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Research on the Intelligent Transformation Path of the Port and Logistics Electromechanical Industry

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Abstract. The port and logistics electromechanical industry underpins port production and supply chain operation, and its level of intelligentization is directly related to the improvement of operational efficiency and industrial capacity. This paper reviews the evolution of this industry from equipment-dominated and system integration toward intelligentization, and, in combination with the implementation of three types of technologies—the Internet of Things and 5G communication, artificial intelligence and big data, and intelligent control and digital twin—in terminals, discusses the drivers behind the shift of the industry's center of value toward software and algorithmic capabilities. Among these, the position of the software segment, represented by the Terminal Operating System (TOS) and the Equipment Control System (ECS), in the industrial chain keeps rising, and the traditional division of labor formed around equipment manufacturing is being adjusted accordingly. On this basis, the paper puts forward suggestions on the transformation path from three dimensions—layered advancement, industrial coordination, and policy support—for reference by the port electromechanical industry.

Keywords: Port electromechanical industry, Industrial development, Intelligent transformation, Automated terminal

1. Introduction

Ports perform a hub function in the global logistics network, and the technical level of the port electromechanical industry affects, to a large extent, the efficiency of international trade and the stability of the global supply chain. Looking back over more than forty years of development, this industry has gone through two rounds of major upgrading: from the late 1980s to the 1990s, along with the deepening and specialization of berths, Chinese ports completed the shift from mechanization to electrification and automation; after entering the 21st century, China's port machinery industry kept breaking through on both the technology and market fronts, and the port industry moved accordingly into a period of transformation and upgrading, with intelligentization and greening becoming the dominant directions [1]. In recent years, a new generation of information technologies such as 5G communication, artificial intelligence, IoT sensing, and digital twin has accelerated its entry into port scenarios, and the basis for operational decisions is shifting from experience-based judgment to data analysis. In December 2021, the 'Smart Port 2.0' jointly built by

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Dongfeng Motor, China Mobile, and China COSCO Shipping was put into commercial operation at the Xiamen Yuanhai Terminal (see Figure 1), and key technologies such as the 5G high-medium-low frequency three-dimensional networking and the mixed operation of unmanned container trucks in open scenarios were systematically verified; the quay crane single-machine operation efficiency of Qingdao Port's fully automated container terminal has repeatedly refreshed world records, and the operational level of the Yangshan Phase IV automated terminal is also at the global leading position. These cases illustrate from different angles that information technology has begun to rewrite the basic logic of port operation. It deserves attention that the center of value of the port electromechanical industry is also shifting: from hardware equipment and integration engineering, to software platforms, algorithmic logic, and data analysis capabilities represented by the Terminal Operating System (TOS) and the Equipment Control System (ECS).



Figure 1. Commercial operation of 'Smart Port 2.0' at Xiamen Yuanhai Terminal

By the end of 2025, the container and dry bulk automated terminals cumulatively built in China have reached 60, and their application scale, operation efficiency, and technical level are all among the world's leading. These practices also show that the changes brought by intelligentization are not limited to the technical forms of equipment and control systems, and the organizational structure, operation process, and even management philosophy of ports must be adjusted accordingly [2]. For ports that are shifting from traditional transport nodes to smart supply chain hubs, this threshold cannot be bypassed, nor can it be achieved overnight.

Around smart ports and port intelligentization, the academic community has accumulated a considerable number of research results in recent years. Belmoukari et al. [3] conducted a systematic review of smart port literature and defined the technical composition and application dimensions of smart ports; Paraskevas et al. [4] summarized the main technical themes and future directions of smart port research from the perspective of Industry 4.0. In terms of specific technologies, Potter et al. [5] investigated the promotion process of 5G in European ports and found that inconsistent standards and uncertain return on investment are the main constraints on large-scale application; Klar et al. [6], drawing on the experience of smart cities and supply chain twins, proposed a construction path for port digital twins; Neugebauer et al. [7] pointed out in their review that digital twins are becoming the core tool for the digitalization of seaports and terminal facilities. In the direction of operation optimization, Guo et al. [8] introduced multi-action deep reinforcement learning into the joint decision-making of vessel scheduling and tugboat allocation; Aslam et al. [9] used port machinery IoT sensing data to train fault prediction models and verified the supporting value of machine learning for maintenance decisions. Domestic research is strong in automated

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terminal engineering practice, and Zou et al. [10] bibliometric analysis outlined the hotspot distribution of research on intelligent shipping and automated port infrastructure. Existing results mostly start from a single perspective of information technology application or port operation management, and systematic reviews specifically oriented to the port electromechanical industry and connecting the two main lines of equipment manufacturing and software systems are still rare.

