

Article

Virtual Simulation Design and Debugging of Lift-and-Transverse Stereo Garage Based on the Digital Twin

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Featured Application: Application of the digital twin concept to a specific scenario of the lift-and-transverse garage. Starting from the design phase to the final field planning and debugging. It not only verifies the feasibility of equipment solutions using virtual models of digital twins but also optimizes design solutions, identifies problems, and solves them. The operational test results of the virtual model can also fully demonstrate the effectiveness of the proposed digital twin model and related design methods, which provide an important reference for the design optimization and operation of future stereo garages. In addition, compared with the traditional development process, the virtual simulation design and debugging method can not only shorten the development cycle and debugging cost but also accelerate the development progress. This new method provides a brand new idea for the development of the enterprise and also makes a positive contribution to promoting the modernization of urban parking lots.

Abstract: In the face of the challenges of limited urban space and the continuous increase of vehicles, stereo garages have been widely used as a solution in cities. In order to improve the automation and intelligence level of the stereo garage, this paper applies the digital twin technology to the lift-and-transverse stereo garage. A five-dimensional model of a digital twin has been developed based on an actual stereo garage. Combined with S7-PLCSIM Advanced, Botu TIA Portal, and NX MCD to build a virtual simulation platform, realizing the virtual simulation design and debugging of the digital twin-based stereo garage. This approach allows to test and optimize operational processes without relying on physical equipment, reducing labor and field debugging costs, shortening deployment cycles, and significantly reducing development costs. In addition, MCD allows real-time monitoring and control of security risks and failures detected. Finally, the feasibility of the virtual simulation and debugging scheme based on digital twin is verified by comparing the operation data of the virtual model and the actual stereo garage, which provides new ideas for the intelligent development of stereo garage but also can be used as an important reference for the development of equipment in other areas.

Keywords: digital twin; stereo garage; NX MCD; virtual debugging



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1. Introduction

With the continuous development of emerging technologies such as cloud computing, the Internet of Things (IoT), and big data, countries around the world are actively promoting the integration of traditional equipment in the physical and digital domains and advancing intelligent operations to achieve intelligent manufacturing [1,2]. Intelligent manufacturing represents the deep integration of intelligent and traditional technologies, and its core purpose is to enhance the traditional manufacturing process by applying intelligent technologies throughout the product life cycle. However, how to realize the real-time interaction between virtual information and physical equipment information in the process of equipment development is one of the main challenges facing the application of intelligent manufacturing concepts in actual production development [3].

As research into digital twins deepens, the integration of the field into the industry is gradually increasing. When the concept of digital twins permeates the development of traditional devices, a novel and viable approach to intelligent debugging emerges. The main idea of this approach is to use digital twin technology to interact virtual information with physical device information in real time so as to achieve virtual control and optimization of the device. By creating a digital model of the equipment, it is possible to simulate and optimize the control process in a virtual environment, improving operational efficiency and operational quality. At the same time, through real-time monitoring and analysis of the state and operation data of physical equipment, the development strategy can be adjusted in time to realize the intelligence and automation of the development process.

Digital twin is an innovative technology that simulates the behavior of physical entities in the real world by creating a virtual model of those entities and using that model and associated data to simulate the behavior of those entities in the real world. This technology injects new functionality into physical entities, enabling interactive feedback between virtual reality and the real world, integrated analysis of data, and continuous optimization of the decision-making process [4]. At all stages of the product lifecycle, digital twin technology uses modeling, data analytics, and interdisciplinary techniques to build a bridge between the physical world and the information world so that it can provide more real-time, efficient, and intelligent services [2,5,6].

With the development of the new round of information technology, digital twin has gradually become the driving force of intelligent manufacturing and the bridge and link between the physical world and the information world [4]. The application of digital twins in industrial and life scenarios typically goes through three phases. Firstly, virtual debugging is performed to optimize the model by solving problems in the design. Secondly, real-world signals interact with the virtual world to enable virtual debugging. Finally, applying digital twins to the real world. Virtual debugging helps to identify and resolve problems early, as well as reduce manufacturing errors and improve R&D efficiency. Many scholars have conducted related research, and digital twins were first proposed by Grieves for full product lifecycle management [7]. In 2015, Rios et al. proposed to build a digital dual model for modern manufacturing [8]. Lee et al. argue that digital twin technology should not be limited to a particular product and can be applied throughout the development process of modern manufacturing [9]. Brenner et al. applied digital twin technology in a logistics smart factory [10]. Uhlemann et al. explored the digital twin factory, implementing methods such as real-time data collection as well as simulation-based data processing [11]. Stojadinovic et al. developed a virtual inspection system for checking the tolerances of standard model mobile mechanical parts based on the digital twin of a CMM as a mirroring process between the physical and virtual measurement systems [12]. Hofmann et al. used virtual debugging techniques in the field of material control [13]. Wang et al. proposed a method to solve the failures of electromechanical equipment by introducing digital twin technology and establishing a predictive maintenance model for electromechanical equipment [14]. Turan et al. proposed a digital twin model to improve process and product quality [15]. Corradini et al. illustrated a digital twin primitive solution for material extrusion three-dimensional (3D) printers, where the twin program is able to directly intervene in the current process in order to pause printing anomalies through the interactive use of print host software [16]. Digital twin technology has been widely used in a variety of fields, such as manufacturing workshops, aerospace, and complex equipment manufacturing [17].

Digital twin technology has shown great potential in a variety of fields, and it can also be used to enhance the operation of automated parking facilities. Simulating debugging by creating virtual models reduces errors and costs in actual operation and increases safety and efficiency.

By optimizing the use of urban space, stereo garages significantly increase the vehicle accommodation rate, while the use of steel structures effectively reduces construction costs and has a positive impact on urban development. However, these facilities face a number

of challenges in actual operation and have relatively high operating costs, which directly affect the sustainability of the program [18]. This is mainly reflected in the dependence on specialized personnel, which exacerbates the cost of manpower; the frequent discrepancies between the debugging of equipment and the actual situation in the field, which leads to longer deployment cycles and makes maintenance and upgrading complex and cumbersome; the mechanical failures may not only damage the vehicle and cause property loss to the user but also pose a safety risk. Although the concept of stereo garages is forward-looking and has the potential to revolutionize urban mobility, their level of intelligence and safety needs to be further improved in order to ensure their wider acceptance and application, thus unlocking their full potential in urban mobility [19].

Stereo garages, as an advanced solution to the conflict between limited urban space and vehicle growth, need to leverage emerging technologies to enhance their automation and user experience. For this reason, this paper integrates digital twin technology into the design and commissioning of lift-and-transverse stereo garages and realizes the virtual simulation and debugging method based on digital twin. Combined S7-PLCSIM Advanced, Botu TIA Portal, and NX MCD to build a virtual simulation platform. This approach enables developers to perform efficient and safe debugging work without physical parking facilities by building virtual models. In addition, with the help of the digital twin model in MCD, real-time monitoring and control of the entire system is realized, which enables potential security risks and failures to be detected and resolved in a timely manner. Finally, the feasibility of the digital twin-based virtual simulation and debugging scheme in engineering applications is verified by comparing the operation and debugging data of the virtual model and the operation data of the actual stereo garage. This provides a way for the intelligent development of automated stereo garages but also provides a valuable reference for the development of equipment in other fields.

2. Digital Twin Five-Dimensional Modeling Framework for Stereo Garages

In order to extend the application of digital twin technology to more fields and penetrate more industries, Tao Fei et al. added two new dimensions of twin data and services to the existing 3D model and put forward the concept of a five-dimensional model for digital twins, as shown in Equation (1).

$$M_{DT} = (PE, VE, Ss, DD, CN), \quad (1)$$

where PE denotes physical entity, VE denotes virtual entity, Ss denotes service, DD denotes twin data, and CN denotes the connection between components. The structure of the digital twin five-dimensional model [20] is shown in Figure 1.

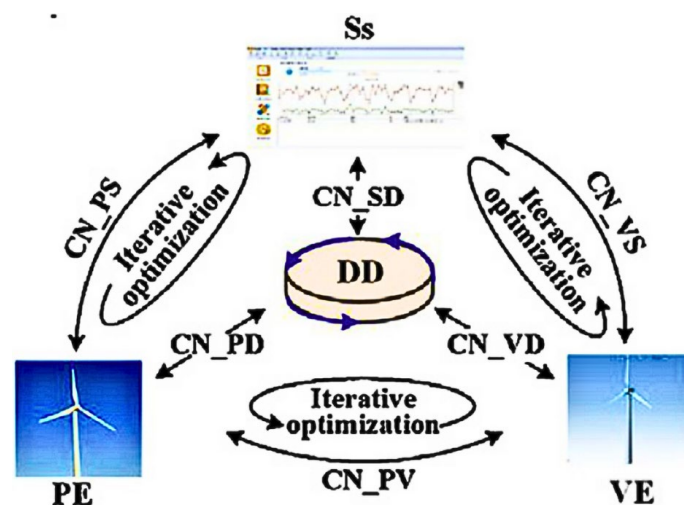


Figure 1. Five-dimensional DT model for complex equipment.

In building digital twin models, M_{DT} provides an interdisciplinary framework that is applicable to a variety of industries and research objects.

The PE is the basis of this model construction, and a system-level analysis of the PE is the first step in exploring the M_{DT} . VE involves the application of different modeling methods, which include the creation of accurately scaled three-dimensional models using 3D modeling software, solid models obtained by 3D scanning technology, and models constructed based on physical principles using mechanical analysis software. Ss are divided into two categories: functional services and commercial services. Functional services include simulation testing, data storage and analysis management after modeling; commercial services cover the enhancement of the digital twin system user experience and intelligent management decision support, etc. DD refers to all data types involved in the construction of digital twins. CN involves the interactions and connections between the above elements.

