Digital Twin Visualization Design for Intelligent Warehousing and AGV Scheduling System

Qiong Song*, Jiarui Long

Chengdu Technological University, Yibin, China

*Corresponding author: Qiong Song

Abstract

To address information silos, delayed equipment-state perception, path conflicts among multiple AGVs, and insufficient visual monitoring capability in conventional warehousing systems, this paper proposes a digital-twin-based visualization design method for an intelligent warehousing and AGV scheduling system. First, three-dimensional models of key equipment, including the automated storage warehouse, underride AGVs, racks, inbound/outbound stations, and handling manipulators, are constructed using the three-dimensional modeling platform, and non-critical structures are lightweighted to balance visualization accuracy and simulation efficiency. Second, rigid bodies, collision bodies, motion joints, sensors, actuators, and signal mapping relationships are configured in the NX_MCD mechatronic concept design environment to establish a virtual warehousing system with kinematic constraints and logical response capability. Third, a virtual PLC control system is developed by integrating TIA Portal and PLCSIM Advanced, enabling real-time signal interaction between the PLC control program and the NX_MCD simulation model. On this basis, virtual commissioning of AGV storage and retrieval paths, manipulator handling actions, and inbound/outbound operation processes is realized. Finally, an HMI interface is used to dynamically monitor and visualize rack occupancy, AGV operating status, and inbound/outbound task information. The results show that the proposed method can achieve coordinated mapping among physical objects, control logic, and virtual models in an intelligent warehousing system. It provides a feasible engineering solution for multi-AGV scheduling process verification, warehouse operation monitoring, and early-stage virtual commissioning, and offers practical reference for reducing physical commissioning costs, improving warehouse system design efficiency, and promoting the digital transformation of small- and medium-sized warehousing systems.

Keywords

Digital Twin; Intelligent Warehousing; AGV Scheduling; NX_MCD; PLC; Virtual Commissioning; Visual Monitoring.

1. Introduction

With the rapid development of Industry 4.0, intelligent manufacturing, and modern logistics systems, warehousing systems are evolving from traditional manual management and single-mode mechanical handling toward automation, informatization, and intelligence. As an important component of smart logistics, intelligent warehousing undertakes key tasks such as inbound storage, storage management, material handling, sorting, and outbound delivery. Its operating efficiency directly affects production-logistics coordination and supply-chain response capability. Existing studies indicate that intelligent warehousing systems integrate the Internet of Things, automatic control, warehouse management

DOI: 10.6919/ICJE.202608_12(8).0011

systems, cloud computing, AGVs, and collaborative robots to realize warehouse information perception, equipment control, operation scheduling, and process optimization, making them an important development direction for modern warehouse management [1]. In addition, the application of 5G and RFID technologies further improves information acquisition, transmission, and monitoring in warehousing logistics, thereby providing technical support for real-time and intelligent warehouse operation [2].

In practical applications, however, conventional warehousing systems still face problems such as information silos, delayed equipment-state perception, insufficient process visualization, and path conflicts among multiple AGVs. In multi-AGV collaborative handling scenarios, the system must simultaneously process task allocation, path planning, vehicle collision avoidance, rack status, and inbound/outbound workflows. Without a unified virtual-real mapping model and real-time monitoring mechanism, path congestion, equipment waiting, and reduced scheduling efficiency may occur. Previous research has shown that the key issues in multi-AGV scheduling are task allocation and path planning, and that handling efficiency and system stability should be improved while collisions are avoided [3-5]. Therefore, using digital technologies to realize warehouse equipment-state perception, AGV operation simulation, and scheduling-logic verification has become an important problem in intelligent warehousing system design.

Digital twin technology establishes a virtual model corresponding to the physical system and realizes dynamic mapping between the physical and virtual spaces through real-time data interaction, simulation analysis, and visual display. It provides a new method for the design optimization and virtual commissioning of intelligent warehousing systems. Existing studies have applied digital twins to warehouse-logistics sorting, three-dimensional warehousing systems, and intelligent manufacturing lines, enabling system modeling, data acquisition, virtual-real mapping, and operation-state monitoring [6-8]. Meanwhile, the integration of industrial software and communication platforms such as NX_MCD, PLC, OPC, and PLCSIM Advanced provides a feasible engineering path for control-logic verification and virtual commissioning of warehousing equipment [8- 9].

