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Research on the Design Method of Virtual Debugging System for Digital Intelligent Production Line

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Abstract

With the rapid transformation of the manufacturing industry to intelligentization, efficient debugging of digital intelligent production lines has become a key link in the product development stage. This paper focuses on the virtual debugging system construction method for the digital intelligent production line. Firstly, digital twin technology is used to construct a digital twin model of the digital intelligent production line of the pager with the help of Tecnomatix digital twin software platform, which covers mechanical, electrical, and control logic, and other fields, realizes the analog simulation of the production process, and effectively solves the problems of model interference and robot path planning. Secondly, according to the system requirements and the characteristics of the application environment, the virtual debugging system platform of the digital intelligent production line is designed, and its components and data communication technology implementation scheme is analyzed in detail. Finally, the virtual debugging system platform of the digital intelligent production line of the call machines is successfully built. This method provides comprehensive, systematic, and practical method guidance for enterprises to build digital intelligent production line virtual debugging systems, which is of great theoretical and practical significance for industrial upgrading.

Keywords

Digital Twins; Virtual Debugging; Tecnomatix; Digital Production Line.

1. Introduction

As a core component of modern manufacturing, the digital intelligent production line integrates advanced automation equipment, information technology, and industrial Internet technology, aiming to achieve high efficiency, precision, and flexible control of the production process. However, with the increasing complexity of production line systems, their design, integration, and commissioning face many challenges. Traditional commissioning methods are not only time-consuming, labor-intensive, and costly but also susceptible to constraints such as the progress of hardware and equipment installation and the on-site environment, resulting in a prolonged commissioning cycle. Digital twin technology continues to develop through the product design, manufacturing and processing, and operation and maintenance of the entire life cycle, with the help of which the digital twin model can be a comprehensive collection of product-related data. At the early stage of product design, digital twin is the core strategy of virtual debugging technology. This technology not only verifies the physical configuration and architectural design of the system under development but also tests the control system code and optimizes the design defects, which has become one of the key research areas that have attracted extensive attention from academics at home and abroad.

In the practical application of intelligent manufacturing, virtual commissioning technology is divided into two levels: production line level and manufacturing unit level. Line-level virtual commissioning focuses on the overall planning of the production process, design verification, and production process simulation experiments. The industry has seen the emergence of representative products such as Delmia, Tecnomatix, Simimumatik3D, and Visual Components. Numerous scholars have utilized such line-level virtual debugging software in industrial manufacturing with significant results. For example, Jakhotiya, Y.[1]et al. used a computer vision system developed in MATLAB to locate the coordinates of an object and simulated the pick-and-place production workflow with the help of a digital twin model of a KUKA collaborative robot generated by the Tecnomatix Process Simulate software to validate the feasibility and realize the integration between different software systems. C. Saavedra Sueldo[2]et al. integrated Tecnomatix with the ROS operating system to facilitate the information interaction between the autonomous decision-making system and the external environment. In addition, B. Wang[4]et al. relied on 3D modeling and visualization technology, constructed a digital model through Demo3D software, established a model database to meet the needs of the production line, and used genetic algorithms to optimize the process layout, and then implemented simulation and virtual debugging, which effectively enhanced the efficiency of equipment use. However, most of the research still focuses on the layout planning and process simulation using the existing simulation platform, and there is still much room for exploration on how to realize more complex system-level virtual debugging in a wider range of manufacturing scenarios by real-time mapping and feedback of virtual and real production environments and applying them to virtual debugging technology.

This paper focuses on the method of building a virtual debugging system platform for a digitalized intelligent production line with the help of the Tecnomatix digital twin development platform. Firstly, the digital twin model of the digital intelligent production line of the pager is constructed by importing mechanical equipment model resources, defining the kinematics of mechanical equipment, constructing sensor and actuator models, interfacing logic signals, and other key aspects. Secondly, the application of digital twin technology and related system integration technology is studied in depth to design the virtual debugging system platform of the digital intelligent production line, and the components of the system platform and the realization scheme for data communication technology are analyzed in detail. Finally, the system software platform is completed to realize the real-time data synchronization between the physical production line and the virtual production line. This method not only helps to shorten the time to market and reduce R&D costs, but also improves the reliability and stability of the production line, and predicts the possible failures and risks of on-site debugging in advance.