Based on the digital twin five-dimensional model, combined with the current development trend and use of the stereo garage, the digital twin system of the stereo garage is divided into an application layer, a data processing layer, a virtual twin layer, a device layer and a connection composition between the layers, as shown in Figure 2.

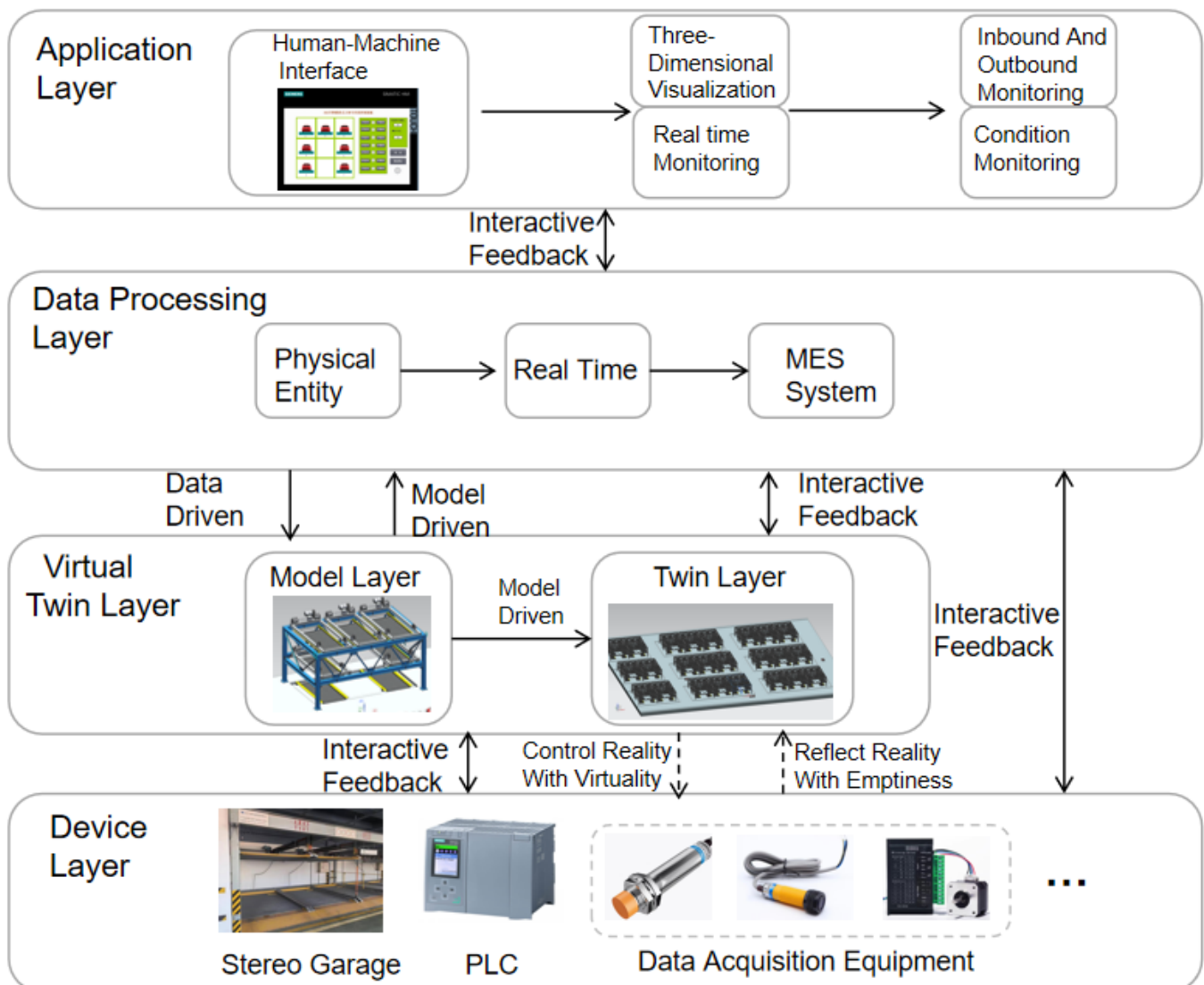


Figure 2. Five-dimensional modeling framework of the digital twin of a stereo garage.

2.1. Application Layer

The application layer corresponds to the service layer in the five-dimensional model, which can realize the simulation and real-time monitoring of the three-dimensional visualization of the physical actions of the stereo garage. The triggering of virtual signals can be targeted to display, analyze, and manage the state information of the actual equipment on the twin model, thus forming a virtual simulation and commissioning platform for the stereo garage to meet the user's needs for real-time monitoring of the stereo garage.

2.2. Data Processing Layer

The data processing layer corresponds to the twin data layer in the five-dimensional model, and the data processing layer is the driver of the whole digital twin system, realizing data acquisition, data integration, and system control. The data processing layer of the stereo garage mainly includes the geometric dimensions of the parts of the stereo garage, the assembly relationship, and the layout of the parking spaces and other structures between the spatial location of the relationship, but also includes the stereo garage twin model of the actuator and the motion sequence of the synergistic relationship between the motion system. In addition, it also includes controlling the control system of the twin model of the stereo garage, the control logic of the system and real-time data display of data between the control system of the relationship.

2.3. Virtual Twin Layer

The virtual twin layer corresponds to the virtual model layer in the five-dimensional model, which is a three-dimensional visualization model of the physical equipment and a digital reconstruction of the stereo garage site. Using NX CAD to complete the drawing of the garage parts and through the assembly to complete the three-dimensional geometric model of the stereo garage, followed by the construction of the digital twin of the stereo garage based on the real stereo garage in NX MCD, set up reasonable actuators and motion control, and realize the same virtual motion as the actual work under the drive of data.

2.4. Device Layer

The device layer, also named the physical layer, corresponds to the physical entities in the five-dimensional model, consists of real existing entities, and is the theoretical basis for the composition of the digital twin system. The physical entity of the stereo garage mainly includes the whole stereo garage, PLC controller, data acquisition equipment (such as photoelectric sensors, stepping motors), etc., in which the three-dimensional garage is the main monitoring object, PLC controller is the main control system, and the data acquisition equipment is the way to obtain the data, which can be transmitted to the various levels through the connection layer.

3. Lift-and-Transverse Stereo Garage Virtual Debugging Program

TIA Portal is an innovative, fully integrated automation software that provides a unified database and platform. The software is compatible with many types of PLC controllers and HMI interfaces. This integrated environment has a variety of communication methods that allow data interaction between different devices, enabling users to monitor PLC data in a variety of situations and in a variety of different ways. S7-PLCSIM Advanced is a simulation software with TIA Portal, which generates a virtual PLC device, enabling users to perform PLC simulation control without actual hardware, and it can also be used in conjunction with HMI to achieve the purpose of simulation monitoring and control without physical hardware.

NX MCD is a specialized tool integrated into Siemens NX software, such as NX 1899, for multidisciplinary conceptual design and simulation in the early stages of mechatronics projects. NX MCD enables the construction of integrated models of mechanical, electrical, and control elements, and the use of simulation capabilities to predict system performance,

make modifications and re-decisions in response to problems, improve quality, and reduce time to market.

The virtual debugging system of the lift-and-transverse garage consists of NX MCD and TIA Portal, in which NX MCD provides the virtual model and simulation environment of the garage, and TIA Portal serves as the development platform of the control system. The virtual debugging system has a bi-directional communication function. The control system can drive the NX MCD actuators via the TIA Portal. At the same time the NX MCD sensors can pass feedback to the controller. The overall architecture of the virtual commissioning of the stereo garage is shown in Figure 3.

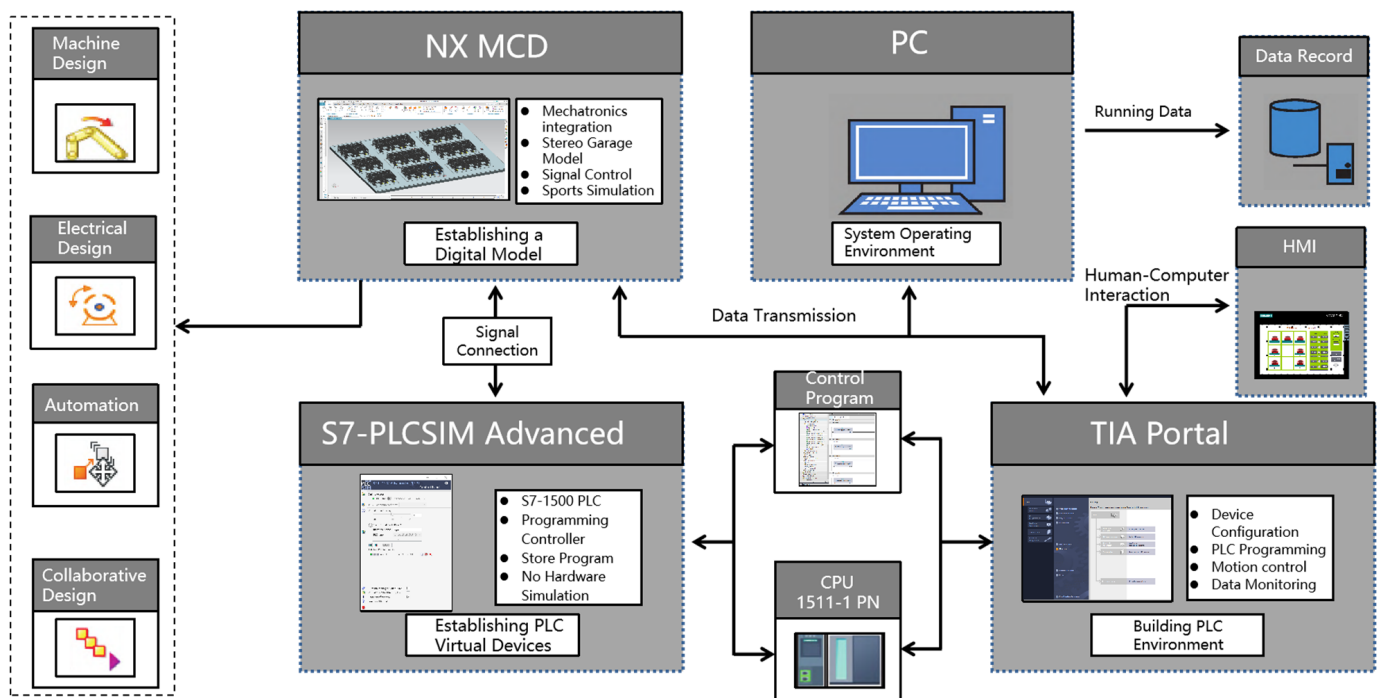


Figure 3. Virtual debugging general architecture.