Based on the above research, this paper proposes a digital-twin-based system construction method for the visualization design requirements of an intelligent warehousing and AGV scheduling system. First, key equipment models are constructed, including the three-dimensional warehouse, AGVs, racks, inbound/outbound stations, and handling manipulators. Second, rigid bodies, collision bodies, motion joints, sensors, actuators, and signal-adaptation relationships are configured in NX_MCD to establish a virtual warehousing system with motion constraints and logical response capability. Third, a virtual PLC control system is constructed by integrating TIA Portal and PLCSIM Advanced, thereby realizing real-time signal interaction between the control program and the simulation model. Finally, the HMI interface is used to visualize rack occupancy, AGV operating status, and inbound/outbound tasks. The purpose of this research is to integrate three-dimensional modeling, virtual simulation, control verification, and status monitoring for intelligent warehousing systems, and to provide an engineering reference for multi-AGV scheduling verification, warehouse-system virtual commissioning, and the digital transformation of small- and medium-sized warehousing systems.

2. Overall Design of the Intelligent Three-Dimensional Warehousing System

The intelligent warehousing system is a complete intelligent automatic execution system. Its functional design and implementation are reflected mainly in two aspects. First, the system should be intelligent: it can perform automated operations based on industrial equipment, track material status online in real time, and respond quickly to abnormal conditions. Second, the system should be information-oriented: it can collect equipment information in real time, process data according to preset logic programs, use intelligent algorithms to calculate dynamic optimum solutions, and optimize the operating mode.

As shown in Fig. 1, the three-dimensional intelligent warehouse consists of two AGVs, two handling manipulators, two racks, one inbound station, and one outbound station. The use of two AGVs mitigates the workload pressure that a single AGV encounters when handling a large number of materials, significantly improves the efficiency of warehouse storage and retrieval, and provides a basis for multi-AGV path planning. Two handling manipulators are used to replace manual handling, and their millimeter-level positioning accuracy reduces the risk of materials falling from the AGV pallet. A sensor is installed at the inbound station to detect whether the material is in position, so the AGV can be notified to pick up and store it. The conveyor can stop once the material reaches its position, thereby reducing energy consumption. Each rack is equipped with a sensor to visualize rack occupancy, preventing operators from being unaware of rack status during AGV storage and retrieval and ensuring accurate and convenient operations.

During the modeling stage, UG is used to reconstruct equipment such as underride AGVs, racks, et al. Non-critical structures are lightweighted while their kinematic and physical characteristics are retained. Sensors and actuators are then configured in NX_MCD, and signal adapters are used to simulate AGV navigation and manipulator handling functions, laying the foundation for virtual-real data synchronization. Finally, the PLC control program is integrated based on the PLCSIM Advanced protocol, and signal mapping is completed so that physical data such as AGV position and rack status can drive the virtual model in real time, reducing data latency. The HMI interface dynamically displays rack occupancy, inbound/outbound flow, and AGV operating status, improving the intuitiveness of monitoring.