2. Digital Twin Model Construction

2.1. Mechanical Motion Modeling

The mechanical motion model construction process is shown in Figure 1, and its modeling method is divided into two parts: geometric model and physical model:

(1) Geometric model construction: Using three-dimensional modeling design software, conduct a comprehensive and detailed design and optimization of the three-dimensional model to ensure that the assembly relationships among all types of production machinery and equipment are effectively coordinated, and then realize the efficient collaborative work among machinery and equipment.

(2) Physical model construction: Based on the geometric model framework, assign kinematic characteristics to the geometric model resources, and then simulate the production behavior of the physical production line to realize the production-process simulation of the virtual model.

The kinematic characteristics focus on the assembly relationships among the joints in the mechanical equipment and utilize the kinematic chain to establish the connections among these joints. Based on the motion principle of the mechanical equipment, set the physical properties of the completed geometric model to construct the physical model of the mechanical equipment.

Figure 1. Mechanical Motion Modeling

In this paper, the Tecnomatix digital twin software is used to complete the construction of the physical model of the digitized smart production line. The software has a specific 3D model file format, so the model needs to be converted to. jt format and saved in a folder with a .cojt suffix before it can be imported into the software for project construction and layout planning. Equipment resource files are imported into the simulation environment through the "Convert and Insert CAD files" option. Resource files can be divided into two categories: parts and equipment resources, which are further subdivided into conveyors, robots, fixtures, and fittings. The equipment resources are further subdivided into Conveyor, Robot, Gripper and so on. Finally, according to the actual site conditions of the pager digital intelligent production line, the parts and equipment resources are laid out according to the predetermined location to complete the overall planning of the pager digital intelligent production line, as shown in Figure 2.

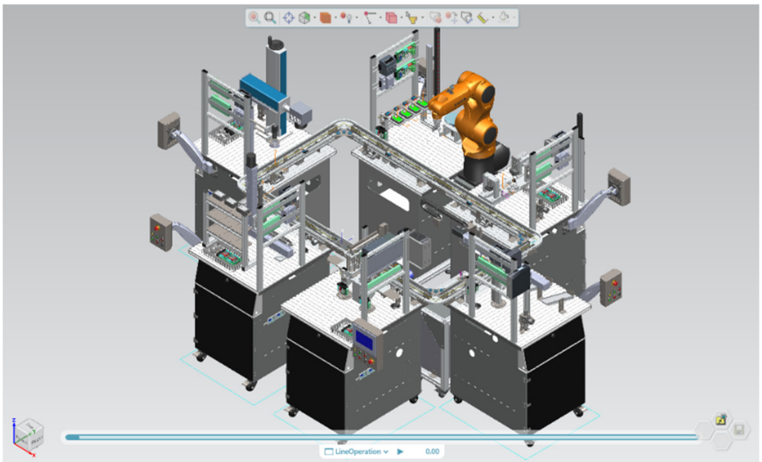


Figure 2. Overall layout of digitalized intelligent production line

Select the appropriate kinematic joints according to the kinematic characteristics of the mechanical device. Use the kinematic editor to set the Parent link as a fixed object and identify the Child link as a kinematic joint relative to the Parent link. Subsequently, parameters such as motion axes, motion types, and motion specifications of the joints need to be defined. After completing the definition of these motion attributes, the parent link, the child link, and their corresponding joints will together constitute a motion chain. Next, if the mechanical device needs to perform a gripping operation, a tool coordinate system should be established at the corresponding kinematic joints and the gripping and releasing actions should be defined. Through motion simulation, observe the motion of the equipment to ensure that it is capable of gripping and placing materials smoothly. If problems are found, the position and range of motion of each joint need to be adjusted. For some mechanical equipment that does not function as a fixture in the production process but still needs to grasp materials or trays when performing actions in the virtual environment, it should also be defined as a fixture (Gripper) type, and a tool coordinate system should be established at the end joints. For example, for equipment such as push cylinders and lift cylinders, the geometric and kinematic constraints of the motion joint structure should be completed, so that when the end joints perform the push or lift action, they can simultaneously grip the production material.

