, an equipment energy consumption data platform was established, and the ship's energy consumption states were controlled [51]. We conducted research on the design of an energy-efficient smart management platform system, key platform data exchange and communication technologies, and platform system data storage to achieve smart management of a ship's efficient energy usage.

3.3.5. Smart Hull

Based upon the characteristics of the hull structure and load characteristics, the measurement variables and point arrangement plan are determined and the corresponding distributed sensor demodulation plan was optimized to obtain large-capacity demodulation data. Then, efficient and accurate multi-scene fusion and characteristic signal extraction algorithms were performed [52]. Stress sensing information in complex environments, such as the ship's total strength distributed stress and local strength structural stress were

acquired, and real-time data support for the safety and reliability of the hull structure was provided, as shown in Figure 12.

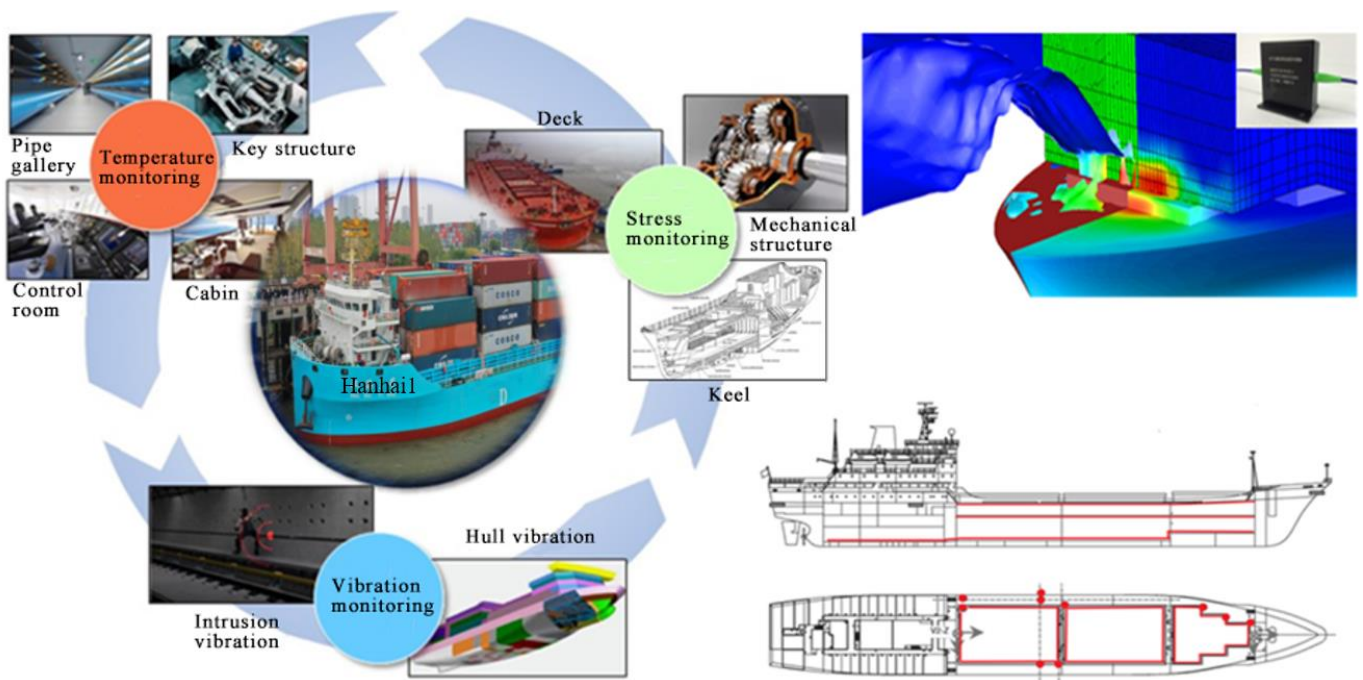


Figure 12. Schematic diagram of intelligent hull system.

3.3.6. Smart Cargo Control

Ship–shore cargo integrated information perception, location, and transmission technology were studied. With ports as the keys to track cargo and coordinate cargo organization, distribution, and dispatching, transparent and efficient logistics processes were achieved, and a logistics framework was built for group intelligence collaboration [53], as shown in Figure 13.

