

RESEARCH ARTICLE

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Design of a material sorting digital twin system based on NX MCD

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Abstract. Current methods of manually checking whether materials meet the required standards are inefficient and harmful to workers' health. To address the complexity and variability of real-world systems, it is imperative to establish highly consistent digital models for subsequent operations. However, there is a challenge in unifying various modules and components into a single system and optimizing them for functionality. A mechatronic solution is proposed for material sorting within the production manufacturing process, leveraging Siemens TIA Portal and NX 2007. The solution involves constructing a physical platform and realizing a digital twin system to enable real-virtual interaction via communication protocols. Initially, a virtual material sorting simulation and debugging platform is established using NX software, while operations are conducted in the TIA Portal. Subsequently, the control program is designed within the TIA Portal, and Virtual PLCs are created using PLCSIM Advanced for virtual debugging and analysis, confirming the solution's feasibility. Following this, the physical material sorting platform is developed, utilizing Siemens S7-1500 PLC to manage inverter and servo motor operations. Ultimately, the OPC UA communication protocol facilitates information exchange between the physical PLC and the virtual platform, establishing effective linkage between the virtual system and the physical model to ensure coordination and consistency. Results demonstrate real-time synchronization and virtual sorting operations during joint real-virtual debugging. This digital twin design solution is poised to significantly enhance manufacturing efficiency, reduce initial hardware costs in factory design, and augment automation and intelligence in production.

Keywords: NX MCD / TIA portal / three-axis material sorting system / real-virtual integration

1 Introduction

Recent studies have extensively explored Mechatronics Concept Designer (MCD) virtual debugging technology. SAS et al. [1] employed MCD and stereo cameras for virtual debugging in robot material sorting. Similarly, Qin et al. [2] integrated MCD with PLCs to facilitate virtual debugging of the drive mechanism in a cold head machine. Moreover, BANK et al. [3] achieved multi-axis synchronous linear and nonlinear motion in a gantry robot using MCD and the TIA Portal. Metzner et al. [4] utilized MCD alongside a stereo camera for virtual debugging in a robot warehouse picking system. Wang et al. [5] applied NX MCD to determine pose by solving the transformation matrix provided by the solver engine, enhancing this with a sampling strategy optimized beyond traditional equidistant approaches by incorporating rigid body constraints. Furthermore,

Al-Saedi et al. [6] leveraged MATLAB and NX software for modeling, using multiple sensors to monitor the machining process within a workshop. Lastly, Huang et al. [7] implemented NX MCD for industrial robots and training related to the "1+X" programming certificate.

The principal technological aspect of automatic material sorting technology involves identifying materials based on their unique characteristics and utilizing appropriate sensors to select target materials accurately and efficiently, while effectively excluding any interference from other substances. This precision enables the accurate capture and placement of materials in their designated locations, thereby facilitating automatic material sorting [8]. In 2002, NASA in the United States introduced the concept of the digital twin within the engineering domain [9]. Thomas et al. [10] introduced a concept for database composition and offered guidelines for the implementation of Digital Twins in the production systems of small and medium-sized enterprises. Jumyung et al. [11] discussed the automatic configuration of a digital environment

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through a generic data model inspired by digital twin technology. Greyce et al. [12] suggested the use of AutomationML to model attributes pertinent to the Digital Twin.

Given these characteristics, this study proposes a mechanical platform based on the Siemens TIA Portal and an electromechanical integrated environment of Siemens NX. Siemens NX, also known as UG NX, is a comprehensive integrated product design, engineering, and manufacturing solution widely used in aerospace, automotive, industrial manufacturing, and other engineering fields. Developed by Siemens Digital Industries Software, it is an advanced computer-aided design and computer-aided manufacturing (CAD/CAM/CAE) software. The TIA Portal, an abbreviation for Totally Integrated Automation Portal, is a fully integrated automation software released by Siemens Industrial Automation Group. It is the industry's first automation software to adopt a unified engineering configuration and software project environment, making it suitable for almost all automation tasks. By establishing an NX electromechanical integrated virtual environment and writing program controls to drive devices synchronously, the study achieves both virtual and physical debugging. Then, it maps physical signals to the virtual model to realize a coordinated design approach between the virtual and the physical. Virtual debugging on a digital twin model can shorten the development cycle of a sorting system. By simulating the actual operating process, the system's performance can be tested under different conditions, potential issues can be identified, and targeted improvements can be made. This reduces the risks associated with on-site testing and enhances the stability and reliability of the system. The system can improve material sorting efficiency and company profits.

2 Virtual debugging environment for a three-axis system

2.1 Design of a three-axis material sorting model based on SolidWorks

Create a digital working model of a three-axis grasping system in the SolidWorks virtual environment and import the models created in SolidWorks into the NX MCD simulation platform [13]. SolidWorks is a 3D computer-aided design (CAD) software developed by the American company Dassault Systèmes. It is widely used in various fields such as mechanical design, industrial design, product design, automotive engineering, and aerospace. SolidWorks supports various modeling methods, including solid modeling, surface modeling, and assembly design, to meet different design and analysis requirements.

Design a 3D model of the intelligent three-axis grasping system and arrange and assemble various mechanical components and equipment units reasonably [14], as shown in Figure 1.