In the process of constructing the kinematic model of an industrial robot, which is usually used to transfer materials at multiple points, it is not only necessary to define the linear or rotational kinematic attributes of each joint but also to set up the BaseFrame and ToolFrame. To realize the motion of the digital twin model of industrial robots, the joints with specific motion characteristics need to be connected to form a kinematic chain so that the child links can move with the motion trajectory of the parent links. According to the basic characteristics of industrial robots, the datum coordinate system is set up with the chassis as the datum plane, and the tool coordinate system is set up with the pneumatic fixture that performs material handling as the datum plane. To construct the robot motion model, it is necessary to connect the motion of each joint according to the following steps: start from the base of the industrial robot, create and connect the kinematic chain sequentially, set all six axes to rotary motion, establish the datum coordinate system and the tool coordinate system, and configure the motion parameters of the joints according to the robot manual.

Due to the complexity of the kinematic joints and assembly relationships involved in each mechanical device in the production line, after completing the kinematic definition of the joints of each mechanical device, problems such as inaccurate definition of the motion and control of the twin model and unreasonable trajectory of the robot's material transportation may occur. If an error occurs when using a virtual controller or hardware controller to drive the twin model, error troubleshooting will become more complex and time-consuming. For this reason, by stimulating the production process of the digital intelligent production line for pagers, the overall workflow of the manufacturing equipment and industrial robots can be checked, laying the foundation for subsequent PLC program design and writing. The production process design timing of the pager digitized intelligent production line mainly includes material supply, inspection, sorting, collaborative assembly of industrial robots, laser engraving, finished product warehousing, etc. The timing of each production process action and the timing logic interaction between the actions of each workstation. Some of the production process simulation sequences of the pager digital intelligent production line are shown in Figure 3.