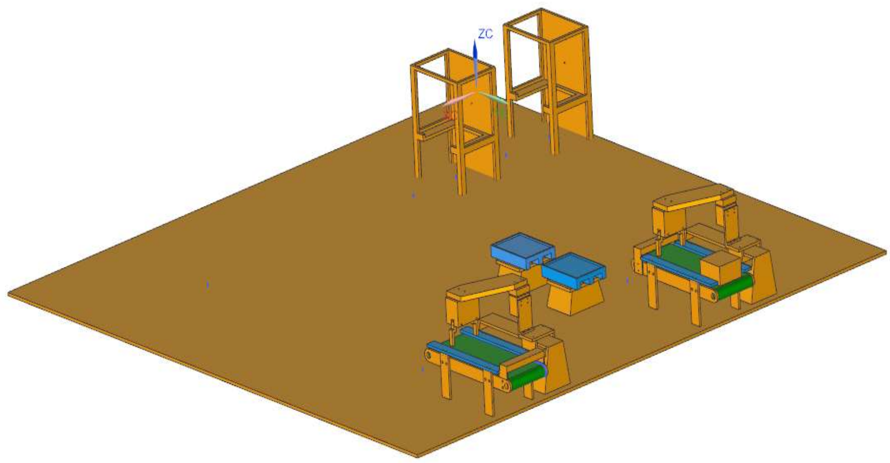

Fig.1 Overall model of the intelligent three-dimensional warehouse

3. MCD Environment Construction

NX_MCD can simulate the physical behavior and control logic of mechatronic systems through digital models, thereby supporting early-stage scheme verification and virtual commissioning in product development. In this study, physical properties are assigned to conveyors, handling manipulators, AGVs, materials, racks, and other objects in NX_MCD, and motion joints, actuators, sensors, and signal-adaptation relationships are configured. Combined with the virtual PLC program, OPC UA or PLCSIM Advanced is used to realize real-time mapping between external control signals and NX model signals, thereby supporting virtual commissioning and optimization of the intelligent warehousing system.

3.1 Basic Mechatronic Objects

In NX_MCD, the configuration of basic mechatronic objects is a prerequisite for physical simulation and virtual commissioning. Unconfigured geometric models only have visual appearance and lack physical properties; therefore, they cannot respond to gravity, external forces, or constraints. As

ISSN: 2414-1895 DOI: 10.6919/ICJE.202608_12(8).0011

shown in Table 1, all objects and components that need to move during simulation are set as rigid bodies, including the AGV bases, AGV pallets, material pallets, warehouse floor, manipulator bases, upper cylinders, middle supports, materials, and related manipulator components. Objects and components that need to contact other objects during simulation are set as collision bodies. Collision bodies highlight relative interference among objects, thereby reducing illegal interference and collision problems during simulation. For example, the outbound conveyor, Rack 1, Rack 2, the inbound rear stop plate, and the inbound conveyor are defined as collision bodies. The material is defined as an object source, which is triggered once at each activation to simulate material placement on the inbound station.

3.2 Motion Joints and Constraints

In NX_MCD, relative motion among rigid bodies depends on basic motion joints, which form the kinematic skeleton of the virtual mechanical system. Their essence is to define virtual constraints describing relative motion relationships among rigid bodies. In the intelligent warehousing and AGV scheduling system, relative motions of multiple three-dimensional models are involved, including AGV path planning and constraints, AGV pallet lifting, horizontal manipulator transfer, and manipulator lifting. Therefore, path-constraint joints, sliding joints, and fixed joints are adopted. In this design, the AGV path planning includes storage and retrieval routes. For storage, the route is origin, pickup, storage, return to origin; for retrieval, the route is origin, pickup point under the rack, outbound point, return to origin. These routes are realized through path-constraint joints. Linear relative motions, such as AGV pallet lifting, manipulator lifting, and horizontal manipulator transfer, are realized by sliding joints. Fixed joints are configured to prevent material pallets from falling off the AGV pallets during movement. The detailed design is shown in Table 2.

Table 1. Mechatronic navigator settings

Name	Type
AGV1 vehicle base	Rigid body
AGV1 pallet	Rigid body
AGV2 vehicle base	Rigid body
AGV2 pallet	Rigid body
Warehouse floor	Rigid body
Outbound conveyor belt	Collision body
Outbound manipulator transfer groove	Rigid body
Outbound manipulator base	Rigid body
Outbound manipulator upper cylinder	Rigid body
Outbound manipulator middle support	Rigid body
Rack 1	Collision body
Rack 2	Collision body
Material	Rigid body
Material pallet 1	Rigid body
Material pallet 2	Rigid body
Material source	Object source
Inbound manipulator base	Rigid body
Inbound manipulator upper connecting plate	Rigid body
Inbound manipulator upper gripper	Rigid body
Inbound manipulator middle support	Rigid body
Inbound conveyor belt	Collision body
Inbound rear stop plate	Collision body