Using virtual debugging techniques can reduce costs and design and field debugging time. By debugging and optimizing in a virtual environment, problems can be identified and solved earlier, avoiding costly and time-consuming trials and corrections in the real environment. Virtual debugging can also provide a more flexible approach to testing and verification, speeding up the system development and deployment process. Therefore, the use of virtual debugging technology can be more effective in the design and development of stereo garages.

Firstly, the development of a virtual debugging system for a lift-and-transverse garage involves the construction of a three-dimensional model in NX software (NX 1899). Subsequently, the mechanical design of the stereo garage is completed in a Mechatronics Concepts (MCD) environment, which includes the addition of rigid bodies, colliding bodies, and properties of the basic motion subs. The electrical design phase covers the configuration of sensors, position control, speed control, signals, and signal adapters. The automation design includes the implementation of functions such as the external configuration of signals, signal mapping, and connectivity. The automation design of the product was further completed using TIA Portal software (TIA Portal V17) to write the PLC control program and design the HMI human-machine interface. Finally, a virtual PLC is created in the S7-PLCSIM advanced software environment and a connection is established with the signals in the MCD for the simulation and debugging of the virtual model of the stereo garage. The workflow of the virtual debugging of the stereo garage is shown in Figure 4.

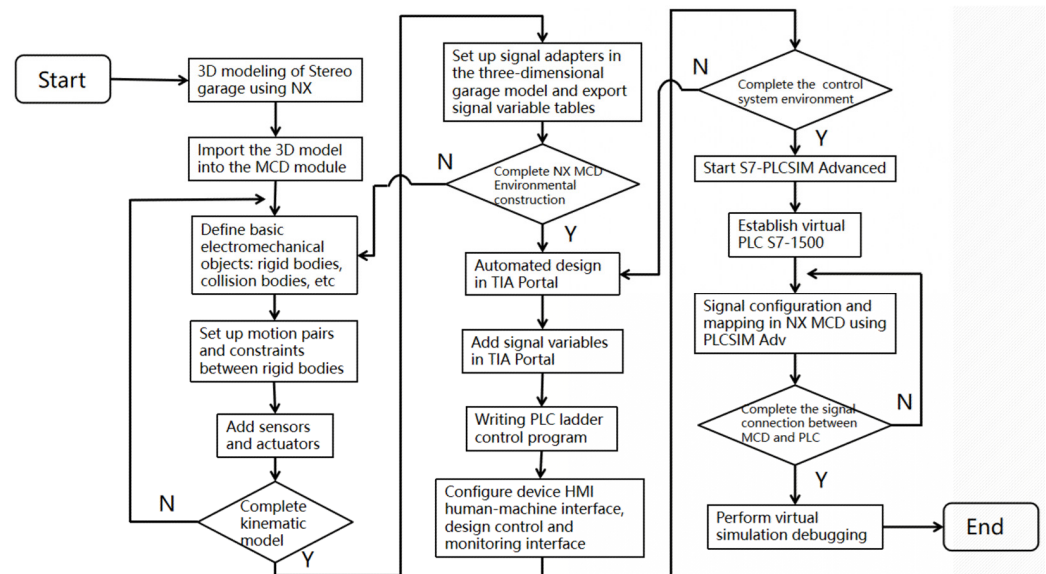


Figure 4. Virtual debugging workflow of a stereo garage.

4. Lift-and-Transverse Stereo Garage Based on the Digital Twin

4.1. Parameter Setting of Lift-and-Transverse Stereo Garage

The dimensional parameters of the equipment used in a stereo garage vary depending on the model used. The referenced stereo garage is a three-story, three-row lift-and-transfer stereo garage, which is mainly suitable for small and medium-sized sedans or SUVs, and parking vehicles of the wrong model is likely to lead to the problem of insufficient parking space, which will lead to a series of accidents. The dimensions of the parking spaces are shown in Figure 5.

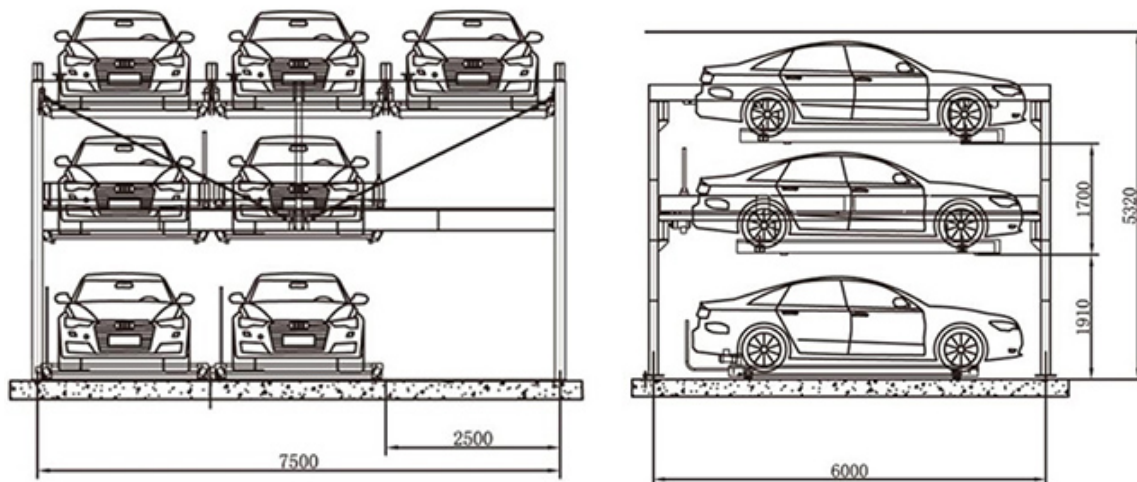


Figure 5. Stereo garage parking space dimensions.

The design and operation of a stereo garage involves a series of finely tuned technical parameters and control methods to ensure that its performance meets stringent engineering and safety standards. Figure 5 shows the dimensions of stereo garage. Table 1 shows the main technical parameters of stereo garage. These parameters are the basis for ensuring the efficient and stable operation of the parking facility. All data are taken from the technical parameters of a stereo garage company, and there is a certain degree of error, but it basically meets the control requirements.

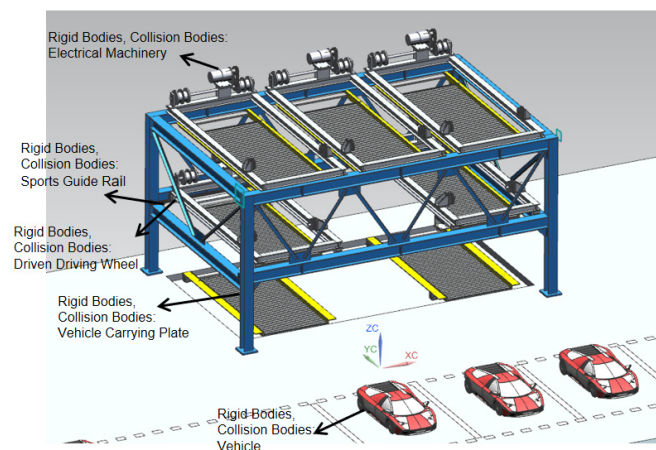
Table 1. Technical parameters of the stereo garage.

Parameter Name	Parameter Content
Equipment Name	Lift-and-Traverse Stereo Garage
Storey	Triple
Applicable Models	Small/Medium Sedan/SUV
Lifting Speed	75 mm/s
Traversing Speed	125 mm/s
Average Access Time	45 s
Driving Method	Motor + Wire Rope

4.2. Digital Twin Modeling of Lift-and-Transverse Stereo Garage

4.2.1. Definition of Lift-and-Transverse Garage Model

All the models are realized in the NX CAD module. According to the operation mode of the lift-and-transverse stereo garage, sketching is carried out in the NX CAD module to construct the geometrical 3D model of each part, and the assembly of the parts is completed by setting constraints. In order to build the virtual model, it needs to be imported into MCD first. Adding basic physical attributes to model components is a necessary foundation in MCD. Only after defining the basic object attributes have been defined can you continue to add mechanical, electrical and automation attributes to complete the definition of the electromechanical object. The electromechanical objects are defined as shown in Figure 6.

**Figure 6.** Definition of virtual model electromechanical objects.

Different types of stereo garages operate in different ways, and it is necessary to analyze the operation of lift-and-transverse stereo garages in order for the virtual model to operate as well as the physical entity. In a lift-and-transverse garage, due to the structural characteristics of the garage, the carrier plate on the top level can only move vertically, while the carrier plate on the bottom level can only move horizontally, but on other levels, the carrier plate can move both vertically and horizontally.

