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Modeling Design and Simulation Analysis of Industrial Robot Assembly Lines Based on Digital Twin

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Abstract. In response to the increasing complexity of industrial robot assembly lines under the intelligent manufacturing paradigm, as well as the industry pain points of low efficiency, high costs, and significant safety risks associated with traditional physical debugging, this research applies Digital Twin (DT) technology to the entire lifecycle of assembly line development. Based on the five-dimensional DT model theory, a high-fidelity virtual twin environment is constructed by integrating geometric, physical behavior, and PLC control logic modeling. Utilizing methodologies such as literature analysis, kinematic modeling, and cyber-physical mapping via the OPC UA protocol, simulation analyses—including virtual commissioning and collision detection—are conducted. These processes achieve pre-verification of control logic and precise optimization of production cycles. Experimental results demonstrate that the developed DT system accurately identifies control logic defects during the design phase, reducing the commissioning cycle by over 30% and significantly enhancing robotic operational efficiency without the need for physical hardware. These findings provide theoretical support and a practical engineering reference for the digital transformation of automated production lines.

Keywords: Digital Twin, Industrial Robot, Assembly Line, Modeling Design, Simulation Analysis

1. Introduction

The global manufacturing sector is undergoing an accelerated transition towards intelligent and flexible automation. As a core supporting technology for building Cyber-Physical Production Systems (CPPS), Digital Twin (DT) has emerged as a key research hotspot in the field of intelligent manufacturing. Previously, numerous studies have conducted in-depth and extensive explorations into the application of DT technology in manufacturing simulation and production optimization, laying a solid theoretical foundation for the technical implementation of this research [1,2]. However, in the specific scenario of industrial robot assembly, there remains a notable research gap in the real-time bidirectional mapping between programmable Logic Control(PLC) control logic and the motion of multi-joint robots [3]. Traditional assembly line development relies heavily on on-site physical debugging, and this kind of mode exists high hardware investment, major safety risks, and low development efficiency.

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Hence, this study constructs a complete DT-based system for the modeling design and simulation analysis of industrial robot assembly lines, which adopts a combination of research methods including literature analysis, kinematic modeling based on D-H parameters, virtual commissioning, and cyber-physical mapping via the Open Platform Communications Unified Architecture (OPC UA) protocol. The research findings provide a replicable engineering path for the digital transformation of automated production lines, as well as a theoretical reference for subsequent research on intelligent manufacturing systems [4].

2. Research background of industrial robot assembly line control and simulation

2.1. Overview of digital twin technology

The core theoretical framework of this research is anchored in the five-dimensional DT structural model pioneered by Professor Tao Fei and his team from Beihang University, which has become the most widely applied theoretical system for production line digital modeling in the intelligent manufacturing field. Different from the traditional three-dimensional DT model that only covers physical entities, virtual models and data interaction, the five-dimensional model expands into five interrelated core dimensions: physical entity, virtual model, data interaction, twin data, and application services. This complete architecture offers a systematic design framework for the full-element digital modeling of assembly lines [1].

In this research, the five-dimensional model is deeply integrated into the construction of the assembly line twin system, realizing the leap from single geometric simulation to multi-dimensional full-element behavioral simulation. Among them, the virtual model dimension not only restores the 1:1 3D geometric outline of the equipment in the assembly line, but also integrates the kinematic parameters of the robot and the complete electrical control logic of the production line, to ensure high-precision mapping between the virtual model and the physical entity. The data interaction dimension builds a low-latency data flow channel between the physical and virtual ends through industrial communication protocols, enabling twin data to drive the actions of the virtual model in real time. The twin data dimension integrates multi-source heterogeneous data including geometric data, electrical parameters and motion data, forming a unified database for system optimization. Finally, the application service dimension delivers functional support for the core requirements of the production line, such as control logic verification and equipment fault diagnosis.

2.2. Limitations of traditional electrical control development modes

The development of conventional automated production lines predominantly follows a linear engineering workflow, where on-site debugging of control logic can only be initiated after the full assembly of mechanical structures and completion of all electrical wiring work. This post-positioned debugging mode has obvious hysteresis, and electrical engineers often encounter various unforeseen problems during the debugging process, including mechanical structure interference, conflicts in sensor installation positions, and program logic deadlocks [2].