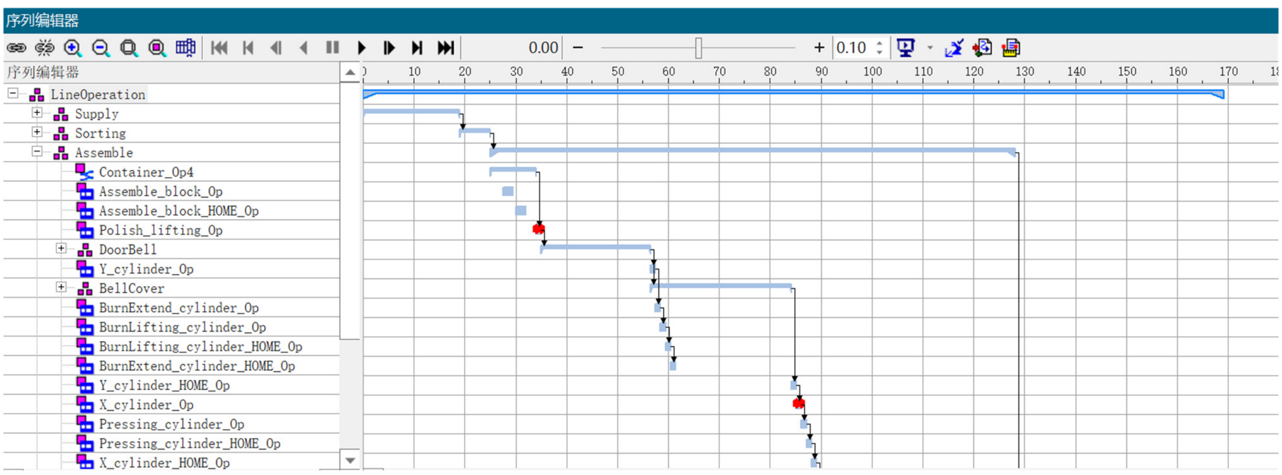
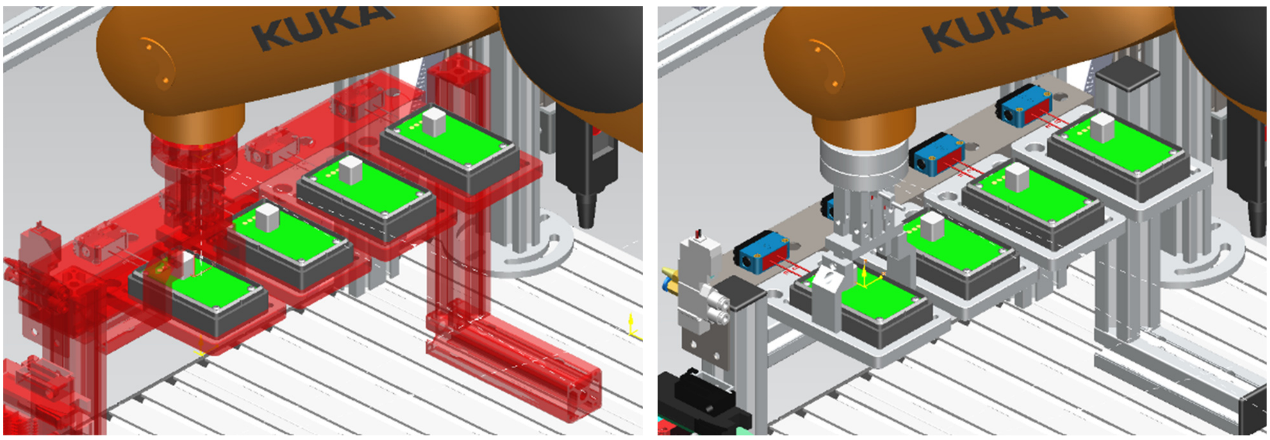


Figure 3. Production Process Simulation Timing

A common method of checking for interference between industrial robots and other machinery is to add “intermediate points” and “entry and exit points” to the path between the robot's gripping and placing points. This is because industrial robots moving between material handling points can easily interfere with other machinery in the vicinity due to their motion characteristics. Intermediate points are usually set as transition points to avoid unnecessary collisions with other equipment near the gripping points; entrance and exit points are usually set as transition points to avoid collisions with other equipment near the gripping points. In this paper, according to the principles of optimizing the path of industrial robots in material transfer, minimizing attitude adjustment and no collision, the necessary intermediate points and entry and exit points are set, and the path of industrial robots is re-planned. In the preliminary work of production process simulation, it is necessary to verify the accessibility of each position point on the planned path of the industrial robot. For the industrial robot in the assembly task to complete the production material transportation, each position point of the robot path was assessed for accessibility to ensure the stability and reliability of the robot in the material handling process.

By simulating the production process simulation, we verify the rationality of the motion path of the industrial robot in the production chain, to avoid omissions or logical errors in the definition of motion attributes or motion associations, as well as interference collisions in the model design process. In the Options window, the Allowable Penetration value is set to 0, and the default value of the Interference Window is 5 mm. For basic interference checking, the color of the interference contact object is set to red by default. As shown in Fig. 4(a), the cylinder fixture collides with the material table during the gripping process of the industrial robot. As shown in Fig. 4(b), the interference problem is successfully solved by adjusting the attitude of the industrial robot.



(a) Pre-check **(b)** Post-check

Figure 4. Equipment Model Interference Checking

2.2. Electrical Behavior Modeling

The flowchart for the construction of the electrical behavior model, shown in Figure 5, is divided into two main categories: sensors and actuators:

(1) Sensor modeling: set the detection conditions according to the working principle of the sensor, and match and correlate the sensor model with the interactive signals of the control system. With the help of sensor modeling technology, the digital model of production machinery and equipment can transmit signals to the control system according to the pre-set detection conditions to realize the feedback of information.