ISSN: 2414-1895 DOI: 10.6919/ICJE.202608_12(8).0011

Table 2. Motion joint and constraint settings

Name	Type
AGV1 pallet fixed to pallet 1	Fixed joint
AGV2 pallet fixed to pallet 2	Fixed joint
AGV car 1 pallet lifting	Sliding joint
AGV car 2 pallet lifting	Sliding joint
Outbound manipulator transfer	Sliding joint
Outbound manipulator lifting	Sliding joint
Outbound manipulator support fixed joint	Fixed joint
Outbound station manipulator base fixed	Fixed joint
Ground fixed	Fixed joint
Rack 1 path	Path-constraint joint
Rack 2 path	Path-constraint joint
Inbound manipulator transfer	Sliding joint
Inbound manipulator base fixed to ground	Fixed joint
Inbound manipulator upper gripper fixed to cover plate	Fixed joint
Inbound manipulator upper cylinder fixed to cover plate	Fixed joint
Inbound manipulator gripper lifting	Sliding joint
Inbound manipulator support fixed to base	Fixed joint
Pallet 1 fixed to material	Fixed joint
Pallet 2 fixed to material	Fixed joint

3.3 Sensors and Actuators

Table 3. Sensor and actuator settings

Name	Type
AGV car 1 pallet lifting-position control	Position control
AGV car 2 pallet lifting-position control	Position control
Outbound transfer surface	Conveyor surface
Outbound manipulator transfer-position control	Position control
Outbound manipulator lifting-position control	Position control
Outbound station distance sensor	Distance sensor
Rack 1 distance sensor	Distance sensor
Rack 1 path-position control	Position control
Rack 2 distance sensor	Distance sensor
Rack 2 path-position control	Position control
Inbound manipulator transfer	Position control
Inbound manipulator lifting-position control	Position control
Inbound distance sensor	Distance sensor
Inbound transfer surface	Conveyor surface
Pallet 1 collision sensor	Collision sensor
Pallet 2 collision sensor	Collision sensor

In the NX_MCD environment, sensors and actuators are key functional units for realizing state perception, signal feedback, and motion response in the virtual model. Sensors are mainly used to detect the positions and in-position states of AGVs, materials, manipulators, inbound/outbound stations, and other objects, and to convert virtual operating information into signals that can be recognized by the control system. Actuators drive conveyors, manipulators, AGVs, and other mechanisms according to PLC control commands to complete start/stop, movement, grasping, releasing, and resetting actions. Through coordinated configuration of sensors and actuators, a closed-loop control chain of perception, feedback, judgment, and execution is formed in the virtual space. This enables the three-dimensional model to obtain logical response capabilities similar to those of real equipment and provides a basis for PLC program verification, AGV scheduling tests, and system virtual commissioning. The specific sensor and actuator settings are shown in Table 3.

3.4 Runtime Behavior

In NX_MCD, runtime behavior is the core mechanism for defining the dynamic logic of a mechatronic system. It enables intelligent control and interactive response of objects during simulation through the code mechanism. Gripper behavior is used to define and simulate the dynamic interaction between gripper-type actuators and materials during operation. By establishing parameterized connections between the rotation type of gripper fingers and the grasped materials, precise simulation of material grasping and releasing behavior can be achieved. The settings are shown in Table 4.

Table 4. Runtime behavior settings

Name	Type
Outbound manipulator	Gripper
Inbound manipulator	Gripper
Pallet 1 fixed to material	Gripper
Pallet 2 fixed to material	Gripper

3.5 Signals and Signal Adapters

In NX_MCD, signals serve as data carriers and interaction channels between the virtual model and external control systems such as PLCs. They are used to transmit control commands and status feedback and are divided into input and output types, supporting Boolean, integer, and double-precision data. Signal adapters act as data bridges by linking signals with the parameters of mechatronic objects through formulas, thereby realizing signal mapping and logical processing. They support multi-protocol communication, allowing the MCD model to respond to external commands and return actual status. In this study, signal adapters are used for signal processing of AGV1, AGV2, the inbound station, the outbound station, the inbound manipulator, and the outbound manipulator. Some signals and signal-adapter formulas are shown in Tables 5 and 6.