The movement of the carrier plate in each direction needs a motor for control, as shown in Figure 7a–c. The design of the uppermost carrier plate is relatively simple, and only one motor is needed to complete the lifting and lowering operation. Through the motor-driven gear system, the control drum makes the wire rope carry on the retracting and releasing action so as to realize the vertical movement of the carrier plate. At the bottom level, the transverse movement of the carrier plate is also controlled by a single motor, which, through gearing, drives the active rod to rotate, thus pushing the carrier plate along the horizontal direction. In other intermediate layers, the design of each carrier plate is more complex, requiring two motors for complete motion control. One of the motors is responsible for vertical movement, which works in a similar way to the top carrier plate, with the lifting and lowering controlled by a motor-driven gear system. The other motor

is used to control the horizontal movement, similar to the movement mechanism of the bottom carrier plate, which is accomplished by the horizontal displacement of the carrier plate through the cooperation of gears and active rods. On the ground level, vehicle access is more convenient and the same as traditional parking space access, but on the other floors, vehicle access needs are met by utilizing the transverse movement of each space to create a dedicated vertical pathway that allows the upper-level target load boards to pass through, thus landing them from the upper level to the ground level.

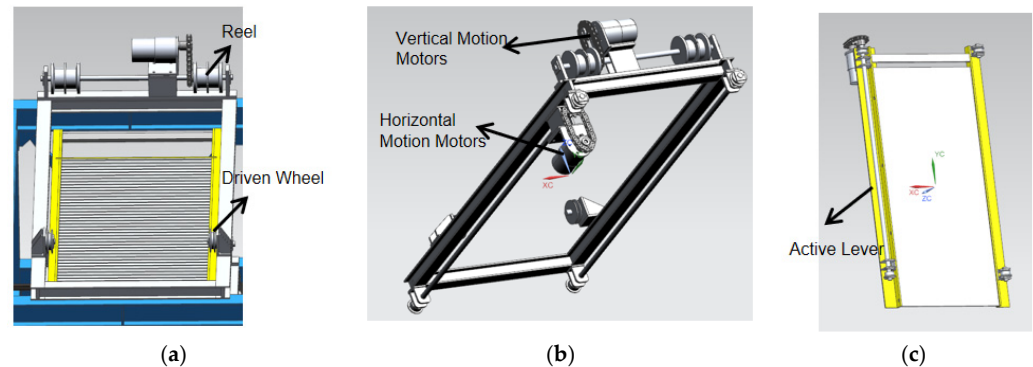


Figure 7. Motion mode of stereo garage: (a) topmost carrier plate; (b) middle-level carrier plate; (c) bottom-level carrier plate.

4.2.2. Definition of the Electromechanical Characteristics of Lift-and-Transverse Garage

Virtual debugging of the construction of electromechanical objects is mainly expressed in the process control of geometric, three-dimensional models, which need to be completed in the NX MCD module for the construction of geometric, three-dimensional models of electromechanical objects. Electromechanical objects mainly include sensors and actuators, two parts; according to the operation of the stereo garage, sensors and actuators have their own electromechanical characteristics. Of course, all the electromechanical characteristics need to be set up on the basis of the physical properties of the parts to be completed. Once the electromechanical characteristics are set up, the corresponding conditions can be triggered to generate signals to be fed back to the control system to make the appropriate control. Stereo garage model basic electromechanical objects, according to the corresponding signal to make the movement. Therefore, it is necessary to give electromechanical characteristics and set signals to the key actuating components of the stereo garage. As shown in Figure 8, the sliding and hinged sub-setups are performed for the motor, and the carrier plate of the parking space and position control and speed control are added to control the forward and reverse rotation of the motor by giving positive and negative speeds.

Joints and Constraints		Sensors and Actuators	
<input checked="" type="checkbox"/>	First layer guide rail-FJ (1)	<input checked="" type="checkbox"/>	Horizontal motor of parki... Speed Control
<input checked="" type="checkbox"/>	FJ(1)	<input checked="" type="checkbox"/>	Horizontal motor of parki... Speed Control
<input checked="" type="checkbox"/>	Horizontal motor of parki...	<input checked="" type="checkbox"/>	Motor for parking space ... Speed Control
<input checked="" type="checkbox"/>	Horizontal motor of parki...	<input checked="" type="checkbox"/>	Motor for parking space ... Speed Control
<input checked="" type="checkbox"/>	Motor for parking space 2	<input checked="" type="checkbox"/>	Motor for parking space ... Speed Control
<input checked="" type="checkbox"/>	Motor for parking space 7	<input checked="" type="checkbox"/>	Motor for parking space ... Speed Control
<input checked="" type="checkbox"/>	Motor for parking space ...	<input checked="" type="checkbox"/>	Motor for parking space t... Speed Control
<input checked="" type="checkbox"/>	Motor for parking space t...	<input checked="" type="checkbox"/>	No.1 parking space moto... Speed Control
<input checked="" type="checkbox"/>	No.1 parking space moto...	<input checked="" type="checkbox"/>	No.4 parking space lifting... Speed Control
<input checked="" type="checkbox"/>	No.4 parking space lifting...	<input checked="" type="checkbox"/>	Number 2 parking space l... Position Control
<input checked="" type="checkbox"/>	Number 2 parking space L...	<input checked="" type="checkbox"/>	Number 4 parking space l... Position Control
<input checked="" type="checkbox"/>	Number 4 parking space L...	<input checked="" type="checkbox"/>	Number 5 parking space l... Position Control
<input checked="" type="checkbox"/>	Number 5 parking space L...	<input checked="" type="checkbox"/>	Number 6 parking space l... Position Control
<input checked="" type="checkbox"/>	Number 6 parking space L...	<input checked="" type="checkbox"/>	Number 7 parking space l... Position Control
<input checked="" type="checkbox"/>	Number 7 parking space L...	<input checked="" type="checkbox"/>	Number One Parking Spa... Position Control
<input checked="" type="checkbox"/>	Number One Parking Spa...	<input checked="" type="checkbox"/>	Parking space 1-PCJ (1)_P... Position Control
<input checked="" type="checkbox"/>	Parking space 1-PCJ (1)	<input checked="" type="checkbox"/>	Parking space 3-PCJ (1)_P... Position Control
<input checked="" type="checkbox"/>	Parking space 3-PCJ (1)	<input checked="" type="checkbox"/>	Parking space 5 lifting mo... Speed Control
<input checked="" type="checkbox"/>	Parking space 5 lifting mo...	<input checked="" type="checkbox"/>	Third Parking Space Vehic... Position Control
<input checked="" type="checkbox"/>	Second level orbital-FJ (1)		
<input checked="" type="checkbox"/>	Second Parking Space Ve...		
<input checked="" type="checkbox"/>	Third Parking Space Vehic...		

Figure 8. Definition of electromechanical characteristics of the virtual model.

4.2.3. Simulation Sequence Construction of Lift-and-Transverse Stereo Garage

The process control of the virtual model of the lift-and-transverse stereo garage also needs to be realized by setting up the simulation sequence, which mainly includes setting up the runtime parameters, runtime expressions, runtime behaviors, and other parts. In order to achieve motion simulation control at runtime and better virtual debugging, the signals are added to the simulation sequence, allowing for a more realistic execution of the motion simulation. The signals mainly simulate external input signals and are used to control some electromechanical objects. The simulation sequence makes the control process smoother and more accurate by adding some of the signals, and some of the simulation sequences are shown in Figure 9.

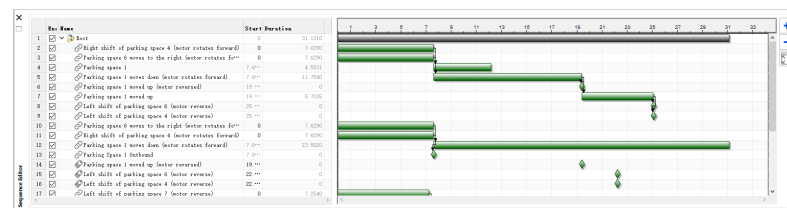


Figure 9. Partial simulation sequence of a stereo garage.

The motion simulation process is shown in Figure 10, and the simulation object is mainly based on the access car of the No. 1 parking space, as an example, which is carried out in accordance with the simulation sequence set up in Figure 8.

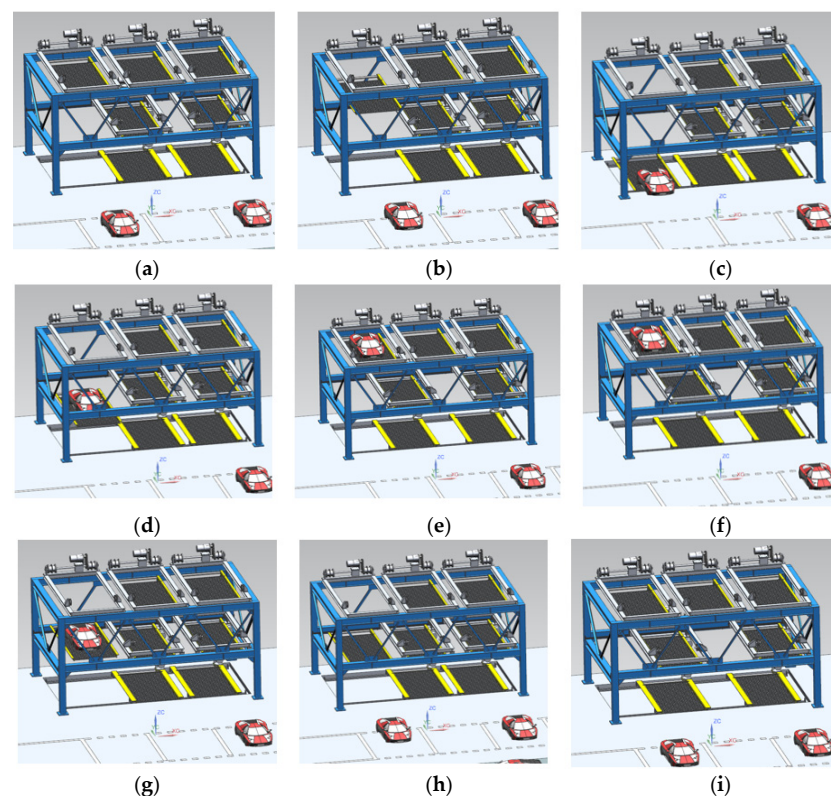


Figure 10. Simulation process of accessing cars in parking space No. 1: (a) Storage: first and second-floor parking space traverse; (b) Storage: Car load board down in bay 1; (c) Storage: Parking; (d) Storage: Vehicle detected, load board rises; (e) Storage: first and second-floor parking spaces are moved across to the right position; (f) Pick-up: first and second-floor parking space traverse; (g) Pick-up: Vehicle and load board lowered; (h) Pick-up: load board rises after pickup is complete; (i) Pick-up: first and second-floor parking spaces are moved across and returned to their original position.