(2) Actuator model: Based on the operation principle of actuator-driven production machinery and equipment to construct the actuator model, it is required that the motion regulation parameters of the actuator components be set in the corresponding three-dimensional model of the production machinery and equipment, and be associated with the communication signals of the control system, the behavioral model, and the mechanical construction model. Through the use of actuator modeling technology, the digital model of the device can respond to the signals output from the control system, thus realizing the motion control of the executive mechanical equipment.

Figure 5. Electrical Behavior Model Construction

The sensor model includes proximity sensors, photoelectric sensors, and attribute sensors. The construction method of the proximity sensor involves setting the type of object to be checked for interference, and once the object interferes with the sensor, it triggers the detection condition and performs the corresponding action. The construction method of the photoelectric sensor is relatively simple, one only needs to set the object to be detected and the beam length, when the object to be measured enters the range of the beam, it triggers the detection condition and performs the corresponding action. In addition, for the motion joints in mechanical motion equipment, this paper creates joint value sensors and joint distance sensors to directly detect the motion distance of the joints to accurately determine whether the motion state of the mechanical equipment is in place.

The skid-machine line is a special drive model that uses a variable frequency drive to drive a three-phase synchronous AC motor, which in turn drives a belt that carries pallets of material for automated delivery of production materials. A path curve is drawn on the virtual model of the conveyor belt, which is formally defined as a skid line by the “Define Conveyor” function option. During this process, the conveyor path, conveyor tolerance (set to 50), collision tolerance (also set to 50), and maximum speed (limited to 60) are set in detail. At the same time, start and stop signals for the skid line are added to effectively control the operation of the conveyor drive. Next, control points are added to the skid line, and signal trigger conditions are set. When the material pallet runs on the conveyor belt to a position that meets these conditions, it will automatically stop moving, thus accurately realizing the start and stop control of the conveyor belt.

2.3. Automated Modeling

In the automation design phase, the verification and optimization of control logic can be carried out directly in virtual space by establishing a data connection between the control system and the digital twin. The digital twin needs to be driven by a PLC control program to simulate the operation of the equipment in a real environment. After completing the simulation of the production process in the digital twin model, the signal interface between the digital twin model and the controller is created so that the digital twin model can receive command signals from the PLC control program. The flowchart of the automation model construction is shown in Figure 6.

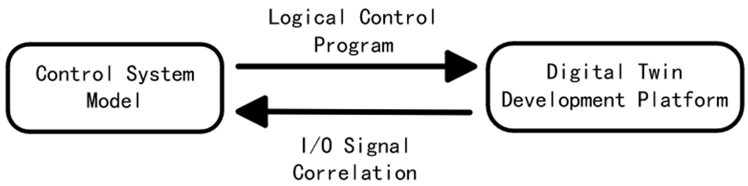


Figure 6. Automated Model Construction

This paper adopts the method of creating the corresponding Logic Block (LB) for the motion joint structure of each device of the production line, to carry out the logic processing of the internal signals of the digital twin model, input/output the correct signal state, to realize the association between the digital twin development platform and the control system model, and to establish the interface of data and signal interaction with the PLC controller. As shown in Figure 7, the creation of the logic block mainly includes two parts: the association of input and output signals and logic operation to realize the motion control of the digital twin model. The input signals are used as the exit signals of the logic block, while the output signals are used as the entry signals of the logic block. After adding the input and output signal calculation formulas to the logic resources, the logic block will use the parameter values of the formulas to perform calculations and output the results to the motion joints of the device.