Table 5. Signals

Name	Type
AGV1 fixed to pallet 1	Signal
AGV1 control	Signal adapter
AGV2 fixed to pallet 2	Signal
AGV2 control	Signal adapter
Outbound manipulator control	Signal adapter
Inbound manipulator control	Signal adapter

ISSN: 2414-1895
DOI: 10.6919/ICJE.202608_12(8).0011

Table 6. Partial signal-adapter formulas

Name	Formula / Type
AGV1 position	If (AGV1 return to origin = TRUE) Then (0) Else If (AGV1 go to pickup point = TRUE) Then (5) Else If (AGV1 go to front of rack = TRUE) Then (35) Else If (AGV1 go under rack = TRUE) Then (40) Else If (AGV1 go to outbound point = TRUE) Then (110) Else If (AGV1 go to front of rack during outbound = TRUE) Then (50) Else If (AGV1 go under rack during outbound = TRUE) Then (45) Else (0)
AGV1 speed	If (AGV1 return to origin = TRUE) Then (15) Else (10)
AGV1 pallet lifting position	If (AGV1 pallet down = TRUE) Then (0) Else If (AGV1 pallet up = TRUE) Then (31) Else (0)
AGV1 fixed to pallet 1	AGV1 fixed to pallet 1
Pallet 1 grasp material	Pallet 1 fixed to material
Pallet 1 release material	Pallet 1 release material fixing

4. PLC Program Environment Construction and Programming

4.1 Construction of the Virtual PLC Environment

This study uses a Siemens S7-1500 series PLC with a 1518-4 PN/DP CPU and a SIMATIC Basic HMI panel, KTP700 Basic PN. The PLC and HMI are connected for device configuration, as shown in Fig. 2.

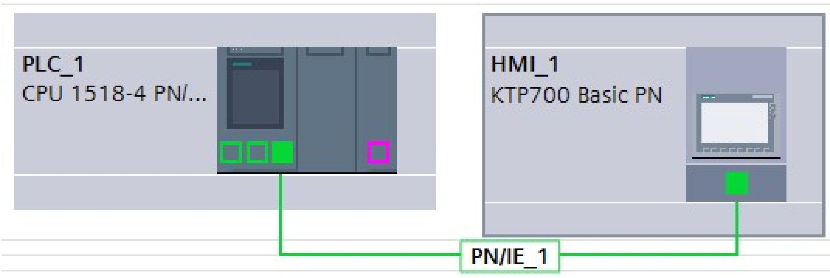

Fig. 2 PLC hardware configuration

ISSN: 2414-1895 DOI: 10.6919/ICJE.202608_12(8).0011

Table 7. Partial PLC variables

Name	Data type	Address
Inbound manipulator transfer return to origin	Bool	%Q0.0
Inbound manipulator transfer	Bool	%Q0.1
Inbound manipulator down	Bool	%Q0.2
Inbound conveyor speed	Bool	%Q0.4
Inbound gripper close	Bool	%Q0.5
Inbound gripper open	Bool	%Q0.6
Material in position	Bool	%I0.0
Outbound conveyor speed	Bool	%Q0.7
Outbound manipulator transfer	Bool	%Q1.0
Outbound manipulator transfer return to origin	Bool	%Q1.1
Outbound gripper close	Bool	%Q1.2
Outbound gripper open	Bool	%Q1.3
Outbound manipulator down	Bool	%Q1.4
Outbound manipulator up	Bool	%Q1.5
AGV1 return to origin	Bool	%Q1.6
AGV1 go to pickup point	Bool	%Q1.7
AGV1 go to front of rack	Bool	%Q2.0
AGV1 go under rack	Bool	%Q2.1
AGV1 go to rack front during outbound	Bool	%Q2.2
AGV1 go to outbound point	Bool	%Q2.3
AGV1 pallet down	Bool	%Q2.4
AGV1 pallet up	Bool	%Q2.5
AGV1 fixed to pallet 1	Bool	%Q2.6
Pallet 1 fixed to material	Bool	%Q2.7
Pallet 1 collision sensor triggered	Bool	%I0.1
AGV1 pickup point reached	Bool	%I0.2
AGV1 outbound point reached	Bool	%I0.3
AGV2 return to origin	Bool	%Q3.1

4.2 PLC Program Development

To accurately control the AGVs, complete material storage and retrieval, and realize manipulator handling and automated intelligent warehousing, a total of 101 PLC variables are defined, and the PLC control program is developed. Some PLC variables are listed in Table 7.

