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Application of Digital Twin Technology in the Development of Flexible Assembly Line for Construction Machinery Cab

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Abstract: In response to the current demands for personalized, multi-variety, and small-batch production of construction machinery cabs, combined with digital twin technology, an intelligent and flexible assembly system integrating functions such as virtual design, dynamic simulation, and real-time mapping is constructed. This paper, based on the actual needs of enterprises, analyzes the core requirements of the flexible assembly line for construction machinery cabs, strengthens the scene adaptability of digital twin technology, and focuses on researching key technologies such as virtual model construction and virtual-real data interaction, effectively integrating digital twin technology with the development of flexible assembly lines. The research results show that digital twin technology can effectively shorten the development cycle of assembly lines, significantly improve production flexibility and assembly accuracy, and reduce material production costs, providing theoretical support and engineering references for the intelligent development of flexible assembly lines for construction machinery cabs.

Keywords: Digital Twin; Construction Machinery Cab; Adaptability; Intelligence

Introduction

Construction machinery has always been the core equipment for infrastructure construction, and the cab is the core unit of construction machinery. The cab is a key component that ensures the safety, comfort, and efficiency of workers, featuring a wide variety of parts, mixed-line production of multiple varieties, and prominent customization demands. With the continuous advancement of China's "Made in China 2025" three-step strategy and the increasing demand for diversity and personalization of construction machinery

products in the external market, the pain points of traditional assembly lines, such as long development cycles, insufficient flexibility, low quality control, and low resource utilization, have become prominent, making it difficult to meet the rapidly changing market demands.

1. Core Requirements of Flexible Assembly Lines for Construction Machinery Cabs

1.1 Demand for Improved Design Efficiency

It is necessary to reuse mature modules (such as general-purpose manipulator design, standardized



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interface design, general fixture structure design, etc.) to reduce the workload of repetitive design. Simulate the layout of the line body, the connection of digital and electrical modules, and the coordination of equipment in advance to reduce design loopholes and lower the frequency of design changes in the later stage, thereby effectively shortening the development cycle. At the same time, it is necessary to reserve space for module upgrade and adaptation to meet the iterative demands of new modules and new configurations in the future.

1.2 Demand for Improved Debugging Efficiency

Conduct corresponding debugging work according to the "module debugging - station debugging - full-process joint debugging" mode. Prioritize the independent pre-debugging of each module/station to minimize the complexity of full-process debugging, and then conduct system assembly joint debugging to solve the coordination and adaptation issues between automated instruments and equipment (such as clamping manipulators, inspection machines, etc.) and the line body, avoiding extended development cycles due to debugging errors.

1.3 Demand for Improved Coordination Efficiency

Establish a coordinated chain across design, procurement, processing, debugging, and acceptance stages to achieve real-time data sharing, avoid information silos, and reduce waiting times at each stage's interface. Establish a rapid communication mechanism to promptly address design changes, component adaptation, and debugging faults during the development process, enhancing coordination efficiency and shortening the overall development cycle.

1.4 Demand for Multi-Model Compatibility

It is necessary to adapt to the mixed-line production of at least five or more mainstream construction machinery cabs, conforming to the trend of modular assembly of cabs, and support the rapid switching of core modules such as frames, electrical systems, interiors, and air conditioning. The switching time needs to be controlled within 30 minutes to avoid excessively long line stoppage times due to model changes.

2. Compatibility of Digital Twin Technology with Flexible Assembly Lines

Digital twin technology builds a virtual digital model corresponding to the physical entity and uses Internet of Things, big data, cloud computing, artificial

intelligence and other technologies to achieve real-time mapping, monitoring, analysis and optimization of the entire life cycle of the physical entity. ^[1] Digital twin integrates multi-disciplinary, multi-physical quantity, multi-scale and multi-probability simulation processes and completes the mapping in the virtual space, thereby reflecting the entire life cycle process of the corresponding physical equipment. Digital twin technology is bringing revolutionary changes to industry. ^[2] Its core features are highly compatible with the core requirements of the flexible assembly line for construction machinery cabs.