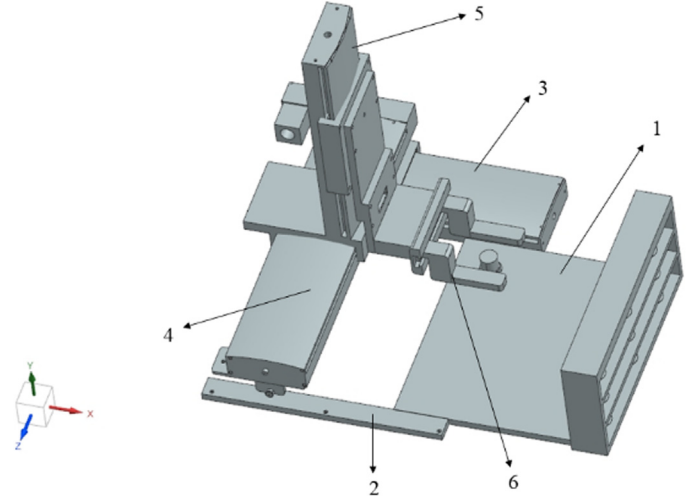


Fig. 1. Three-axis grasping robot model. 1. Item placement stand. 2. Three-axis base. 3. X-axis transport seat. 4. Y-axis transport seat. 5. Z-axis transport seat. 6. Mechanical claw arm.

2.1.1 Dimensional parameters

The radius of the material is 24 mm, as shown in Figure 2a. The lengths of the three axes are 414.4089 mm, 210.0000 mm, and 450.7829 mm, as shown in Figures 2b–2d.

2.1.2 Kinematic parameters

Based on the geometric dimensions, the X, Y, and Z axes of the three-axis device have lengths that represent their maximum range of motion. A three-axis device, performing linear motion, possesses three degrees of freedom, allowing it to move independently along each of the three axes. This capability enables the device to perform tasks in various directions and positions, adapting to different working environments and requirements. In accordance with subsequent programming needs, the device can be precisely positioned and moved along each axis, allowing for precise manipulation.

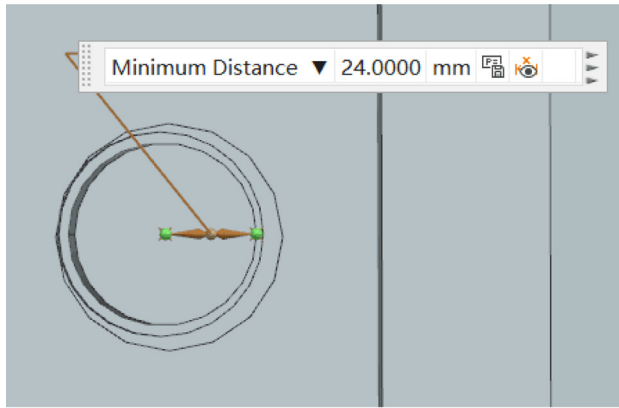
2.1.3 Build kinematic model

Create a D-H parameter Table 1 for a three-axis motion model [15].

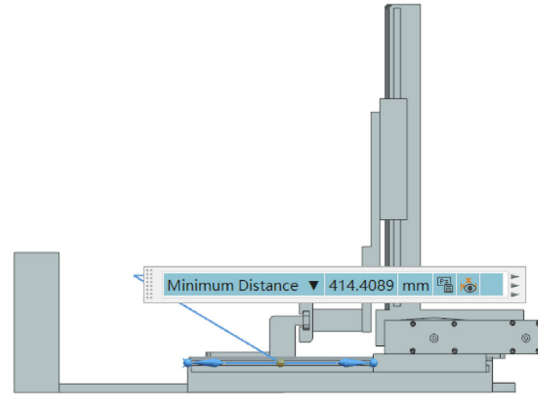
Obtain the transformation matrix T_i for each axis based on the D-H parameter table of the three-axis system.

$$T_0 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (1)$$

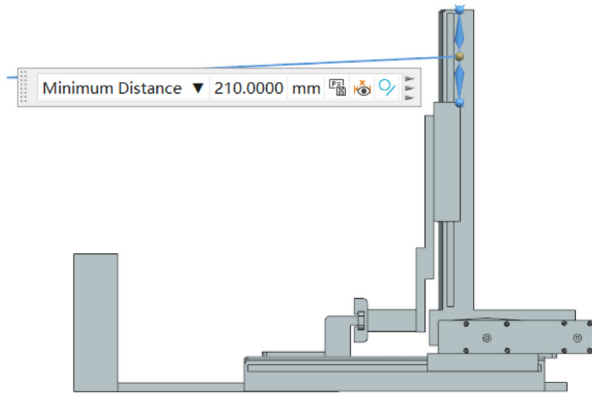
$$T_i = \begin{pmatrix} \cos\theta_i & -\sin\theta_i & 0 & a_i \\ \sin\theta_i \star \cos\alpha_i & \cos\theta_i \star \cos\alpha_i & -\sin\alpha_i & -\sin\alpha_i \star d_i \\ \sin\theta_i \star \sin\alpha_i & \cos\theta_i \star \sin\alpha_i & \cos\alpha_i & \cos\alpha_i \star d_i \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (2)$$