4.3 PLC Configuration

PLC simulation is used in this design to virtually simulate controllers such as the S7-1500, thereby enabling PLC program simulation and verification without physical hardware. First, after opening the software, PLCSIM connection is selected in Online Access. Then the CPU signal is selected as S7-

1500, and a virtual PLC named "1518-4" is created. After the Start button is clicked, the indicator of "1518-4" flashes and then remains green, indicating that the virtual PLC has been created and is running on the computer. Finally, S7-PLCSIM V20 is opened, and the download button is used to download the developed PLC program, PLC variables, and other parameters to the newly created virtual PLC "1518-4". The virtual PLC then waits for signal mapping with NX_MCD so that the PLC program can control the simulation model.

5. MCD-PLC Joint Commissioning

5.1 MCD Signal Mapping

For signal mapping between MCD and PLC, the signal mapping option is first selected in the interface. The type is set to PLCSIM Advanced, and the PLCSIM Advanced instance is selected as "1518-4". The MCD signals shown in Table 8 are then selected in the signal column, followed by the external signals shown in Table 9. The signals must correspond one-to-one and should not be confused. After the corresponding signals are selected, the mapping signal button in the middle is clicked. Finally, all signal mappings are completed according to the above steps, as shown in Table 10.

Table 8. Partial MCD signals

Name	Adapter name	I/O type
AGV1 outbound point reached	AGV1 control	Output
AGV1 go to front of rack during outbound	AGV1 control	Input
AGV1 front-of-rack position reached during outbound	AGV1 control	Output
AGV1 go under rack during outbound	AGV1 control	Input
AGV1 under-rack position reached during outbound	AGV1 control	Output
AGV1 go to outbound point	AGV1 control	Input
AGV1 go to front of rack	AGV1 control	Input
AGV1 go under rack	AGV1 control	Input

5.2 Virtual Commissioning

After all the above operations are correctly completed, the HMI device in the PLC virtual simulation can be used to select Screen 1 and start simulation after compilation is completed. The NX model is then opened, and the Play button is clicked in the simulation option to start MCD mechatronic simulation, thereby realizing real-time linkage between PLC control logic and the virtual model. The HMI touch screen is designed with various functional control points and displays corresponding state variables. After compilation is confirmed to be correct, the program is downloaded to the PLC. Once the simulation starts, the first material can be observed moving on the conveyor. When the inbound-station material-in-position indicator on the HMI turns green, any idle AGV can be started to perform storage or retrieval operations. During simulation, the key observations include whether the two AGVs perform storage and retrieval according to the one-to-one rack binding strategy, whether any path conflict occurs during operation, whether the sequence of manipulator grasping, transfer, and release is accurate, whether the HMI displays rack occupancy status and inbound/outbound counts in real time, and whether all components move smoothly. Redundant steps can be removed, and virtual-real synchronization delays and motion stuttering can be resolved by fine-tuning signal mapping parameters, path coordinates, and motion position controls, thereby achieving stable system operation.

Table 9. Partial MCD external signals

Name	I/O direction	Data type
AGV1 outbound point reached	Input	Bool
AGV1 go to front of rack during outbound	Output	Bool
AGV1 front-of-rack position reached during outbound	Input	Bool
AGV1 go under rack during outbound	Output	Bool
AGV1 under-rack position reached during outbound	Input	Bool
AGV1 go to outbound point	Output	Bool
AGV1 go to front of rack	Output	Bool
AGV1 go under rack	Output	Bool

Table 10. Partial mapped signals (PLCSIM Adv. 1518-4)