4.3. Build Control System Equipment Environment

According to the virtual debugging scheme, after constructing the electromechanical characteristics and simulation sequence of the digital twin virtual model, a virtual control system needs to be designed to control the virtual model. All the control systems in this paper are performed in the TIA portal.

4.3.1. Create Virtual PLC Devices

Before designing the control system, start S7-PLCSIM Advanced and select Virtual S7-1500 PLC to establish a virtual S7-1500 PLC and start it; the prerequisite needs to set the name as well as the IP address of the PLC. This time, the name is set to signal, and the IP address is set to 192.168.0.1, which corresponds to the setup line in the PLC. This is shown in Figure 11.

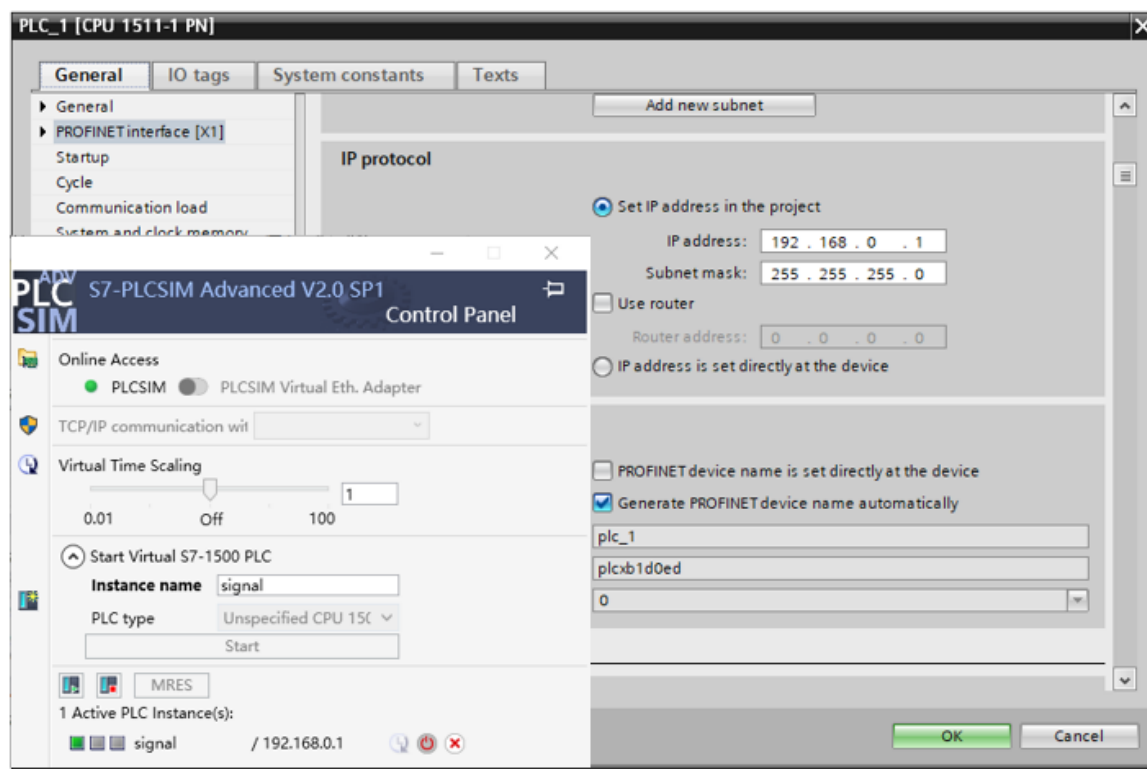


Figure 11. Creating virtual PLC.

4.3.2. Control System Programming

The signals created in the MCD are exported and turned into PLC variables to be added to the variable table of the PLC, and the motion of the simulation sequence is controlled by writing the corresponding control program. The whole program is modularized to control each parking space individually. The program includes motion control, position simulation and counting for seven parking spaces. As shown in Figure 12, the required parking space is selected through HMI. Then, PLC will start the motor of the corresponding module according to the selected parking space, carry out the movement according to the pre-set parameters, vacate the corresponding downward channel to let the upper parking space descend, and record the vacant parking space after the access is completed, and reset the parking space. The entire process is ensured by a coherent, sequential control flow that ensures smooth machine operation. Once the limit signal is detected, the system automatically determines and sends out the next working signal, which guarantees the synergistic and efficient operation of the whole stereo garage system.

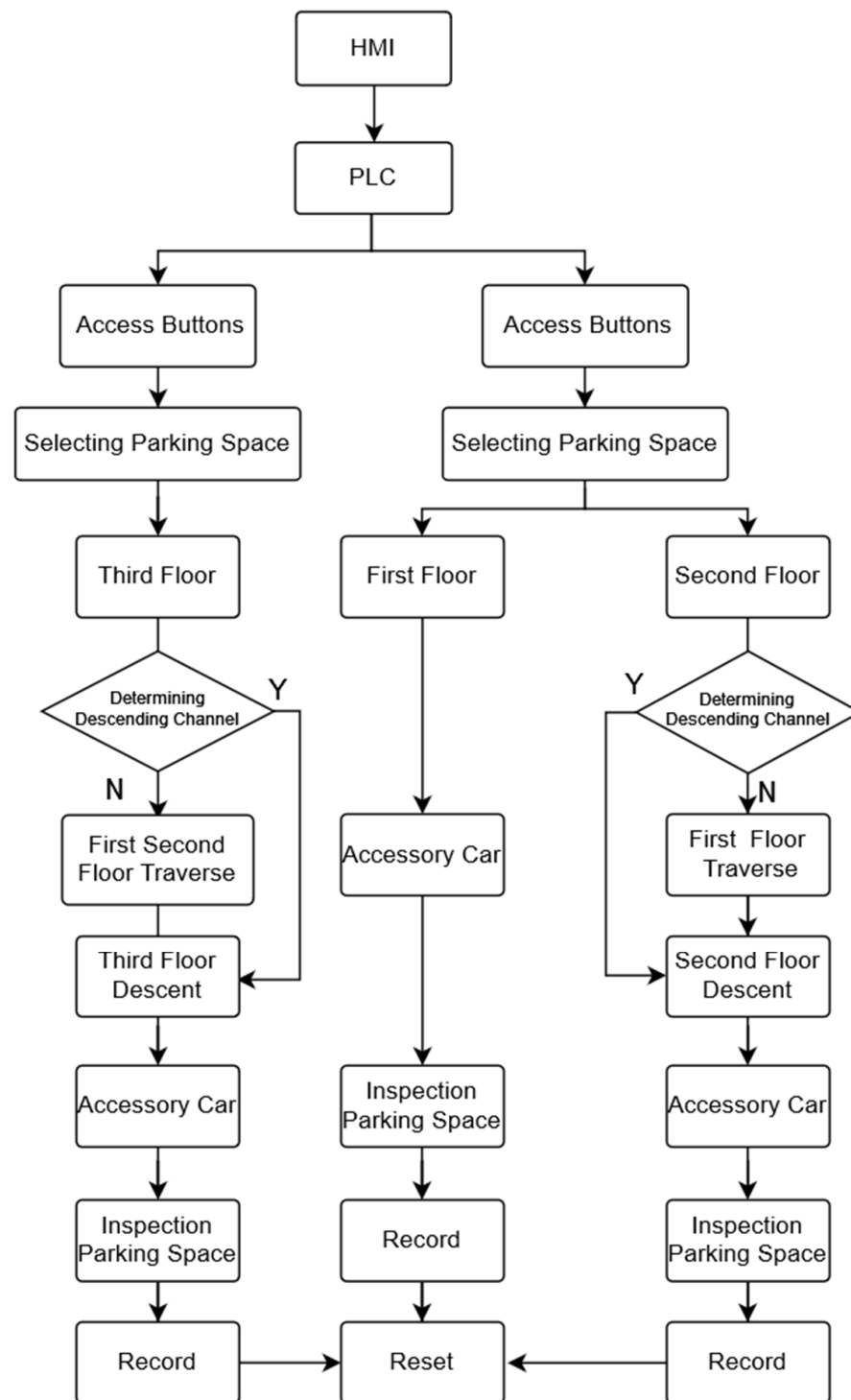


Figure 12. Stereo garage control logic.

4.3.3. Human–Machine Interface Design

The HMI configuration device is used to display the current working status, and the virtual model in NX MCD can be controlled through the HMI configuration device display interface, which includes the storage buttons for parking spaces from 1 to 7, the pickup buttons for parking spaces from 1 to 7, the emergency stop button, the reset button, the running position of parking spaces from 1 to 7, the number of times that each parking space is run on the display, and the number of remaining and used parking spaces in the garage, as shown in Figure 13.