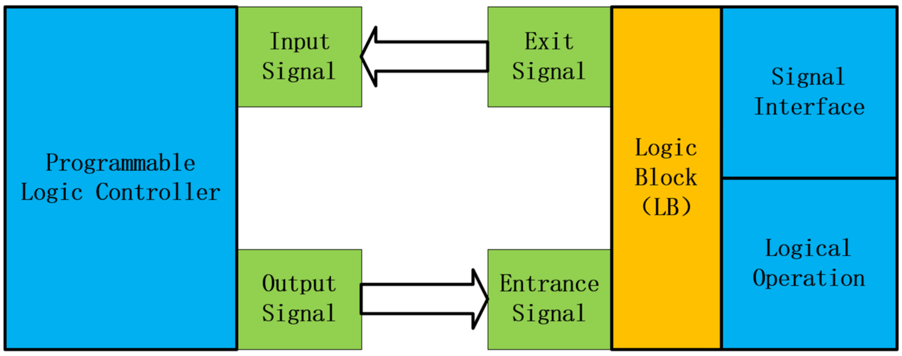


Figure 7. Relationship between PLC and Logic Block

(1) I/O signal correlation

To realize the precise motion control of the digital twin system, the logic block completes the interaction between the input signal and the output signal by connecting with the control signal of PLC. The inlet signal is directly connected to the PLC's output signal, and the outlet signal is connected to the PLC's input signal, to not only effectively monitor the changes of the motion state in the virtual environment, but also feed the motion data back to the digital twin system to complete the closed-loop control.

(2) Logical operation relationship

Logic operation drives the digital twin model movement through various control methods and the characteristics of the equipment motion joints. For cylinder devices with only two states, open and closed, define their joint value sensor parameters to monitor whether the model moves to the specified position according to the control mode set in the operation. When the twin model is in place for a certain motion attitude, the rising edge sets the sensor parameter to “1”, which triggers the twin model in place exit signal. For models with complex motion characteristics, such as servo motors, the parameters of the joint distance sensors are set to monitor the motion of the model in real-time according to the control mode selected in the operation, and the operation data is provided to the output signal, which is later received by the PLC to determine whether the current operation state is ready for the next step of the program.

3. Virtual Debugging System Design

3.1. Data Communication Links

Due to the complexity and variety of equipment brands used in the pager digital intelligent production line, this paper needs to introduce the third-party software platform KepServer EX6 to build the OPC server. In this process, two data connections need to be established separately: one is the connection between the control system and the OPC server, and the other is the connection between the OPC server and the digital twin simulation software platform. These two connections are realized through a third-party OPC server software platform to ensure that data can be transferred efficiently and accurately between the control system and the digital twin model, as shown in Figure 8.

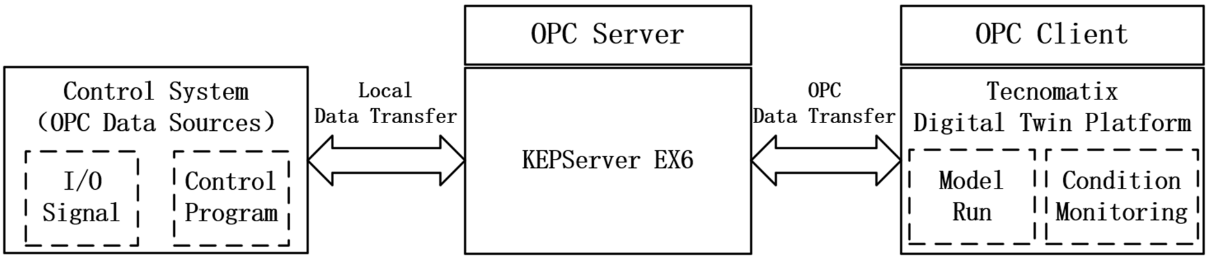


Figure 8. OPC Communication Technology Realization Scheme

3.2. System Design

In this paper, a virtual debugging system for a digital intelligent production line is designed, and its system components are shown in Figure 9. The system platform mainly integrates several functional modules, covering the digital twin software platform, controlled object debugging platform, control system debugging platform, and automation debugging platform.