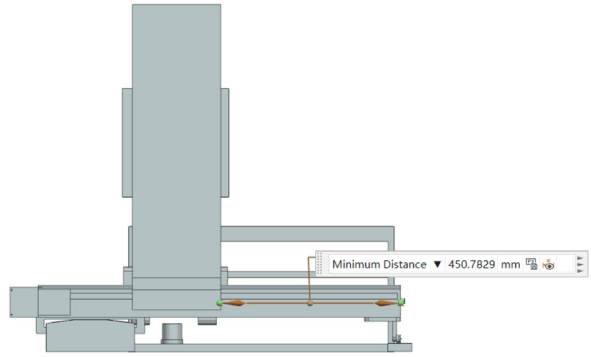
(a) Radius of material



(b) Length of X-axis



(c) Length of Y-axis



(d) Length of Z-axis

Fig. 2. Dimensional parameters.**Table 1.** D-H parameter table.

i	α_i	l_i	d_i	θ_i
1	0	90	414.4089	0
2	0	0	210	90
3	0	0	450.7829	0

According to formulas (1) and (2), the total transformation matrix T can be obtained.

$$T = T_0 * T_1 * T_2 * T_3$$

$$= \begin{pmatrix} 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & -d_1 - d_2 - d_3 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (3)$$

When all three axes are linearly moving, the 3D trajectory is shown in Figure 3. After modeling each unit of equipment, assemble the components and constrain their

spatial positions according to the design layout of the three-axis grasping system to complete the assembly of the system's geometric model [16].

2.2 Conceptual design of modeling mechatronics

The three-dimensional models exported from SolidWorks lack basic physical properties such as mass, elasticity, and hardness. To achieve better real-time synchronization of the three-axis system, it is necessary to import the exported three-dimensional mechanical concept model into NX for electromechanical concept design. This process simulates the physical motion of the actual object to a great extent.

2.2.1 Mechanical module design

Define some components of the three-axis model as rigid bodies or collision bodies, as illustrated in Figure 4a. Set their physical properties to enable the motion simulation of the model's physical characteristics. Then, to mirror the motion of the physical system, add motion joints or specify motion behaviors to define the relationships between the



Fig. 3. Simulation of the motion trajectory of a three-axis sliding joint.

components, as illustrated in Figure 4b. Configure the corresponding motion parameters and control check parameters [17].

2.2.2 Electrical module design

Setting up sensors and actuators is the core of electrical module design. To control the position and velocity of the components in the three-axis system, it is necessary to define their corresponding motion joints for position and velocity, as illustrated in Figure 4c. This definition makes them actuators that can reach the target position at a specified speed [18]. In addition to position control, it is also essential to add signals or signal adapters, as illustrated in Figure 4d. There are two types of signals: input and output. These signals can either transmit real-time data from the virtual model to the PLC or receive control signals from the PLC and execute them. This functionality enables the exchange of information between the MCD and the communicating PLC [19].

2.2.3 Automation module design

After completing the design of the two modules mentioned above, a virtual simulation sequence can be developed. This sequence is based on the entire motion process of physically grasping materials on three axes, along with the operation mechanisms of sensors and actuators. It facilitates the verification of the three-axis model's capability to perform the required movements before proceeding with both virtual and real-time synchronization [20].

3 TIA portal environment setup

3.1 Equipment configuration

3.1.1 Network topology structure

The PC is connected to the PLC's CPU, S120, and human-machine interface panel via an Ethernet bus, and communication is done through PROFINET. Figure 5 shows the network topology diagram.

3.1.2 Brake system

Select the S7-1500 PLC as the controller, SIMATIC S120 as the drive, and Siemens KTP700 BASIC PN as the human-machine interface panel. This setup controls the X, Y, Z three-axis servo motors as well as the stepper motor that operates the gripping hand.

3.1.3 Servo motor

The servo motors for the X, Y, and Z axes serve as position axes with a rotation axis type. The drive unit's mechanical device is connected to the load gear. The motor's rotation speed is set at 50 RPM, and the load's rotation speed at 1 RPM. The reduction ratio is 50:1, as illustrated in Figure 6.

3.1.4 Stepper motor

The stepper motor's process object is a speed axis, with a reduction ratio of 50:1. Figure 7 illustrates the stepper motor's setup.

3.1.5 PLC module configuration

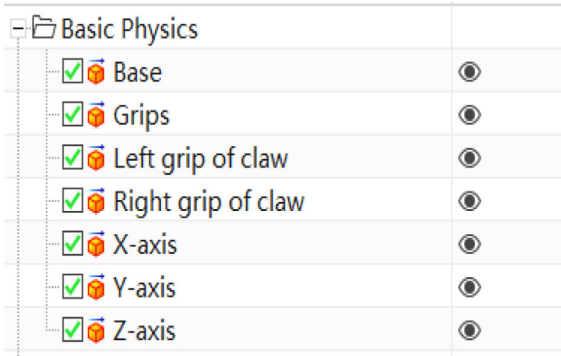
Based on the hardware configuration of the physical device, selecting the correct CPU firmware version on the PC and connecting it to the device allows for online reading of the hardware configuration. Consequently, firmware modules such as DI 32 × 24VDC HF_1, DQ 32 × 24VDC/0.5A HF_1, AI 8xU/I/RTD/TC ST_1, and AQ 4xU/I ST_1 can be obtained. Figure 8 illustrates the installation configuration of the PLC module.