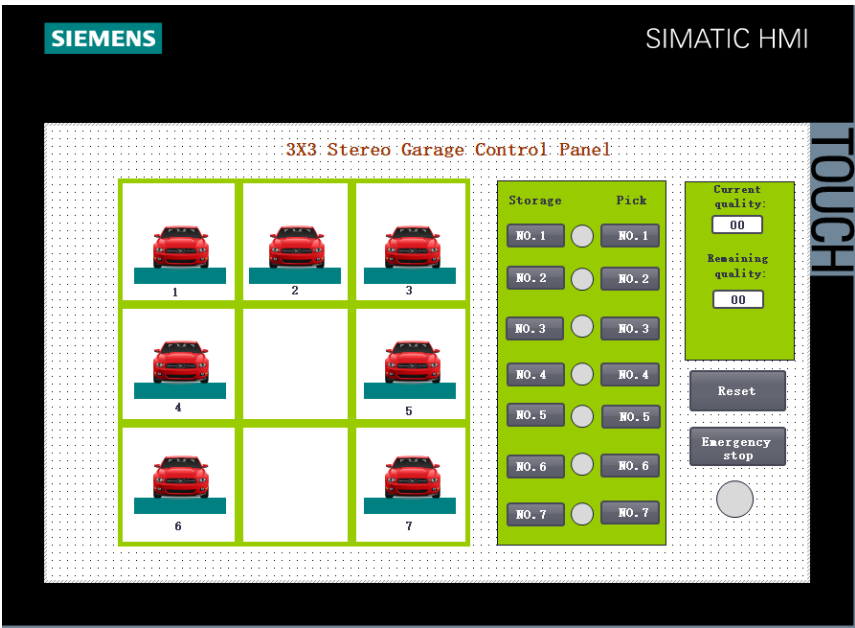


Figure 13. Human–Machine-Interface.

4.4. Signal Mapping

After the above is completed, the signals in the MCD and the input/output variables in the PLC can be mapped to each other through the signal mapping function, thus realizing the control of the models in the NX MCD through the PLC in the TIA portal. The signal mapping is shown in Figure 14, where the input signals of the access car mainly represent the motor signals, which are used to control the start and stop of the motors in the MCD.

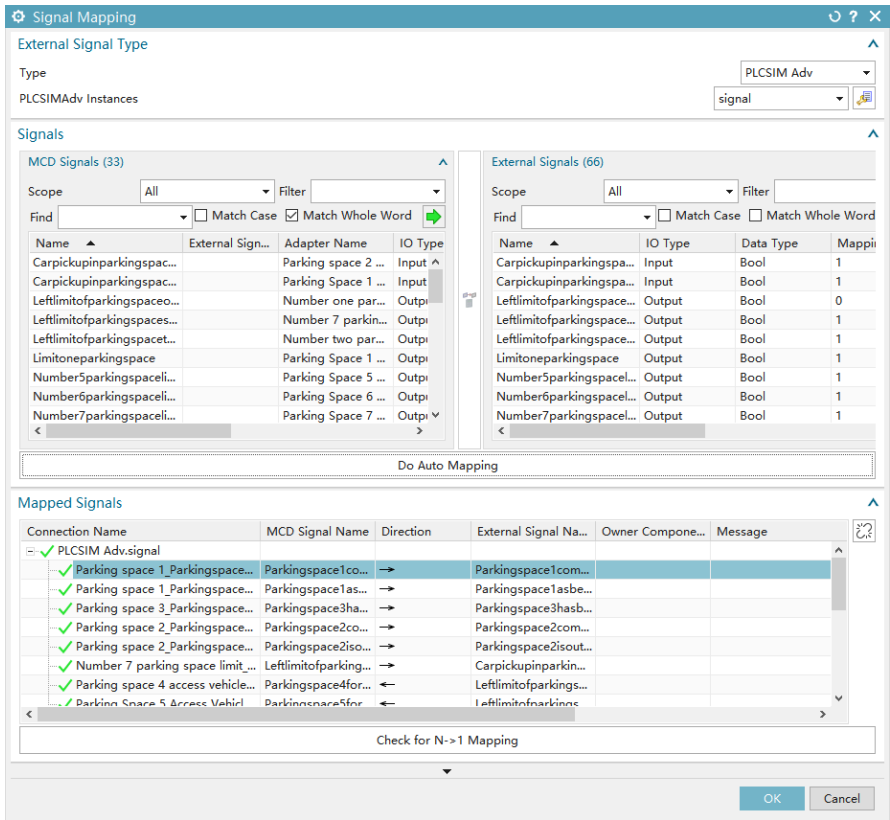


Figure 14. PLC and NX MCD signal mapping.

4.5. Virtual Debugging

4.5.1. Virtual Debugging Process

The test system's computing environment is based on an Intel i7-11800H CPU (Central Processing Unit) and an RTX 3060 6G GPU (Graphic Processing Unit), which is slightly lagging due to the many parts in the virtual run but is relatively smooth and basically meets the requirements of virtual debugging. In order to verify the rationality and validity of the model established in the paper and its motion sequence and control system, the virtual commissioning process of the project is carried out for storing and picking up cars to verify the feasibility of the system.

The main debugging steps are as follows:

1. Start S7-PLCSIM, configure the instance name, and start the instance;
2. Start the simulation in PLC, download the program, and connect the virtual device;
3. Connect the PLC with the signal mapping function in NX MCD;
4. Start the HMI simulation and debug the virtual model in NX MCD in the Human–Machine Interface.

Take parking space No. 1, for example. Push the storage button for parking space No. 1 to debug the storage. The green light is on in the running, and parking spaces No. 4 and No. 6 transverse to the right to make way for parking space one to move down the street. After detecting that a vehicle is parked in place, the No. 1 parking space motor is activated, and the motor reverses so that the carrier plate rises. When parking space No. 1 is in place, parking spaces No. 4 and No. 6 move left to return to their original positions, and parking space No.1 is stocked. Then, press the No.1 car pickup button to pick up the car for debugging. The specific debugging interface is shown in Figures 15–21.

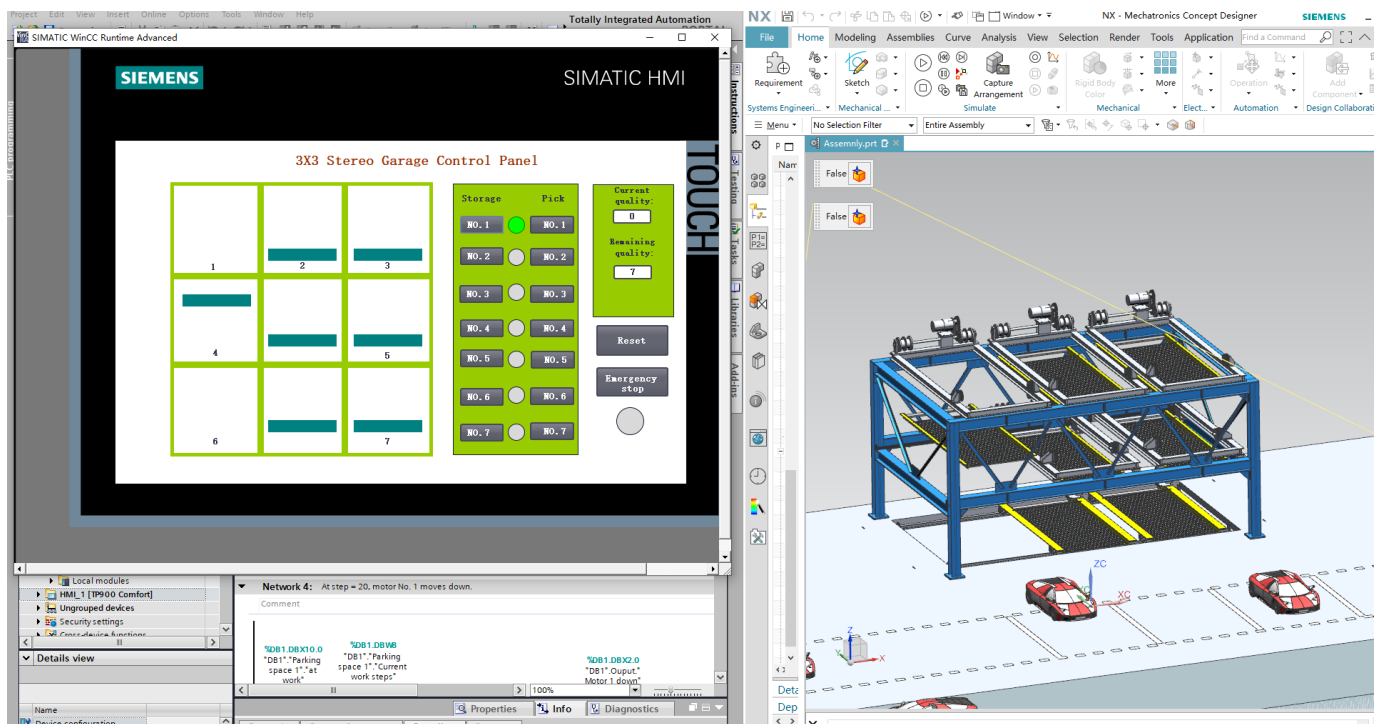


Figure 15. Virtual debugging interface of storage car.

Figures 15–17 for the NO.1 Parking space storage debugging, in the debugging interface, press the No. 1 Parking space storage button, the stereo garage in accordance with the pre-set mode of operation, the internal motor operation program, and the virtual model of the normal movement, storage car debugging success.