2.1 The virtual-real mapping feature is compatible with flexible production requirements.

Digital twin technology can build high-fidelity virtual models of production equipment, material components, and assembly lines, achieving a one-to-one mapping between the physical assembly line and the virtual assembly line. It can simulate the assembly process of various types of cabs, verify the operability of the model change plan in advance, meet the requirements of multi-variety mixed-line production, and effectively solve the problems of slow model change and low efficiency in traditional assembly lines. The high mapping capability of digital twin can complete the full process simulation of the production process, providing reliable support for flexible production.

2.2 The real-time interaction feature is compatible with efficient debugging requirements.

Digital twin technology can achieve real-time data synchronization between the virtual model and the physical entity through intelligent sensors, industrial big data and other technologies. It can feed back the operation parameters of the physical entity to the virtual model in real time and send the new parameters after virtual debugging to the physical entity, achieving dual coordination in debugging and significantly shortening the debugging cycle and reducing debugging costs. Currently, the real-time interaction feature of digital twin can achieve millisecond-level data response, ensuring the efficiency and accuracy of the debugging process.

2.3 The full life cycle management feature is compatible with quality and resource management requirements.

Digital twin technology can dynamically collect quality data, material data, etc. during the operation of the

assembly line, and optimize them according to virtual simulation algorithms to achieve early warning of quality risks and optimal allocation of resources. At the same time, the data of the entire product assembly process can be collected in a timely manner, enabling full traceability of product quality and meeting the requirements of quality management and efficient resource utilization.

3. Key Technology Research on Flexible Assembly Lines Driven by Digital Twin

3.1 Precise Virtual Model Construction Technology

Precise virtual models are the foundation of digital twin technology application, and their accuracy directly affects the effect of virtual simulation and virtual-real interaction. In view of the complexity of the flexible assembly line for construction machinery cabs, the method of "multi-dimensional modeling + parameterized driving + physical characteristic mapping" is adopted to build high-fidelity precise virtual models, referring to the construction concept of the five-dimensional model of digital twin ^[3] to ensure the accuracy and practicality of the model.

Using 3D modeling software such as NX CAD, based on the design drawings and physical entity data of cab components, 3D geometric models of cab products, assembly line equipment, and production environments are constructed to ensure the consistency of geometric dimensions with physical entities. At the same time, the model is simplified as much as possible to reduce redundant details and improve the simulation efficiency, balancing model accuracy and simulation speed.

By collecting the operational parameters of physical equipment (such as the torque and precision of the clamping manipulator) and material properties (such as the hardness and elastic modulus of components), the physical characteristic parameters are integrated into the virtual model to ensure consistency between the physical characteristics of the virtual model and the physical entity, thereby guaranteeing the authenticity of the simulation results. For instance, in the robot assembly model, parameters such as its actual movement trajectory and load capacity are incorporated to simulate its actual operation state. By drawing on the physical characteristic modeling approach in collaborative manufacturing with swarm robots ^[4], the

simulation accuracy of the model is enhanced.

3.2 Real-time Data Interaction Technology between Virtual and Physical Worlds

Real-time data interaction technology between virtual and physical worlds is crucial for achieving synchronous operation of the virtual model and the physical entity. The core lies in addressing the real-time and accurate issues of data collection, transmission, and synchronization, and establishing a closed-loop interaction mechanism of "physical entity → data collection → data transmission → virtual model → instruction issuance → physical entity". By referring to the interaction framework of edge-cloud collaboration ^[5-6], the interaction efficiency is improved.

Sensors (such as pressure sensors and counting sensors) are installed on the equipment and facilities, as well as material components in the physical layer to collect data in real time, including equipment operation parameters, assembly accuracy, and material quantities. Production management systems (such as MES and ERP) are utilized to collect production orders, process parameters, and historical data, achieving comprehensive data collection of all elements in the assembly line.

3.3 Flexible Scheduling Optimization Technology

Flexible scheduling optimization is a core technology for addressing multi-variety and small-batch production. Based on the digital twin model and real-time production data, a multi-level flexible scheduling optimization model is constructed to achieve dynamic resource allocation, enhancing the production efficiency and flexibility of the assembly line. By referring to the task scheduling methods under edge-cloud collaboration, the adaptability and optimization effect of the scheduling are improved.