At the same time, it should also be seen that, although China's port automation construction has made considerable progress, there are still many difficulties in the transformation: the intelligentization level gap between coastal and inland ports, and between large hub ports and small and medium-sized ports, is obvious; the degree of independent controllability of core software such as TOS and key algorithms is not high, and the localization rate needs to be improved; intelligent renovation often involves billions of yuan in investment, compounded by organizational structure adjustment, and both industry and academia are still exploring how to evaluate input-output and how to choose the path. Against this background, a systematic review of the evolution, key technology system, and implementation path of the intelligent transformation of the port electromechanical industry has both theoretical significance and practical value for guiding the high-quality development of the industry.

2. Evolution of industrial development

2.1. Equipment-dominated stage — large-scale and mechanization

In the late 20th century, the economic globalization and the popularization of container transport drove the rapid growth of international trade volume—the proportion of world export trade in GDP rose from about 10% in 1970 to 20% in 2000, and the large-scale port equipment completed multiple rounds of technological iteration during this period. At that time, the competitiveness of the port electromechanical industry was mainly reflected in the design, manufacturing, and on-time delivery capabilities of large port machinery, and the operating parameters such as the lifting capacity, outreach, trolley speed, and overall stability of quay cranes and yard cranes were the basic yardsticks for measuring whether a piece of equipment was advanced.

After Zhenhua Port Machinery delivered its first quay crane to the Port of Vancouver in Canada in 1991 (see Figure 2), by 1998 its order volume had accounted for more than half of the global total, breaking the long-term monopoly of European and American manufacturers. However, during this period the automation and informatization level of port equipment was still at a primary stage; all kinds of equipment generally adopted independent unitized electrical control schemes, the coupling degree between systems was low, equipment operation lacked overall collaborative optimization, and operations were highly dependent on manual operation. This mode oriented toward single-point efficiency improvement improved the operation capacity and labor productivity of ports to a certain extent, but there was a lack of overall strategic planning between ports and the industry, and the functional connection stayed at the level of logistics links, making it difficult to support the industrial chain in forming a joint force for linked development.

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Figure 2. Quay crane built by Zhenhua Heavy Industries (then Zhenhua Port Machinery) for the Port of Vancouver

2.2. System integration stage — automation and informatization

After entering the 21st century, with the growth of throughput and the complication of operation processes, isolated and scattered equipment units could no longer meet the operation efficiency needs of ports, and the electromechanical integration of multiple equipment and heterogeneous systems became a new bottleneck. The rise of system integration services gave birth to the engineering general contracting model, and the center of value of the port electromechanical industry shifted from single equipment manufacturing to system integration capability. ABB's early shore power scheme adopted the supply model from equipment packaging to system integration, integrating modules such as medium and high voltage switchgear, transformers, variable frequency and voltage transformation, and control and protection into a complete system.

In the same period, some terminals in Europe began to introduce automated rail-mounted gantry cranes and other equipment at the yard level to explore operation automation, but integrators faced huge technical challenges such as inconsistent communication protocols and data formats when connecting the automation systems of different suppliers with manual operation systems. After 2010, the successful commercial operation of the world's first batch of fully automated terminals brought about a substantial leap in port transport efficiency. Taking the Yangshan Phase IV Terminal of Shanghai Port as an example, as the world's largest automated container terminal, its operation efficiency is more than 10% higher than that of traditional terminals; after digital-intelligent upgrading (see Figure 3), the overall operation efficiency of Qingdao Port's fully automated container terminal is 30% higher than that of traditional terminals, and its highest loading and unloading efficiency has refreshed the world record 13 times. During this period, the value core of the port electromechanical industry underwent a fundamental shift: from equipment and integration engineering to software platforms, algorithms, and data analysis capabilities represented by TOS and ECS. Software systems are no longer mere auxiliary tools, and have gradually become the core element occupying a dominant position in the port electromechanical industrial chain.