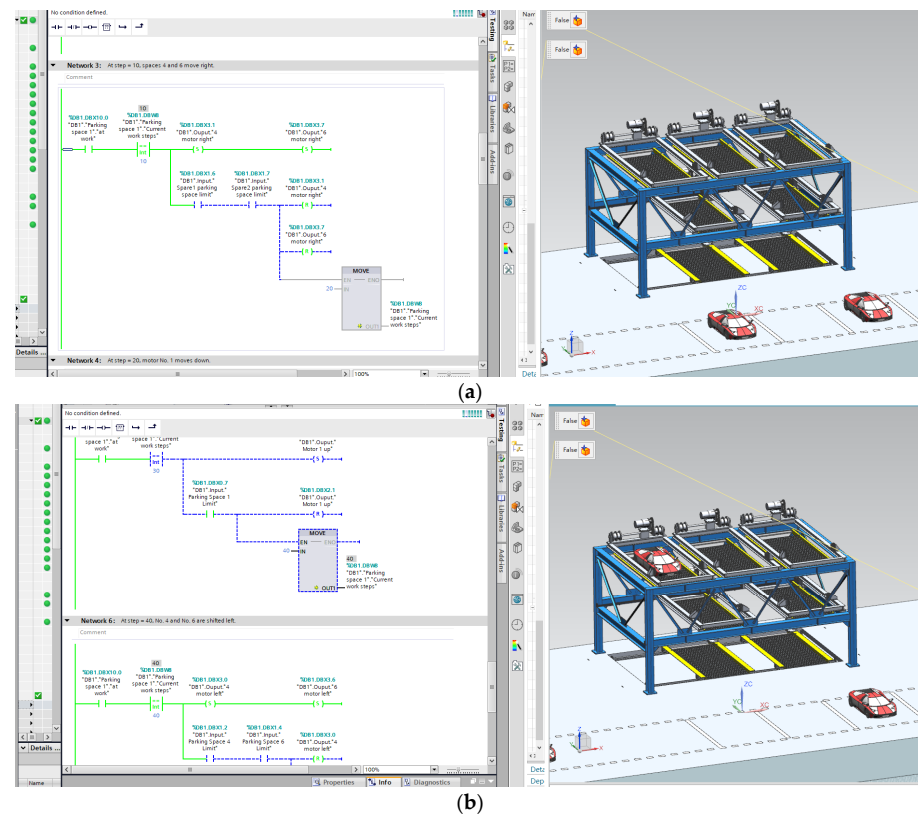


Figure 16. Transverse debugging for parking spaces No. 4 and No. 6: (a) right transverse debugging of parking spaces No. 4 and No. 6; (b) left transverse debugging of parking spaces No. 4 and No. 6.

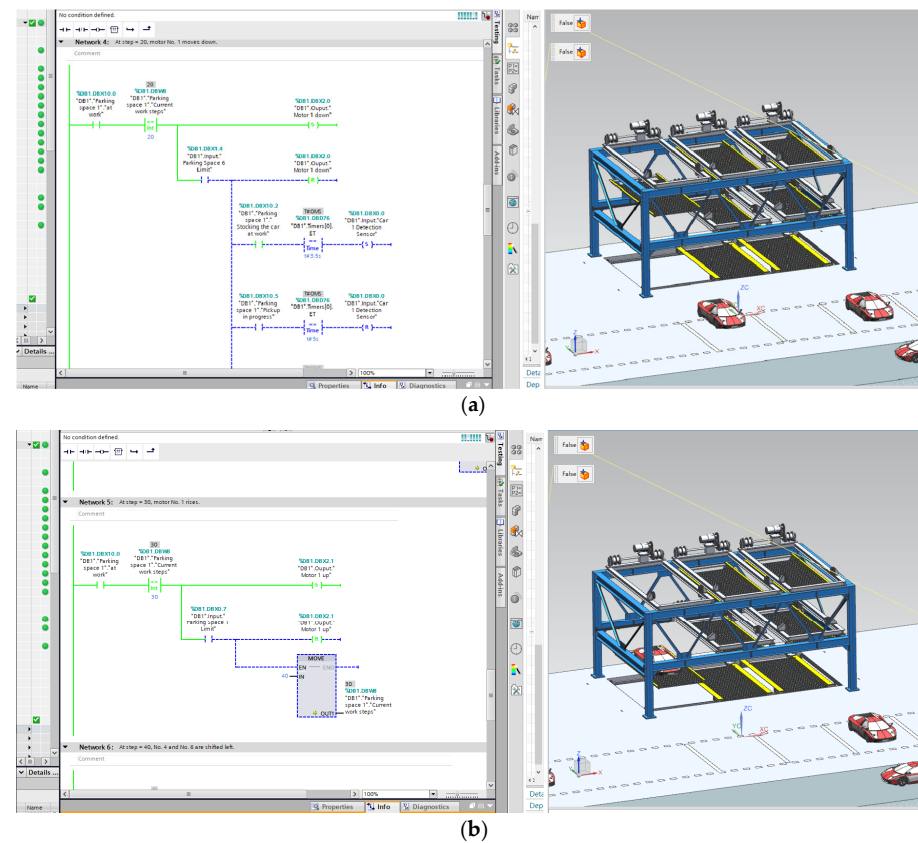


Figure 17. Lifting and debugging of parking space No. 1: (a) debugging of parking space No. 1; (b) upward debugging of parking space No. 1.

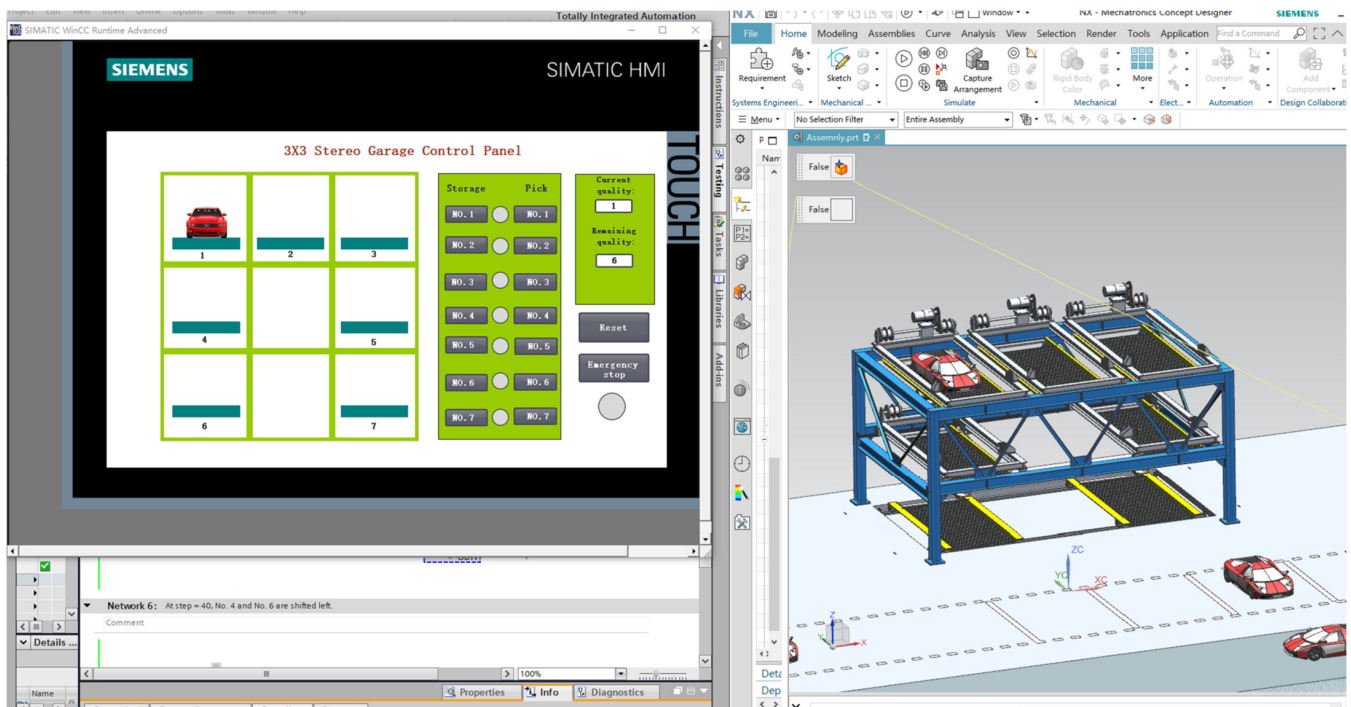


Figure 18. Pickup virtual debugging interface.

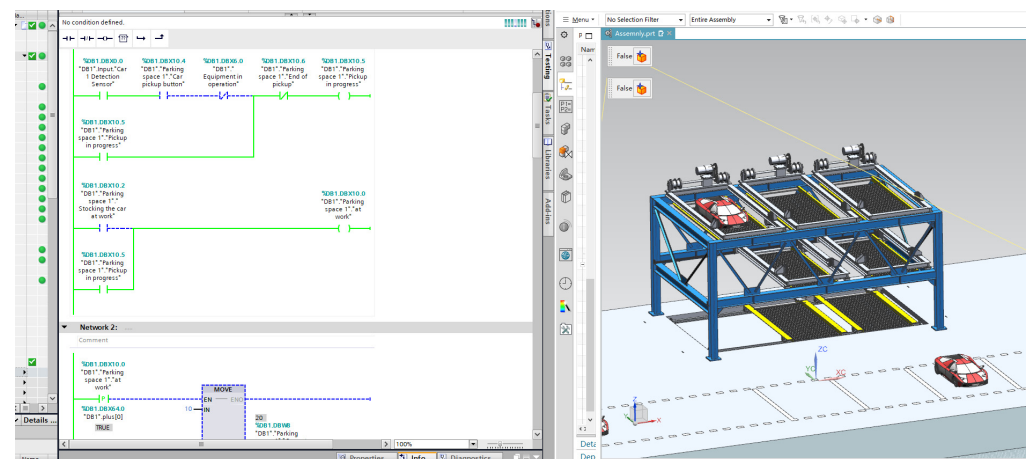


Figure 19. Picking up the car working state debugging.