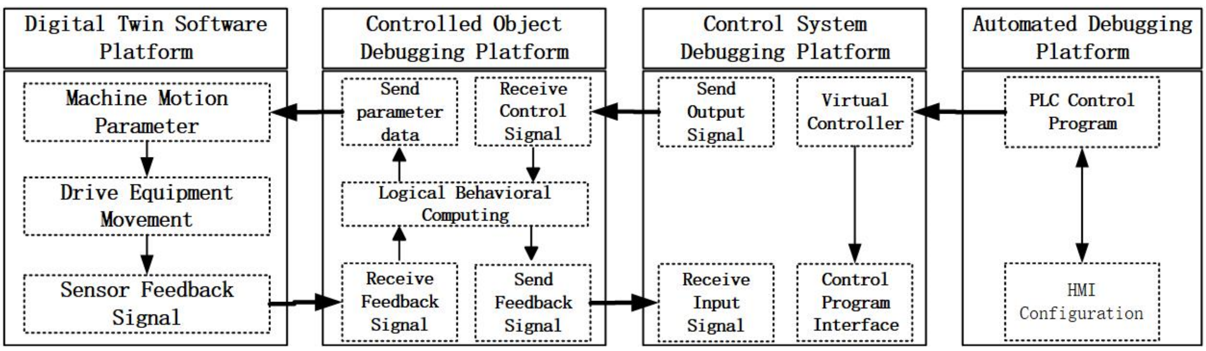


Figure 9. Digital Intelligent Production Line Virtual Debugging System Composition

(1) Tecnomatix digital twin software platform. It is mainly used to set up the data communication interface and mechanical motion equipment, such as motion properties and constraints, model construction, and simulation of the production process. The digital twin model receives motion parameter data from the control object debugging platform to drive the mechanical equipment movement. At the same time the production machinery and equipment movement, the sensor's real-time detection of the movement state, and the data information detected by the sensor as a feedback signal back to the controlled object debugging platform.

(2) The control object debugging platform adopts Siemens SIMIT simulation software. It is mainly used to receive the output signals sent by the control system debugging platform,

generate motion parameter data through logical behavioral calculations to be sent to the digital twin model, and send the sensor feedback signals from the digital twin model to the control system, and generate the control signals to be sent through logical behavioral calculations to be fed back to the control system debugging platform.

(3) Siemens PLCSIM Advanced simulator is used for the control system debugging platform. It mainly involves the integration of sensors, drives, and actuators and the realization of control algorithms, and is used to simulate the PLC controller in the hardware control system in the virtual debugging environment, its main functions include driving the twin model, control logic, and information decision-making. The connection between the control system and the twin model is completed through the control signal interface and communication interface, and the logical verification of the control program is completed. The specific method adopts the industrial Ethernet Profinet communication network interface to establish the data communication connection with the mechanical equipment in the physical production line, to realize the acquisition of real-time equipment status and environmental information, and to drive the actuator to realize the control of the production line.

(4) The automation debugging platform adopts Siemens TIA Portal programming software. It mainly includes control system configuration, control program, and human-computer interaction interface, and is mainly used for writing automatic control programs for driving equipment movement, human-computer interaction interface development, and controller-based program online monitoring.

According to the above virtual debugging system composition and data communication connection design scheme, the virtual debugging system software platform is built for the pager digital intelligent production line, as shown in Figure 10.