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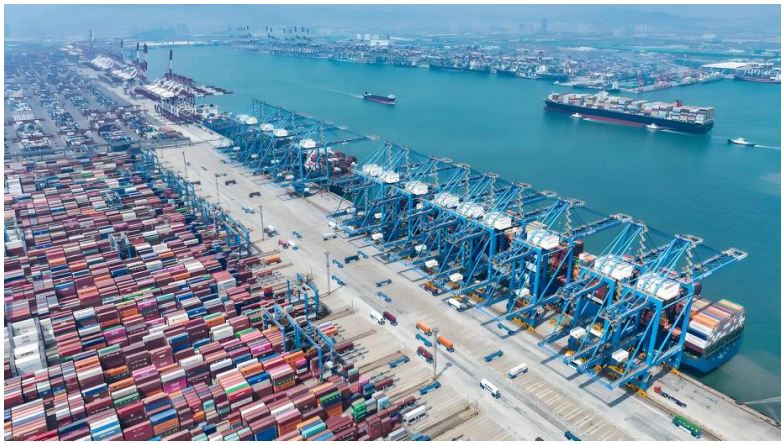


Figure 3. Qingdao Port fully automated container terminal

2.3. Intelligent stage — data-driven and autonomous decision-making

In recent years, the competition focus between ports has gradually shifted from the degree of automation to higher-level intelligentization and digitalization capabilities. The market position of TOS manufacturers represented by Navis has been continuously consolidated—TOS is equivalent to the 'brain' of automated terminals, scheduling quay cranes, yard cranes, and automated rail-mounted gantry cranes in real time, coordinating the links of loading and unloading, yard, ship schedule, and gate, so terminal operation gradually reduces its dependence on manual experience. About 70% of the world's top 100 container ports have deployed commercial TOS systems, and case studies of Japanese ports also show a clear association between the selection of terminal operation systems and the port governance structure [11]. After technologies such as 5G, artificial intelligence, and digital twins entered ports, the functional boundary of automation systems was further broadened, and software capability began to determine the efficiency ceiling, expansion space, and operational resilience of terminals. An international hub port, after three phases of smart upgrading, used intelligent algorithms, automated equipment, and digital twin systems to compress the time ships spend in port and increase throughput; the digital twin platform of a coastal port can simulate the operation status of the port area in real time, providing an intuitive reference for management decisions. In terms of technical characteristics, the systems at this stage begin to have self-learning, predictive maintenance, and global optimization capabilities, and machines no longer merely execute tasks according to preset programs.

3. Key technologies for intelligent transformation

3.1. Internet of things and 5G communication

Port intelligentization first depends on the construction of the sensing layer. After deploying sensors and intelligent terminals in equipment and the operation environment, the equipment status, vehicle trajectory, cargo information, and environmental parameters can be collected continuously, the cargo flow process can be checked and traced, and the transparency of the supply chain is improved accordingly; the accumulated data is then used for demand prediction and path optimization, and experience-based decision-making gradually gives way to data-based decision-making. At the communication level, the low latency, large bandwidth, and high reliability characteristics of 5G create conditions for millisecond-level collaboration between terminal equipment, and network

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slicing can also allocate resources according to business needs—remote control uses ultra-low latency slices, video surveillance uses large bandwidth slices, each taking what it needs. However, the large-scale implementation of 5G private networks in ports is not easy, and problems such as inconsistent standards and uncertain investment recovery are still practical obstacles in promotion. As for the electromechanical equipment itself, IoT sensors have been embedded in quay cranes, yard cranes, conveyors, and other equipment, undertaking tasks such as structural stress monitoring, reduction gearbox temperature detection, and belt deviation warning, and traditional port machinery have thus gained the capabilities of state self-perception and fault pre-diagnosis.