3.1.6 Message configuration

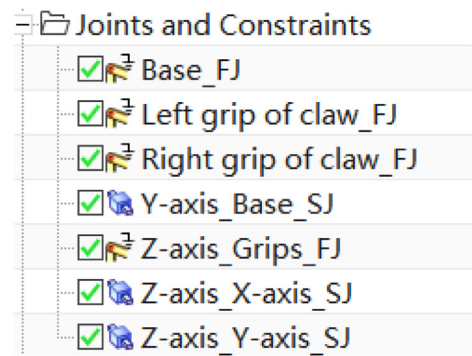
PROFIdrive messages are used to transmit set and actual values, control and status words, and other parameters between the controller and the drive/encoder. With the PROFIdrive message connection, the drive unit will operate both the drive and encoder according to the PROFIdrive configuration parameters and files. Therefore, it is necessary to configure the free message in the drive's closed-loop control system (i.e., the CU unit) to change the length to 2 bytes and to select Siemens message 105 for the drive shaft. Figure 9 illustrates the configuration of specific messages.

3.2 Programming

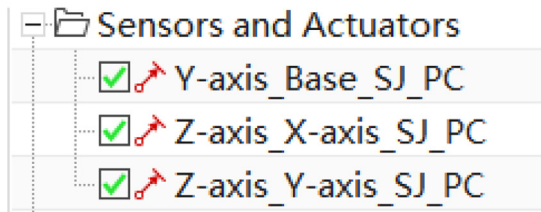
The project aims to realize the fixed-point grasping function of materials using the three-axis system. Therefore, establishing a complete list of variables in the project



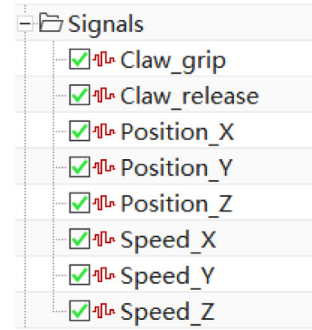
(a) Definition of basic physics



(b) Definition of joints and constraints



(c) Definition of position control



(d) Definition of signaling

Fig. 4. Electromechanical conceptual design of the sorting system.

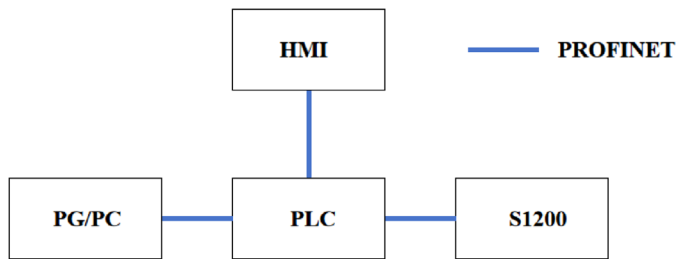


Fig. 5. Network topology.

to monitor the program is essential. Subsequently, these variables should be mapped to the MCD model. Then, create the corresponding process objects for the X, Y, Z three-axis motors and the mechanical gripper stepper motors, respectively.

Since the material placement position of the control object is arranged vertically in a nine-cell grid, realizing fixed-point grasping of the material requires experimental verification. Before operating the project, it is essential to preset the origin position of the mechanical gripper, establish a coordinate system, and determine the specific positions of the three axes corresponding to the nine fixed points. The project is designed to accomplish the functions of returning to the origin, grasping materials at fixed points, placing materials down at predetermined locations,

and monitoring variables throughout the entire process. The program flow design of the intelligent grasping system is illustrated in Figure 10.

3.3 Human-machine interface design

The human-machine interface (HMI) consists of four parts: the login interface, the manual operation interface, the fixed-point grasping material interface, and the interface for monitoring the motion status of each axis.

- Login interface: After downloading the program into the PLC, i.e., after the HMI powers up and starts successfully, users can log in by entering their account number and password through the corresponding I/O domain. Only after a successful login can the design be managed with the administrator's authority, ensuring the safe operation of the entire project and preventing accidental touches.
- Manual operation interface: This interface is designed with buttons for the X, Y, and Z axes as well as for the forward and backward movement of the mechanical gripper. It allows users to click and operate on each process object. The I/O domain is set to output the position value of each process object, making it convenient to observe whether the movement of the entity or the model matches the variables. A gripper return-to-zero button is also designed, enabling the gripper to return to the preset zero position to facilitate subsequent fixed-point grasping operations.