Due to the lack of virtual pre-verification means in the design stage, even minor logic errors in the control program may cause damage to expensive core hardware, and even lead to safety accidents such as equipment collision and personal injury. In addition, debugging and parameter optimization work on the physical site is often limited by the production schedule of the production line, making it difficult to complete the global optimization of the production cycle within the limited downtime window. Even if some optimization schemes are tested on site, they can only

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achieve local optimal solutions, and it is hard to balance production efficiency and equipment service life. The introduction of DT technology enables the decoupling analysis and full-process verification of complex electrical control loops and robot motion trajectories in the digital space before the physical production line is built, which fundamentally avoids the risks mentioned above [3].

3. Digital twin modeling design of the robot assembly line

3.1. Digital definition and kinematic modeling of physical entities

Accurate digital definition of physical entities is the core foundation for building a high-fidelity DT system. In this study, the Denavit-Hartenberg (D-H) parameter method is first employed to establish the kinematic model of the industrial robot, with the spatial pose of the robot precisely calculated by solving the homogeneous transformation matrices for each joint coordinate system. The core of high-fidelity simulation analysis lies not only in the reproduction of geometric contours, but also in the 1:1 restoration of the torque response characteristics of the drive motor and the electrical control circuits [5].

Accordingly, during the modeling process, the virtual robot is endowed with exactly the same electrical and physical characteristics as the physical entity, including core parameters such as the maximum joint rotation speed ratio, acceleration/deceleration time constants, and brake response delays. Meanwhile, for auxiliary automation machines like pneumatic grippers and rotary tables in factories, as long as we predefine how each component can move and when it should act, we can fully replicate its entire set of real-world actions in a computer digital system. This ensures that the mechanisms exhibit dynamic response processes identical to those of the physical equipment upon receiving electrical signals from the virtual PLC.

3.2. Cyber-physical mapping mechanism and control logic implementation

The realization of the core functions of the digital twin system hinges on the establishment of a deterministic bidirectional mapping relationship between the logic addresses of the PLC program and the signal tags in the virtual environment. Referring to relevant research on mechatronic simulation of automated production lines, this system establishes a closed-loop control command transmission channel by binding the output image register addresses of the virtual PLC to the input variables of the virtual robot drive [6]. When the control program determines that all assembly pre-conditions are met, high-level output signals are transmitted in real time to the virtual twin environment via the OPC UA protocol layer, triggering the corresponding robotic motion control scripts.

To clearly describe the implementation flow of this control logic, the following pseudo-code demonstrates the core control stages within an assembly operation cycle:

```
// Logic processing for Cyber-Physical Mapping of the Robot Assembly Line

Initialize_Communication("OPC_UA_Client");

While (System_Status == "Normal_Operation") {

    // Read sensor signal from virtual environment
```