3.2. Artificial intelligence and big data

The application of artificial intelligence in ports concentrates on several directions: scheduling, prediction, and operation and maintenance. In the scheduling link, algorithms can synthesize information such as ship arrival time, cargo type, and yard utilization to generate loading and unloading operation plans; a multi-action deep reinforcement learning framework realizes the joint optimization of vessel scheduling and tugboat allocation, providing a new line of thinking for collaborative scheduling in complex scenarios. In the equipment operation and maintenance link, machine learning-based predictive maintenance is gradually replacing periodic overhaul and post-failure repair: fault prediction models are trained through port machinery IoT sensing data, and the supporting value of machine learning methods for maintenance decisions has been verified on container loading and unloading equipment. In terms of data platforms, multi-source data such as AIS, GIS, and collection and distribution are integrated into a unified digital foundation, serving operation scheduling, energy consumption optimization, and environmental management. The infrastructure form of ports therefore changes: a digital architecture is superimposed on top of physical facilities, and data, like equipment and labor, becomes a factor of production. For port machinery equipment, the control method is also being upgraded—the anti-sway control algorithm for quay cranes based on deep reinforcement learning has been put into use in some automated terminals, and both the spreader positioning accuracy and operation efficiency have improved.

3.3. Intelligent control and digital twin

Intelligent control systems undertake the autonomous operation of port electromechanical equipment, and are composed of components such as programmable logic controllers, motion control units, and distributed I/O, responsible for the position control and speed regulation of quay cranes, yard cranes, and conveying systems. Digital twins map the port area into virtual space: equipment operation data, yard status, and operation processes enter the virtual model in real time, and managers can deduce scheduling schemes and predict operation bottlenecks before actual ship operations. By drawing on the experience of smart cities and supply chain twins, a layered construction method for port digital twins is formed; related terminal case studies also show that after the twin model is used for operation deduction, there is room to compress the equipment empty-running rate and energy consumption level. At the industrial level, this technology has changed the development process of port machinery equipment—the serial chain of 'design—manufacturing—debugging—operation' is replaced by the parallel mode of 'virtual simulation—synchronous verification—continuous optimization', the R&D cycle of new equipment is compressed, and the full-life-cycle management of in-service equipment is also supported by data.

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4. Paths and countermeasures for intelligent transformation

4.1. Layered advancement — from single-machine intelligence to system intelligence

Intelligent transformation is difficult to achieve in one step, and a more realistic approach is layered advancement and step-by-step upgrading. The most basic layer is equipment-level intelligentization, which adds sensors, controllers, and communication modules to existing equipment, so that a single machine has intelligent perception and autonomous operation capabilities; the upper level is process-level intelligentization, which connects the control systems of different equipment and different processes to realize the automatic collaboration of operation flows; the top level is system-level intelligentization, which uses the digital twin platform covering the whole port area and the intelligent decision-making system to support the global optimization and adaptive management of operations. This layered idea is in the same line as the cyber-physical system (CPS) advocated by Industry 4.0, that is, to realize the autonomous optimization of the system through the deep integration of the physical world and the digital world.

As for the implementation strategy, different types of ports do not need to apply the same template. Large hub ports have strong capital and technology accumulation, and can directly benchmark against international first-class levels to promote the intelligent construction of the whole process; small and medium-sized ports are more suitable for taking a modular and extensible gradual renovation route, giving priority to projects with a high input-output ratio; inland ports should base themselves on the relatively concentrated characteristics of scenarios, and find low-cost and high-efficiency intelligent solutions around key links such as bulk cargo loading and unloading, yard management, and vessel scheduling. Regardless of the type of port, the existing equipment should be put to good use—by adding sensors, edge computing modules, and communication interfaces, in-service port machinery is connected to the intelligent system, which is much more economical than starting all over again.

4.2. Industrial coordination — building an intelligent ecosystem

The intelligent transformation of the port electromechanical industry is a technological upgrade as well as a reconstruction of the industrial ecosystem. In the upstream of the industrial chain, design institutes, equipment manufacturing enterprises, and information technology enterprises need to strengthen coordination to realize the whole-chain intelligentization from design, manufacturing, to integration. In the middle of the industrial chain, port operation enterprises need to cooperate deeply with system integrators to jointly develop intelligent solutions adapted to port scenarios. In the downstream of the industrial chain, comprehensive logistics enterprises and park operators need to achieve information interconnection and process coordination with ports, and promote the integrated operation of ports and logistics parks.