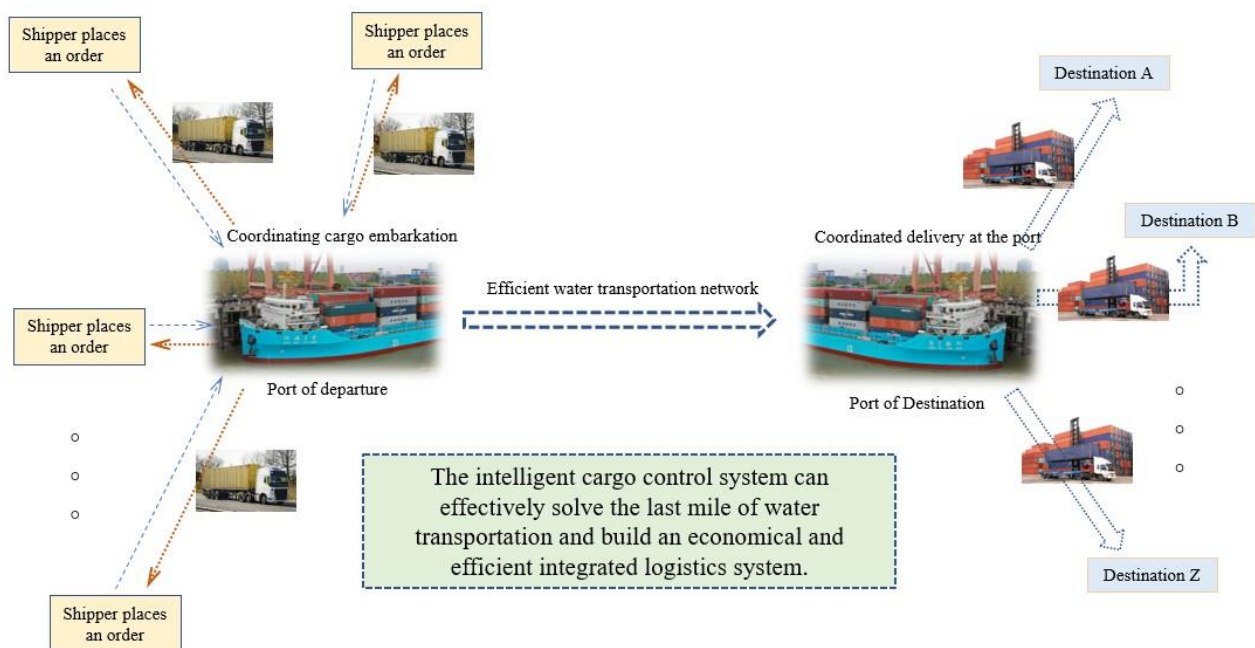


Figure 13. Schematic diagram of the intelligent cargo control system.

4. Inland Green Smart Test Ship

Ships are complex floating on the water and green smart ship technology needs to be fully verified before it is applied and industrialized. It is therefore necessary to build an inland green smart test ship to provide a stable and reliable test platform for the technology on-board applications and multi-level actual navigating route testing.

4.1. Introduction to Test Ship

Based on the purpose and requirements of the test, the overall design of the inland water green smart test ship was determined. The ship could test and verify low-drag and high-efficiency ship types, high-efficiency propulsion systems, energy-conservation appendages, and other ship-type technologies; surface drag reduction systems, clean energy power systems, DC networks, other green ship technologies; and smart perception, smart control, smart engine, smart decks machinery, smart hull, and smart information integration, and other smart ship technologies.

Using the test ship in the closed waters, Han River, and Yangtze River performs multi-level testing and verification in order to address the major issues, such as the integration of green and smart key technologies, formulation of standards, smart equipment innovation, smart assurance of channel security, and channel environment monitoring for inland ships. We provided tests and a test basis for real-world ship applications. This work can guide the R&D and application of high-end smart supporting products for inland waterway shipping, promote the smart technological innovation and industrial upgrading of China's inland ship, and promote the high-quality development of the inland waterway industry. This will further promote the development of China's smart ship research and development, design and construction, operation, and management toward the integration of green, smart, safe, and efficient informatization. It will also promote the development of China's ship-supporting industry with core smart technology and China-owned brands.