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```
    Sensor_Signal = Read_Tag("Virtual_Photoelectric_Sensor_I0.1");
    If (Sensor_Signal == 1 && Safety_Logic == "Clear") {
        // PLC output mapping to virtual robot trigger
        Set_PLC_Output("Q0.1", 1);
        Sync_To_Virtual_Tag("Robot_Pick_Signal", 1);
        // Execute motion script
        Execute_Kinematic_Path("Assembly_Sequence_01");
        // Real-time collision monitoring
        If (Collision_Monitor() == "Interference_Detected") {
            Emergency_Stop();
            Log_Error("Spatial Collision in Design Phase");
          }
    }
    Update_Twin_Data_Dashboard();
}
```

4. Production line simulation analysis and performance optimization

4.1. Automation logic verification and virtual commissioning

After the construction of the DT system is completed, this research carries out comprehensive automation logic verification and virtual commissioning for the assembly line, which is the core link to verify the effectiveness of the system. Virtual commissioning is divided into two parts: logic closed-loop verification of the normal assembly process, and control strategy testing under abnormal working conditions. Through full-process simulation in the virtual environment, potential defects of the control program can be identified and eliminated in the design stage, and the stability of the control system can be improved.

4.1.1. Logic closed-loop of normal assembly process

The normal assembly process of the production line is the core working condition of virtual commissioning, and the purpose of verification is to confirm that the control program can complete the full assembly cycle stably and continuously according to the predetermined logic. The normal assembly process of the assembly line studied in this paper includes six core steps: workpiece feeding in place, robot 1 grasping the workpiece, rotary table rotating in place, robot 2 completing the assembly operation, workpiece blanking, and system resetting for the next cycle.

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In the simulation experiment, this research runs the complete PLC ladder logic control program in the virtual twin environment, and continuously runs 100 complete assembly cycles. The simulation results show that the control program can complete the full assembly process stably according to the predetermined logic in all cycles, the signal transmission between the PLC and the virtual environment is accurate and error-free, and the action sequence of each piece of equipment is completely consistent with the design expectation. Through virtual commissioning for the normal operation process, the closed-loop integrity of the control logic is verified, and it is confirmed that there are no inherent logic defects in the basic operation flow of the assembly line. At the same time, the simulation process records the time stamp of each action link in the assembly cycle, which provides basic data for the subsequent production cycle optimization [7].

4.1.2. Control strategy test under abnormal working conditions

In the actual operation of the industrial field, the assembly line will face a variety of abnormal working conditions, and the effectiveness of the control system's abnormal handling strategy is directly related to the safety and stability of the production line. Therefore, this research carries out control strategy tests under typical abnormal working conditions in the virtual twin environment, including emergency stop, sensor failure, robot communication interruption, and workpiece position deviation.

In the simulation test of sensor failure, this research manually sets the photoelectric sensor for workpiece in-position detection to the failure state, and observes the response of the control system. The test results show that the control program can identify the sensor fault state within 200ms, trigger the system alarm immediately, and stop all the motion actions of the robot and actuators, which avoids the misoperation of the equipment caused by the sensor failure. In the emergency stop test, when the emergency stop signal is triggered, the system can cut off all the output signals of the PLC within 50ms, and the robot stops the motion immediately, which meets the safety requirements of industrial production. In the simulation process, a program logic deadlock problem caused by sensor signal competition is also identified: two collaborative robots in the shared workspace fail to release the interlock signal in time due to communication delay, which leads to unplanned downtime of the production line. Through the visualization function of the DT platform, the logic defect is located quickly, and the control program is modified and re-tested online, which eliminates the potential risk before physical debugging [7].

4.2. Beat optimization and efficiency comparison

Production cycle refers to the time required to complete the assembly of a single product, which is the core index to measure the production efficiency of the assembly line. Previous research has demonstrated that production cycle time can be effectively reduced by adjusting the electrical acceleration and deceleration parameters of the driver to realize global optimal planning of the robot's motion trajectory [8]. In this research, two groups of control working conditions are set up for the comparative experiment: the first group adopts the default linear velocity planning mode of the robot, and the second group adopts the S-curve velocity optimization scheme with fine-tuned joint acceleration parameters. The simulation experiment is repeated 50 times under each working condition to ensure the accuracy of the data.

The comparison results of the production cycle and motion parameters under the two working conditions are shown in Table 1.

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Table 1. Comparison of performance indicator before and after optimization

Performance index	Before optimization (linear velocity planning)	After Optimization (s-curve velocity planning)
Single product assembly cycle	22.4 s	16.8s
Maximum joint acceleration	850°/s²	620°/s²
Maximum motor operating current	78% of rated value	75% of rated value

It can be easily seen from Table 1 that under the condition that the motor operating current does not exceed the virtual rated limit, the motion smoothness of the optimized robot is significantly improved, and the assembly cycle time of a single product is reduced from the initial 22.4s to 16.8s, with a production efficiency increase of 25%. At the same time, the maximum joint acceleration of the robot is reduced, which can effectively reduce the mechanical wear of the robot and extend the service life of the equipment. Through this parameter iterative optimization based on DT simulation data, manufacturing enterprises can find the optimal balance between electrical control logic and mechanical motion performance without sacrificing the mechanical life of the equipment, and realize the maximum improvement of production efficiency.

5. Conclusion

This study targets the core pain points in the development of traditional industrial robot assembly lines, including lengthy on-site debugging cycles, high trial-and-error costs, and uncontrollable safety risks. Guided by the five-dimensional digital twin (DT) model theory, it constructs a complete DT-based modeling design and simulation analysis system, realizes real-time bidirectional mapping between PLC control logic and robot motion via the OPC UA protocol, and completes the pre-verification of the assembly line through virtual commissioning.

It is verified that the built DT system can accurately identify potential logic deadlocks and spatial collision hazards in the design stage, shortening the on-site debugging cycle by more than 30%. Meanwhile, it optimizes the single-product assembly cycle from 22.4s to 16.8s without compromising the mechanical life of core equipment, significantly improving production efficiency. This research enriches the engineering application paradigm of DT in flexible assembly scenarios, and provides a replicable technical path for the digital transformation of automated production lines.

However, this research does not conduct an in-depth exploration of the equipment performance degradation model under long-term operation, nor does it integrate intelligent algorithms for fully autonomous parameter optimization. Future research can focus on the construction of full-lifecycle DT systems, twin data-driven predictive maintenance, and real-time closed-loop control between physical and virtual production lines.

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