1. With the goals of meeting order demands, shortening production cycles, controlling production costs, and improving resource utilization, while considering the actual needs of multi-variety mixed-line production, a multi-objective and multi-level optimization model is established to balance the optimization objectives and maximize production benefits.

2. A hybrid intelligent scheduling algorithm based on genetic algorithms and particle swarm optimization is designed. According to the assembly requirements of different cab models, resources such as equipment

and facilities, material components, and personnel are dynamically allocated, and the assembly process and production sequence are adjusted in a timely manner. Meanwhile, the assembly line should have adaptability, dynamically optimizing the scheduling plan in response to unexpected situations (such as equipment failure, material shortage, and personnel shortage). Under certain circumstances, the Environment Adaptive Multi-factor Optimization Genetic Algorithm (EAMO-GA) [7] can be introduced to enhance the convergence and effectiveness of the algorithm, meeting the requirements of large-scale and parallel scheduling.

3. Validate the scheduling plan through virtual models, simulate the production process under various scheduling plans, analyze indicators such as production cycle, equipment availability rate, and resource utilization rate, and select the optimal scheduling plan to ensure the feasibility and effectiveness of the scheduling plan and reduce resource waste and process conflicts in actual production. Drawing on the idea of the collaborative learning framework for cluster robots, optimize the scheduling plan through virtual simulation to reduce the actual scheduling cost.

4. Case Background

A construction machinery accessory enterprise, in order to effectively enhance its ability to supply international well-known construction machinery enterprises and improve the flexibility and intelligence level of its cab assembly line, introduced digital twin technology to carry out assembly line research and development work. The original assembly line of the factory adopted a traditional rigid structure, with low automation level, insufficient overall flexibility, weak production process monitoring, and great difficulty in process optimization, resulting in low production efficiency and unstable product quality.

4.1 Application Process

4.1.1 Virtual Modeling

Using software such as NX CAD, a three-dimensional virtual model of the assembly line was constructed stereoscopically, including equipment and facilities, workstations, and material components, and a unified data model was established to achieve semantic description of the geometric state and workload state of the assembly line.

4.1.2 Real-time Monitoring and Data Collection

Various sensors (such as material sensors, pressure sensors, counting sensors, etc.) were deployed on the assembly line to collect real-time data on equipment operation status, production progress, and material information, and the data was transmitted to the digital twin virtual model through industrial Ethernet and 5G to achieve real-time synchronization between the physical assembly line and the virtual model.

4.1.3 Simulation Optimization

In the Plant Simulation software environment, the production process of the assembly line was simulated and analyzed, and problems such as component assembly misalignment, material blockage, and process imbalance were successively discovered. By adjusting equipment layout, processes, and process parameters, optimizing logistics paths and production rhythms, the production efficiency and resource utilization rate of the assembly line were effectively improved.

4.1.4 Predictive Maintenance

Combining machine learning algorithms to independently analyze equipment operation data, a predictive model for equipment failures was gradually established. Based on the prediction results, maintenance plans for each component were formulated in advance, and preventive maintenance was actively carried out to increase equipment availability, ensuring the reliability and service life of the assembly line equipment.

4.2 Application Effects

Through the introduction of digital twin technology, the design cycle of this assembly line was shortened by 40%, production efficiency was increased by 25%, the first-time pass rate of products rose from 75% to 91%, equipment availability rate increased by 27%, and maintenance costs were reduced by 20%. Meanwhile, the flexibility of the assembly line has been significantly enhanced, enabling it to quickly adapt to the assembly requirements of various types of cabs and greatly reducing the time for product model changes.

5. Conclusion

This paper focuses on the application of digital twin technology in the development of a flexible assembly line for the cabs of construction machinery. Through demand analysis, adaptation consultation, key technology research, and engineering case

verification, and by drawing on advanced domestic and international technical experiences, a digital twin technology system suitable for the flexible assembly of construction machinery cabs has been gradually formed. The engineering case verification shows that the technical solution is feasible and effective, and can provide theoretical support and engineering reference for the intelligent development of similar flexible assembly lines, and has relatively wide application and promotion value.

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