At present, China's port electromechanical industrial chain has formed a pattern of coordinated development with equipment manufacturing enterprises represented by Zhenhua Heavy Industries and Nanjing Port Machinery, information technology enterprises represented by Huawei and Alibaba Cloud, and system integrators represented by CCCC Mechanical & Electrical Engineering Bureau. As the 'chain leader' unit of CCCC's modern electromechanical industrial chain, CCCC Mechanical & Electrical Engineering Bureau has provided highly reliable solutions for port intelligent upgrading through deep participation in major port projects such as the Huanghua Port automation renovation, the Qingdao Port ore terminal system, and the Shanghai Luojing Port full variable-frequency handling system. In the future, coordination and innovation among all links of the industrial chain

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should be further strengthened, the independent controllability of core technologies should be promoted, and an intelligent technology ecosystem covering the whole port electromechanical industrial chain should be built. The synergy effect of the industrial ecosystem helps reduce transaction costs between links, eliminate technical barriers, and thereby accelerate the promotion and application of intelligent technologies.

4.3. Policy support — institutional guidance and talent

The national '15th Five-Year Plan' fully implements the 'Artificial Intelligence Plus' action, requiring the promotion of the digital-intelligent upgrading of infrastructure such as transport and energy. New infrastructure such as 5G-A, 10-gigabit optical networks, BeiDou navigation, and low-earth-orbit satellite communication will provide stronger support for port electromechanical systems. The 'Opinions on Accelerating the Construction of Smart Ports and Smart Waterways' issued by the Ministry of Transport in 2023 clarified the development goal of building a batch of world-class smart ports and smart waterways by 2027. The 'Implementation Opinions on Accelerating Scenario Cultivation and Opening to Promote the Large-scale Application of New Scenarios' issued by the General Office of the State Council in 2025 listed 'smart port and shipping' and 'smart logistics hub' as key scenarios for cultivation, providing policy support and market space for the industrial application of port intelligentization technologies.

Talent is another practical constraint. Industry research reports show that the improvement of the port intelligentization level will significantly amplify the demand for versatile talent: there must be people who master information technologies such as the Internet of Things, artificial intelligence, and big data analysis, and people who are familiar with port operation, equipment management, and engineering implementation, and both types of talent are currently in short supply. A feasible approach is to promote universities, research institutes, and port enterprises to jointly build talent training bases, and use practical training projects and joint R&D to train teams that understand both technology and business. At the same time, they should also actively participate in the formulation of international standards and promote the wider international recognition of China's port intelligentization technology standards. What needs to be pointed out is that intelligent transformation ultimately tests the organizational capability of enterprises: overall planning at the strategic level, steady advancement at the execution level, and technology investment alone cannot automatically translate into transformation results.

5. Conclusion

This paper, focusing on the intelligent transformation of the port and logistics electromechanical industry, reviews its evolution, key technology system, and implementation path, and the main understandings are as follows:

From the perspective of development stages, the industry has successively gone through three periods—equipment-dominated, system integration, and intelligentization—and its center of value has shifted from large-scale equipment manufacturing to core software, algorithms, and data analysis capabilities. The position of software in the port electromechanical industrial chain has changed from an auxiliary tool to a dominant link.

From the perspective of the technology system, the Internet of Things and 5G communication, artificial intelligence and big data, and intelligent control and digital twin cooperate with one another: perception relies on the Internet of Things, real-time communication relies on 5G, autonomous decision-making relies on artificial intelligence, and virtual-real mapping relies on the

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digital twin. The superposition of the four types of capabilities forms the technical foundation for the intelligent operation of ports.

From the perspective of the implementation path, layered advancement, industrial coordination, and policy support need to work at the same time: the three levels of equipment-level, process-level, and system-level are advanced step by step, the upstream and downstream of the industrial chain innovate in coordination, and with the support of policies such as the 15th Five-Year Plan and the reserve of talent, the transformation can be sustained.

This study also has limitations: port intelligentization technology iterates quickly, and the actual effects of some frontier applications still need longer-term practical testing; follow-up work can be carried out around issues such as the economic evaluation of intelligent transformation, the selection of technology routes, and the differentiated strategies for different types of ports.

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