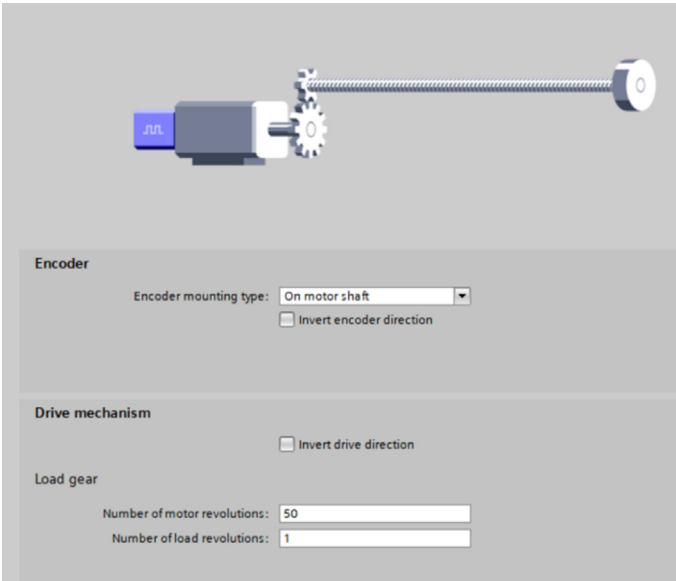


Fig. 6. Reduction ratio of servo motor.

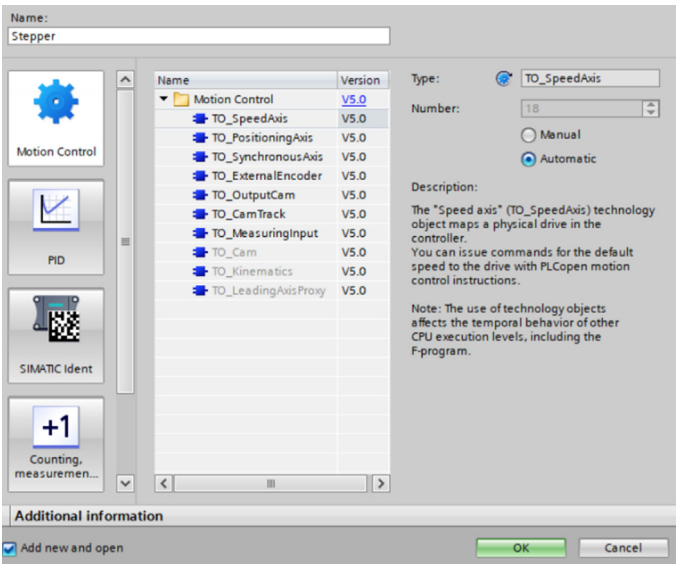


Fig. 7. Stepper motor.

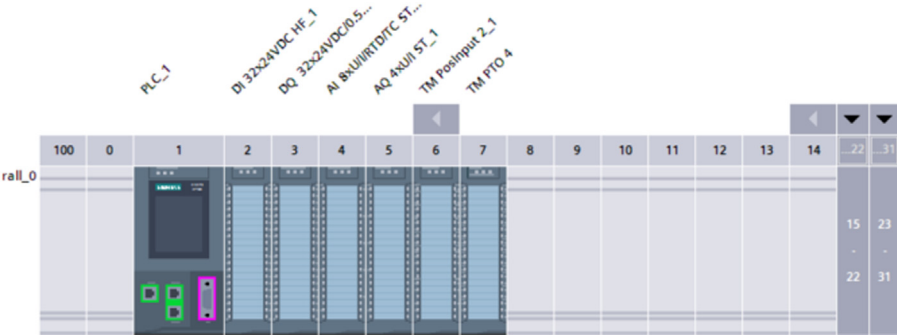


Fig. 8. PLC module configuration.

	Name	Item	Link	Telegram	Length	Extension	
▼	Drive control-Telegrams	1					
	Send (Actual value)		➡	Free telegram	2	words	—
	Receive (Setpoint)		➡	Free telegram	2	words	—
	<Add telegram>						
▼	Drive Shaft_1-Telegrams	2					
	Send (Actual value)		➡	SIEMENS telegram 105	10	words	0 words
	Receive (Setpoint)		➡	SIEMENS telegram 105	10	words	0 words
	<Add telegram>						
▼	Drive Shaft_2-Telegrams	3					
	Send (Actual value)		➡	SIEMENS telegram 105	10	words	0 words
	Receive (Setpoint)		➡	SIEMENS telegram 105	10	words	0 words
	<Add telegram>						
▼	Drive Shaft_3-Telegrams	4					
	Send (Actual value)		➡	SIEMENS telegram 105	10	words	0 words
	Receive (Setpoint)		➡	SIEMENS telegram 105	10	words	0 words
	<Add telegram>						

Fig. 9. Message configuration.