4.2. Overall Design of Test Ship

The test ship plan was implemented in three phases. The first phase was to achieve onboard intelligence, the second phase was to achieve ship–shore interconnection and formation of a group smart collaboration framework, and the third phase was to achieve unmanned autonomy. 5G technology, industrial internet, artificial intelligence, and other information technologies were combined with traditional ship technology. Based on traditional ships with steel frames, a smart ship was built with a thinking ability and characteristics of a living organism, using distributed optical fiber sensing as the nerves, a digital twin as the muscles, and information integration as the brain. Smart tests were conducted along specific routes in closed waterways, on the Han River, the Yangtze River, and other waterways, to form a series of guides for Yangtze River smart ships, and to demonstrate applications to form a new framework for Yangtze River shipping with comprehensive information perception, super energy-saving and environmental-protection abilities, intrinsic safety and reliability, and group smart collaboration. This work promotes the development of large-scale, green, smart, and standardized ships on the Yangtze River, and it promotes the construction of China's smart shipping regulation system.

While the overall design of the test ship needs to solve the basic problems of traditional ship design (e.g., displacement, principal dimensions, and ship form factors), the preliminary design of various smart system modules also needs to be considered. Based on the functional division, we plan to develop the following seven modular designs: a smart perception module, smart control module, smart engine module, smart deck machinery module, new energy-saving module, smart hull module, and smart information integration module. All of the smart system modules will be arranged reasonably to ensure the smooth installation and test verification of each module. At the same time, the installation and replacement of major smart systems on new and old ships must be considered.

The smart perception module will use distributed optical fiber sensing technology for real-time data collection and analysis to monitor the health of various smart system

modules. The smart control module will apply smart control technology to achieve assisted driving, speed planning, and collision avoidance. The smart engine module will use smart robot technology to inspect the engine room to realize the condition-based maintenance of the engine room equipment. The smart deck machinery module will adopt smart hoisting equipment for the rapid and safe lifting of goods. The new energy-saving module will adopt new energy-saving devices to achieve the best trim, equipment energy efficiency management, and integrated drag reduction. The smart hull module will use perception and hull technology to achieve structural health monitoring and reliability assessment, to synchronously perceive the external environment and the hull structural response, and to collect real-time analysis of data to provide a basis for the captain to make decisions. The smart information integration module will use information management and processing technology to aggregate, analyze, display, store, and transmit multi-source information of the ship's equipment and systems.

4.3. Modular Function Arrangement Optimization

According to the functions to be implemented by the major modules, the respective characteristics of each module were analyzed, and the environmental and arrangement requirements, such as the space and temperature requirements, during independent operation of each module were studied. The cross-correlation between the major modules was also studied, and a local area network system of integrated and interconnected systems in the ship was established. This included the integration of the infrastructure, such as integrated network design and construction, cloud platform construction, and database cluster construction.

For application integration, the smart navigation, engine room, and energy efficiency management systems are integrated on the platform's service-oriented architecture, and the network remote monitoring interface is unified. For service integration, there are common systems for smart navigation, engine room, and energy efficiency management systems. For the services that are of a public nature and are reused, service integration is performed on a software data bus, while the platform provides public services for each subsystem. For data integration, according to data integration specifications, two-way data are provided between the platform and each subsystem. For transmission integration, data are transmitted in a timely, reliable, and safe manner, in accordance with data collection and transmission specifications and ship–shore data interaction specifications. Through the corresponding auxiliary decision-making functions of the smart navigation, engine room, and energy efficiency management systems, as well as the comprehensive auxiliary decision-making function of the platform's integrated management system, the auxiliary decision making of ship operation and management is achieved. By intelligent perception and online monitoring of the main engine, auxiliary engines, and pumps in the cabin, the working condition of the equipment is clarified, and “condition-based maintenance” is achieved. By perceiving and analyzing the energy consumption status of ships and energy consuming equipment, navigation strategies are formulated to achieve energy efficiency improvement.

Smart hull and sensing systems were integrated to simultaneously sense the external environment and the ship's structural response. The form of the hull longitudinal strength monitoring measuring points, local strength monitoring measuring point network arrangement, and hull monitoring strength analysis and evaluation technology was researched to achieve real-time monitoring of the health of the hull structure and assessment of the structural reliability.

All of the smart system modules are reasonably arranged on the test ship. To ensure the smooth installation, testing, and verification of each module, the actual operation of each smart module was considered, and characteristic analysis and parameter evaluation was conducted. According to the defined objective function, modular arrangement optimization to obtain the overall function with demand optimization was also conducted. To ensure the installation and replacement of various smart systems on new and old ships, the test

ship was designed with an open structure that can be reconfigured in various ways. Based on the task requirements, it can be assembled and matched with different smart modules to achieve plug-and-play capabilities.