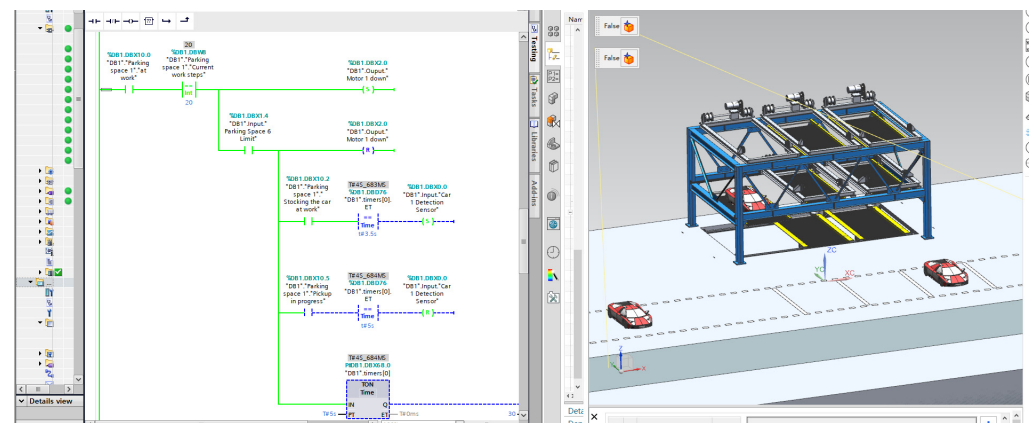
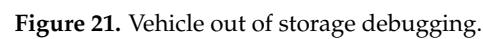
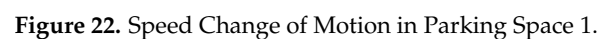


Figure 20. Load drop debugging of carrier plate.



4.5.2. Virtual Debugging Results

Relevant debugging data were collected through careful debugging in Section 4.5.1. As demonstrated in Figures 22 and 23, the lifting speed was maintained at a stable level of 75 mm/s during the storage process in the first parking space, and the overall storage operation took about 49.59 s. This result is very close to the reference data mentioned in Section 4.1, ensuring the reliability of the virtual debugging.



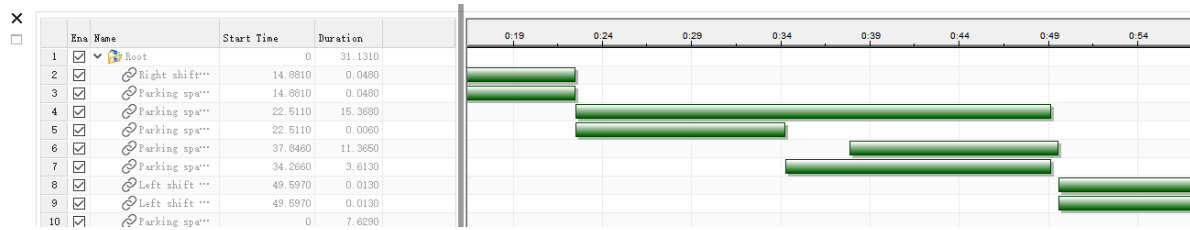


Figure 23. Storage Time.

With the data in Table 2, the storage time recorded during the debugging process was, on average, 4.59 s longer than the actual storage time provided by the company, while the pickup time was 7.75 s longer than the actual data. While the actual times provided by the company may contain a certain amount of error, they still provide a relatively reliable benchmark for evaluating the accuracy of the virtual debugging data. In the actual operation of a stereo garage, small delays in response time and the timing of the operator's maneuvers, as well as the performance factors of the debugging equipment, can lead to slight variations in the timing of the operation of the parking spaces. Although the access operations flow consistently for each parking space, the run times may be slightly different for each of the operations targeting parking space number one, as shown in the debugging data in Table 2. However, these fluctuations do not affect the overall performance, and the overall operating parameters closely match the preset reference data, ensuring the reliability of the simulated operation of the stereo garage.

Table 2. Virtual debugging data comparison.

Parameter Name	Actual Data	Debugging Data
Storage Time	45 s	49.59 s
Pickup Time	45 s	52.75 s
Lifting Speed	75 mm/s	75 mm/s
Traversing Speed	125 mm/s	125 mm/s

5. Discussion

As shown in Figure 24, the advantage of the digital twin-based virtual simulation debugging of the lift-and-transverse stereo garage is that the virtual debugging can be carried out without the use of physical objects in the process of equipment development. Although the early stage will be due to the construction of the digital twin virtual model, the progress will lag behind traditional debugging, but later debugging can completely make up for this progress. Through virtual debugging, you can find the size of the equipment after the equipment or operational problems. The advantage of virtual debugging is that problems can be found and solved in advance, which will greatly reduce the actual debugging time of the stereo garage. Where t_1 is the time required for the debugging of the traditional equipment and t_2 is the time required for the debugging of the virtual simulation of the stereo garage based on the digital twin. The value of time saved is the difference between t_1 and t_2 , and the time saved is represented by the blue dashed rectangular box in the figure. Through comparison, it can be concluded that the lift-and-transverse virtual simulation debugging based on digital twins can complete the hardware debugging without physical objects, thus greatly reducing the deployment time of field debugging, accelerating the entire R&D progress and improving the market competitiveness of enterprises.

In Figure 24, compared with the traditional mode of equipment debugging, the virtual debugging of the stereo garage based on digital twin used in this paper can be carried out by virtual debugging of the hardware. Effectively save the time of equipment field debugging, reduce the time of the later field debugging of the Department of time and repeated debugging and modification time, reduce the cost of materials in the process of equipment debugging and labor costs. The shortening of the entire development cycle can enable enterprises to develop new equipment faster and occupy a better market.

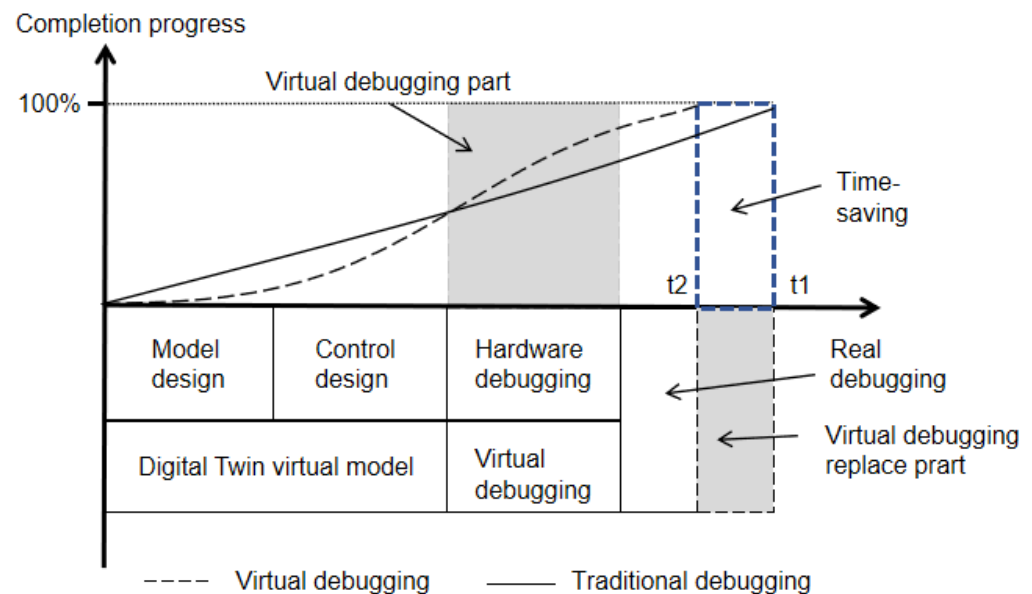


Figure 24. Advantages of virtual debugging over traditional debugging.

6. Conclusions

In this paper, digital twin technology is applied to the virtual debugging of the lift-and-transverse stereo garage, and the virtual simulation platform is constructed by using S7-PLCSIM Advanced, Botu TIA Portal, and NX MCD to realize the virtual simulation design and debugging of the stereo garage based on the digital twin, and the main contents of the work are as follows:

1. Apply the digital twin technology to the stereo garage, build a five-dimensional model framework of the stereo garage, explain the role of each level and the relationship between the five levels, and put forward the program and workflow of virtual debugging;
2. Analyzed the working mode and technical parameters of the lift-and-transverse stereo garage and established the digital twin virtual model of the stereo garage;
3. The simulation and debugging of the digital twin system for the stereo garage is accomplished by interacting the electromechanical model in S7-PLCSIM-Advanced, NX MCD, with the PLC signals in TIA Portal;
4. Comparing the debugging data with the actual data proves the feasibility of utilizing the virtual model of digital twin technology to verify the stereo garage. Physical debugging without a physical object in advance reduces the manpower and development cycle of professionals, which is an important reference significance for the development of equipment.

Through the above work content, the debugging data of the virtual debugging of the stereo garage were obtained. The storage time was 4.59 s longer than the actual average storage time, and the pickup time was 7.75 s slower than the average pickup time. Factors in the performance of the commissioning equipment and the operator's operating time may affect this time. However, the data basically prove the feasibility of the virtual debugging program. Compared with the traditional development process, such a virtual debugging solution, which can be debugged in advance without physical objects, reduces the risk of physical debugging and increases the efficiency of debugging. Through the virtual model in MCD, the actual operation can also be observed, achieving a virtual verification means of real-time monitoring and control. Such a debugging method also provides a way for the intelligent development of the stereo garage, as well as a valuable reference for the development of equipment in other fields.

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