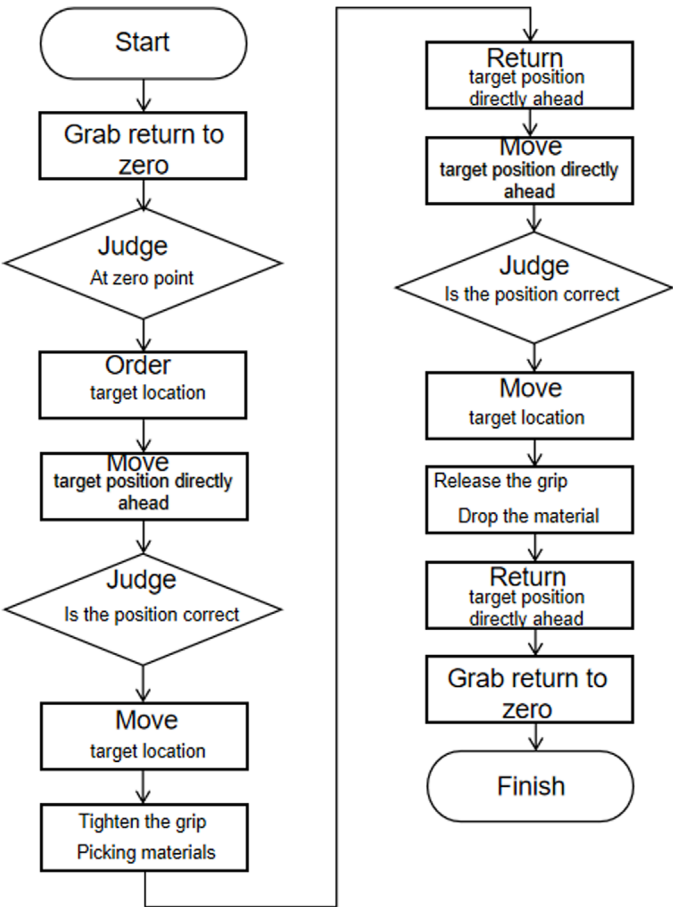


Fig. 10. Flowchart of intelligent gripping system program.

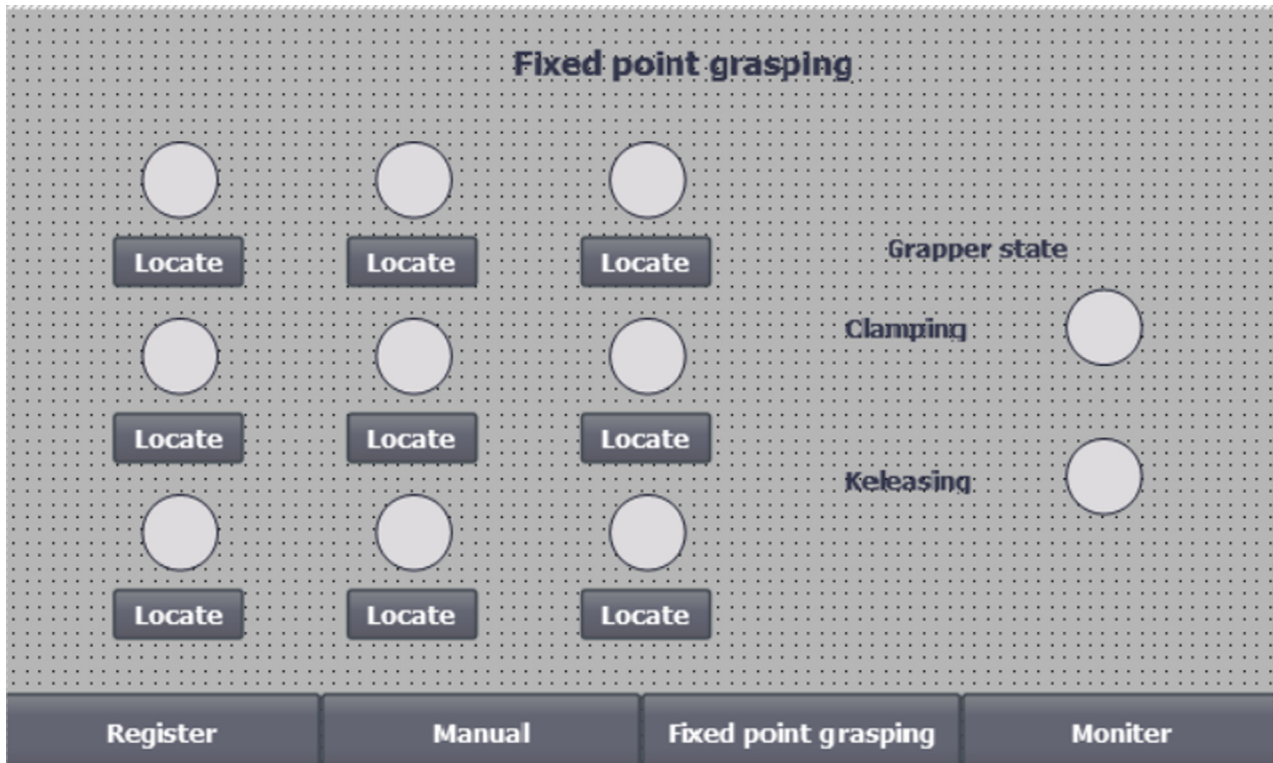


Fig. 11. Fixed-point capture interface.

Fixed-point grasping interface: Based on the nine-cell model of the material placement, nine buttons are designed at the corresponding positions. Pressing a button causes the mechanical gripper to automatically move to the target position to grasp or release the material according to the program design. An indicator light is designed for easy observation of the gripper's status, indicating whether the material has been successfully grasped or released, as illustrated in Figure 11.

- Interface for monitoring: To track the movements of each process object in real-time, trend graphs for the X, Y, and Z axes, as well as for the mechanical gripper's speed and position variables, are incorporated into the monitoring interface. This is illustrated in Figure 11, the Fixed-point grasping interface.

4 Virtual debugging

4.1 Configuring a virtual plc

To simulate the operation and achieve simulation effects, it is necessary to construct a virtual PLC on the PC side. This is accomplished by manipulating the MCD model through the TIA application. Therefore, by using Siemens' S7-PLCSIM Advanced simulation program, a virtual S7-1500 PLC is generated, as illustrated in Figure 12. To execute and monitor the program, the settings are downloaded to the virtual PLC.