4.4. Design of a Dynamic Test System

Based on multiple sensing monitoring methods, such as traditional point sensors, fiber grating sensors, and ship-borne system operating parameter sensors, changes in parameters, such as the key equipment parameters of the ship's smart compartment, image signals, and audio signals of the ship's operating states, are sensed. The distributed temperature, optical grating array fiber-based strain, and vibration sensing are used to obtain a comprehensive recording of the safety and damage of ship cabins, engine rooms, cables, corridors, and other hull structures, and real-time online monitoring of the health of the key equipment of the smart modules.

In addition to the perception data of external sensors, ship operation data also include real-time readings from the shipboard operation system. There are many types of shipboard smart operation modules, and their core controllers are also different. According to the different controller models and operating system types, a suitable state data reading method is adopted to realize multi-parameter real-time reading of shipborne operating data. A distributed data processing server was established and a rapid data processing system for smart ship data in complex waters was designed. The multi-source heterogeneous data organization method of the distribution differences of various systems was also studied. The effective key information obtained by the ship's smart perception capabilities is extracted to achieve the spatiotemporal registration and standardization of these data. Based on the optimized arrangement of each smart module, the scene knowledge map of the shipboard system is constructed to achieve the rapid integration of the data.

The operation of ships involves heterogeneous transmission networks, such as perception networks, shipborne data transmission networks, and equipment networks. Transmission networks have heterogeneous characteristics due to differences in the transmission protocols, data capacities, and data types. Based on the heterogeneity of the transmission network in the ship's operation process, a transmission network for the ship was constructed. Based on the characteristics of the ship's operation data, the structure and transmission protocol characteristics of the perception data can be described in the form of data information modules. To realize automatic analysis and access of perception data, adapters were dynamically generated to allow the ship operation process to adapt to and access these data. By combining the characteristics of the ship's operation process data, and through the dimensionality reduction processing of the data, we can perform dynamic aggregation of perception data and integration of smart information in the ship operation process.

The ocean–river test ship integrates the seven system modules described previously. By dynamically testing the parameter characteristics that each module needs to achieve in independent operation, the safety, reliability, and stability of each module's operation and the achievement of various indicators can be verified. This also allows for the determination of core input–output variables, building of an overall dynamic test system, conduct of joint testing of the multi-module cooperative operation of the smart ship ecosystem, analysis of the coordination of the integration of each smart module, and provision of real-time feedback to the terminal to assist in decision making and correction.

4.5. Multi-Level Test Verification

The test ship is a smart organism composed of the ship's hull and distributed system modules. First, a closed-waterway test was conducted on the hull to meet various navigation requirements of inland ships. Independent product tests were then conducted on each smart module system to verify that the specifications met the boarding requirement, and that each independent module matched the reserved interface standards of the ship's hull. Next, the major modules were installed on the test ship platform to form a complete

system, and the system was debugged to ensure that all subsystems met independent operation specifications and the coordinated operation specifications. Further, the stability and reliability of the integrated operation of each module were verified. Finally, the entire smart ship system was tested in an all-round and multi-scale manner using the dynamic test system to assure that each module met independent test specifications as well as the overall system operation specifications.

Through the digital twin, a technology that combines virtual and real systems, a virtual navigation environment was built to test the real ship systems under various scenarios in different waterways. A closed waterway test field was established and evaluation of the ship's smart systems was conducted to verify the stability of each system and various product performances when operating in a simple waterway. Multi-level navigation tests of the smart ship were conducted on specific routes, such as the Han River and the Yangtze River, including actual operation tests on various smart system modules. Tests completed included the smart perception of the navigation environment for specific routes, the autonomous evasion of multi-ship counterparts, the smart host combined propulsion, the autonomous planning of navigation trajectories, and the smart operation of engine room deck machinery. The "virtual navigation environment" is a ship navigation environment model formed by multi-source perception of the ship's surrounding environment information, image stitching, enhancement, and fusion.

5. Conclusions

Inland waterway shipping is an inevitable element of a highly developed economy. Along with the development of China's economy and society, inland waterway shipping has developed rapidly in recent years. Based on our team's research on inland waterway shipping over the years, we have described the current state of China's inland waterways and ships, the current technical research on green and smart inland ships, and the overall state of planned smart tests. The development of smart technology is still growing. With the continuous breakthrough of information technology, such as cloud computing, artificial intelligence, and big data, ship intelligence will also continue to develop, pushing ships toward a safer, more environmentally friendly, and more reliable application. The goal is for various industries to work collaboratively to develop the core technologies of smart ships, to promote the progress and adoption of smart ships, and to provide high-quality and efficient shipping support for global societies.

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