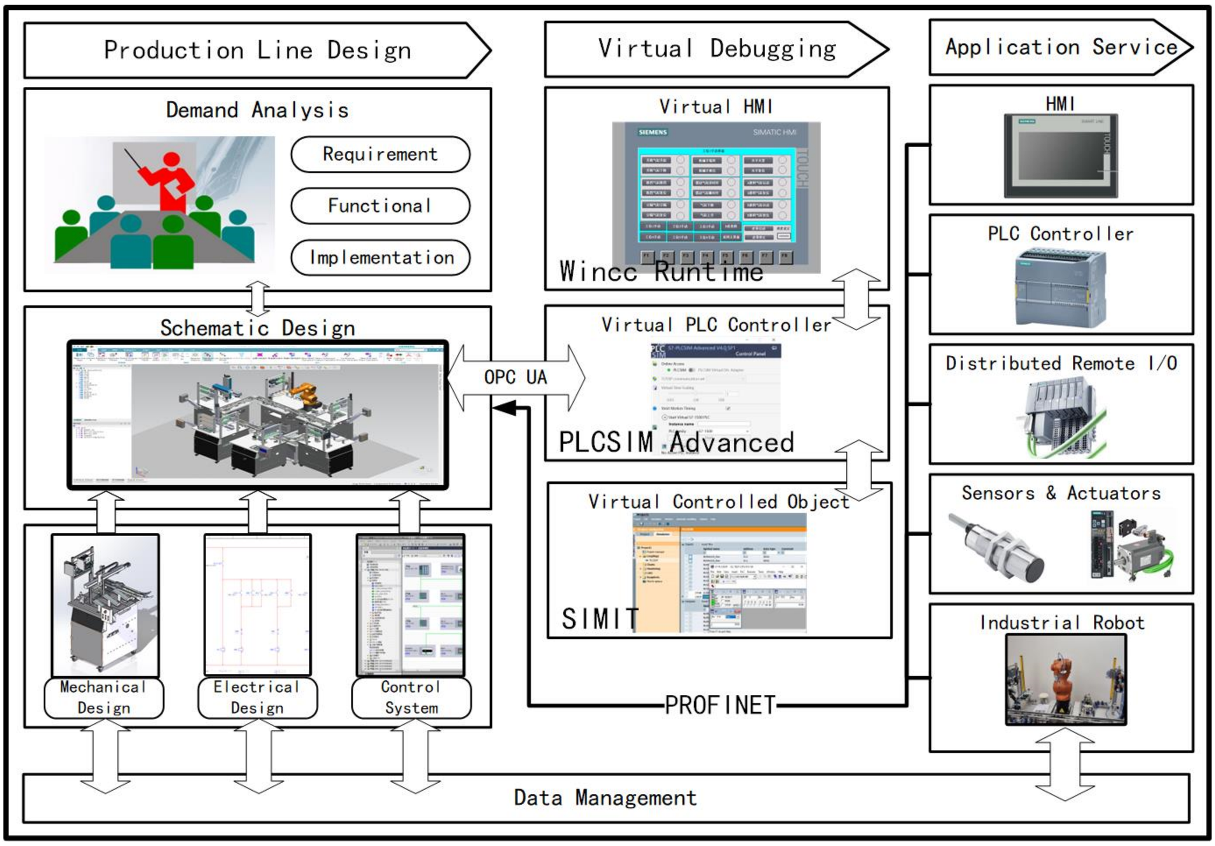


Figure 10. Digital Intelligent Production Line Virtual Debugging System Software Platform

4. Conclusion

This paper mainly completes the process of building a virtual commissioning system platform for a digitalized intelligent production line relying on Tecnomatix digital twin software. First of all, in the Tecnomatix virtual environment for the production line of the three-dimensional model of the resource division and organization, complete the overall layout planning of the production line. Then, the kinematic definition of the mechanical motion model in the production line is carried out, and the digital twin model interference and industrial robot path planning problems are solved through the production process simulation. At the same time, the assembly of the mechanical motion model and the sensor and driver model in the electrical behavior model is completed. The construction of the automation model is completed by creating the I/O signal interface and setting the logical operation relationship. Then, the virtual debugging system platform is designed based on digital twin technology, and the system components and function realization are elaborated in detail. To ensure the real-time and reliability of data connection, the system platform adopts an OPC communication protocol to realize cross-platform data interaction. Finally, the virtual debugging system platform of the digital intelligent production line is successfully constructed to provide technical support and guarantee the real-time dynamic control of the hardware control system.

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