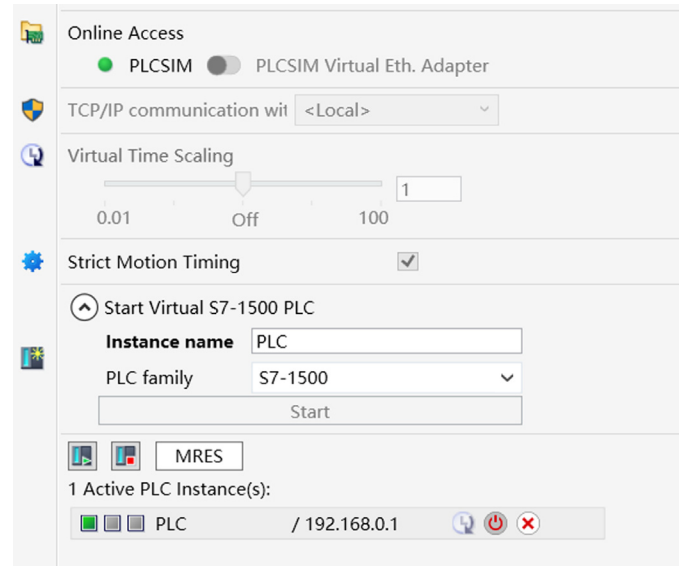


Fig. 12. Configuring a virtual PLC.

4.2 Download

Open the Siemens TIA Portal and download the program and configuration to the virtual PLC.

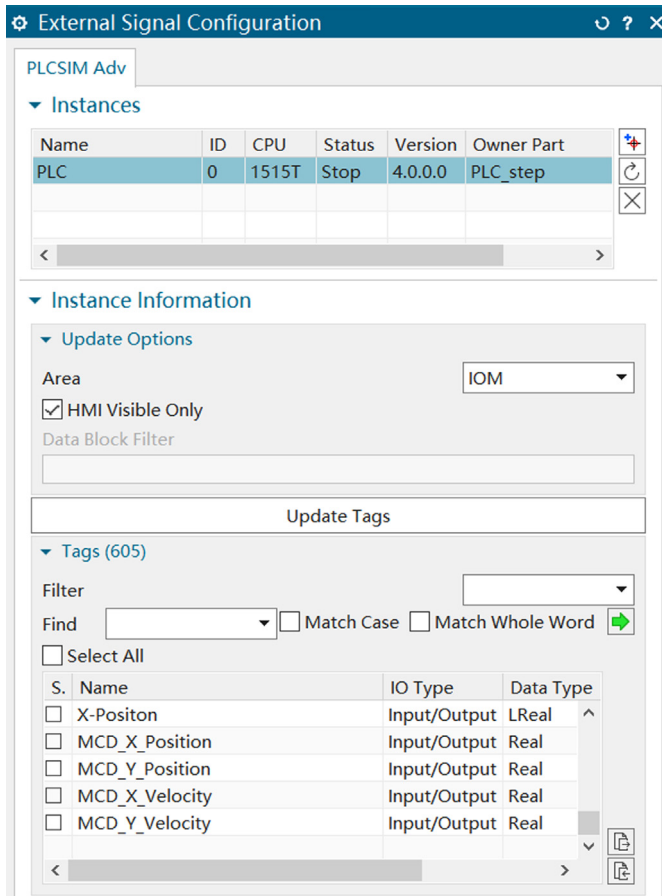


Fig. 13. External signal configuration.

4.3 External signal configuration

By configuring external signals, it is possible to facilitate communication between a PLC and an MCD, thereby enabling collaboration among various devices and enhancing the overall functionality and flexibility of the system. As illustrated in Figure 13, once the external signal is established, the variables are updated to reflect the latest external signal.

4.4 Mapping signals

To achieve the required motion of the MCD model, it is necessary to map the matching variables in the PLC program and the MCD model based on their input-output relationship. This encompasses both the PLC program commands and external manual operations.

To display the variables set in the PLC, edit the tags in the NX MCD's external signal settings, select the PLCSIM Advanced interface, and add the virtual PLC instance generated on the PC side. Complete the signal mapping by connecting these to the appropriate MCD variables using the input-output logic [20]. The process of mapping PLC variables to MCD variables is illustrated in Figure 14.

4.5 Virtual debugging

Launch the MCD simulation, download the project setup and program to the virtual PLC, and ensure internet access for both TIA and MCD. The HMI panel buttons and I/O fields can be utilized for input-output activities, allowing the MCD model to display the corresponding motion changes of the associated axes.

Online monitoring of variable changes in TIA and MCD can facilitate a better understanding of the compatibility between the model and the program. To track changes to the variables online, add the variables from MCD to the "Run Monitor". TIA enables direct monitoring of variables in the variable table and allows for the creation of variable trend graphs on the HMI or through tracing, providing a visual means to analyze the temporal changes of each variable.