Connection name	MCD signal name	Direction	External signal name
AGV1 control_AGV1 outbound point reached_AGV1 outbound point reached	AGV1 outbound point reached	→	AGV1 outbound point reached
AGV1 control_AGV1 go to front of rack during outbound_AGV1 go to front of rack during outbound	AGV1 go to front of rack during outbound	←	AGV1 go to front of rack during outbound
AGV1 control_AGV1 front-of-rack position reached during outbound_AGV1 front-of-rack position reached during outbound	AGV1 front-of-rack position reached during outbound	→	AGV1 front-of-rack position reached during outbound
AGV1 control_AGV1 go to outbound point_AGV1 go to outbound point	AGV1 go to outbound point	←	AGV1 go to outbound point
AGV1 control_AGV1 go to front of rack_AGV1 go to front of rack	AGV1 go to front of rack	←	AGV1 go to front of rack
AGV1 control_AGV1 go under rack_AGV1 go under rack	AGV1 go under rack	←	AGV1 go under rack

6. Conclusion

This paper aims to realize digital twin visualization design for an intelligent warehousing and AGV scheduling system. To address the problems of information silos, multi-AGV path conflicts, and insufficient real-time monitoring capability in traditional warehousing, a digital-twin-based solution using NX_MCD is proposed. First, UG is used to complete three-dimensional modeling and lightweight processing of functional components such as the three-dimensional warehouse, underride AGVs, manipulators, racks, and inbound/outbound stations. Then, NX_MCD is used to construct a mechatronic concept model, in which motion joints, sensors, and signal adapters are configured to realize digital mapping of physical properties. Finally, a virtual PLC control system is built by combining Siemens TIA Portal and PLCSIM Advanced, and real-time signal interaction between the MCD model and the PLC is realized through the PLCSIM Advanced protocol. In this way, virtual commissioning of AGV storage/retrieval path planning, manipulator handling logic, and inbound/outbound processes is completed. In addition, the system uses an HMI interface to realize visual monitoring of warehouse status. Indicator lights dynamically display rack occupancy, AGV operating status, and inbound/outbound counts. The results verify the effectiveness of digital twin technology in optimizing path conflicts during multi-AGV motion, reducing physical commissioning costs, and improving system coordination efficiency, and they provide a reusable engineering digital model for the digital transformation of small- and medium-sized warehousing enterprises.

Acknowledgments

This work was supported by Chengdu Technological University 2024 University-Level Research Projects (Yibin Campus): Digital Twin Technology-Based Optimization of the Design Process for Packaging Systems (No. 2024YB013).

References

[1] Zhang, C. J., Li, H. L., & Fan, Z. Y. (2025). Research status and application of intelligent warehousing. Die & Mould Manufacture, 25(6), 32–35.

[2] Zhang, Z. Z., & Su, J. (2023). Design of an intelligent warehousing management system based on "5G + intelligent logistics equipment". Journal of Qingdao University (Natural Science Edition), 36(2), 58–63.

[3] Fan, M. C. (2023). Research on digital twin of automatic sorting system for warehouse logistics [Master's thesis]. Zhejiang A&F University.

[4] Yao, W., Sun, J., & Wu, S. (2022). Construction and simulation research of logistics automation stereoscopic storage system based on digital twin. In 2nd International Conference on Applied Mathematics, Modelling, and Intelligent Computing (CAMMIC 2022) (Vol. 12259, p. 122593B). SPIE.

[5] Zheng, B., Tan, M. K., Yang, S. S., Chen, H. B., Bai, Y., & Wang, H. B. (2024). Development of digital twin technology based intelligent system for the manufacturing processing line. In 2024 IEEE 22nd Student Conference on Research and Development (SCOReD) (pp. 427–432). IEEE.

[6] Zhou, H. (2024). Research on multi-AGV scheduling system for intelligent warehousing [Master's thesis]. Wuhan Institute of Technology.

[7] Chen, S. Y. (2025). Research on path planning and scheduling strategy based on AGV [Master's thesis]. Anhui University of Science and Technology.

[8] Ji, S. T. (2024). Design and virtual debugging research of digital tridimensional warehousing system [Master's thesis]. Wuhan Polytechnic University.

[9] Xiong, Y. Q., Hu, S. K., Xu, X. A., et al. (2023). Design of a virtual simulation control system for robot material handling and AGV storage based on MCD and PLC. Software, 44(6), 15–20.