5 Entity debugging

Once the hardware configuration is completed, download the TIA engineering project to the actual PLC for debugging and connect the PC end of the system to the system via an Ethernet bus. The HMI buttons and the input/output external switches installed on the hardware devices can be used to control the three-axis equipment according to the program design. Inaccuracies can be identified and improvements made by monitoring the accuracy of the three-axis movement, the mechanical gripper's reset functionality, and the precision of material grasping. The entity model of the three-axis gripping system is illustrated in Figure 15.

6 Online-offline collaborative debugging

As illustrated in Figure 16, the PLC and MCD models must communicate with each other via the OPC UA server. This is because the model, created using the electromechanical concept in NX software, cannot exchange data directly with the physical PLC over Ethernet.

The control system used in this study is the newly researched and developed SIMATIC S7-1500 by Siemens. The CPU model is CPU 1516-3 PN/DP, which comes with an OPC UA communication module. The specific steps for virtual commissioning include:

- Selecting the option "Support simulation when compiling blocks" in the project properties column to avoid errors during simulation.
- Activating the OPC UA server in the properties of the PLC and adding the license type for the OPC UA operation system.
- Allowing communication access for PUT/GET from remote objects.
- Selecting the OPC UA interface in the external signals configuration of NX 2007, and adding the server with the endpoint URL <http://opc.tcp://192.168.0.204:4840>.
- Achieving the mutual transmission of signals created in NX 2007 and those in the PLC through signal mapping. By setting the signal as input or output in NX, control of

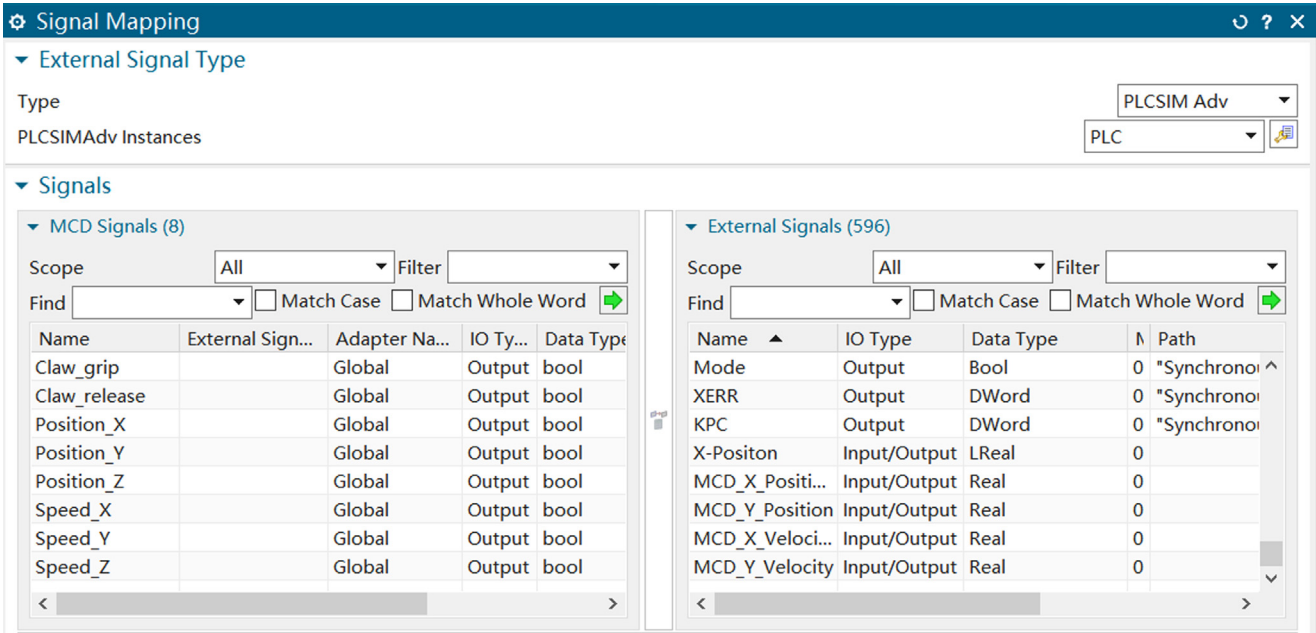


Fig. 14. Mapping signals.

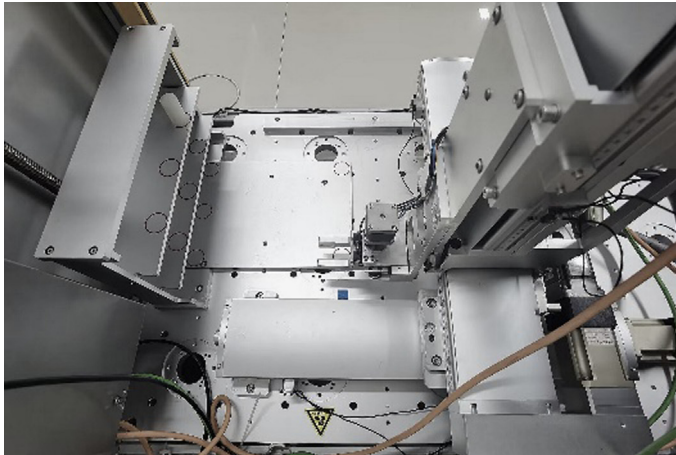


Fig. 15. Entity model of the three-axis gripping system.

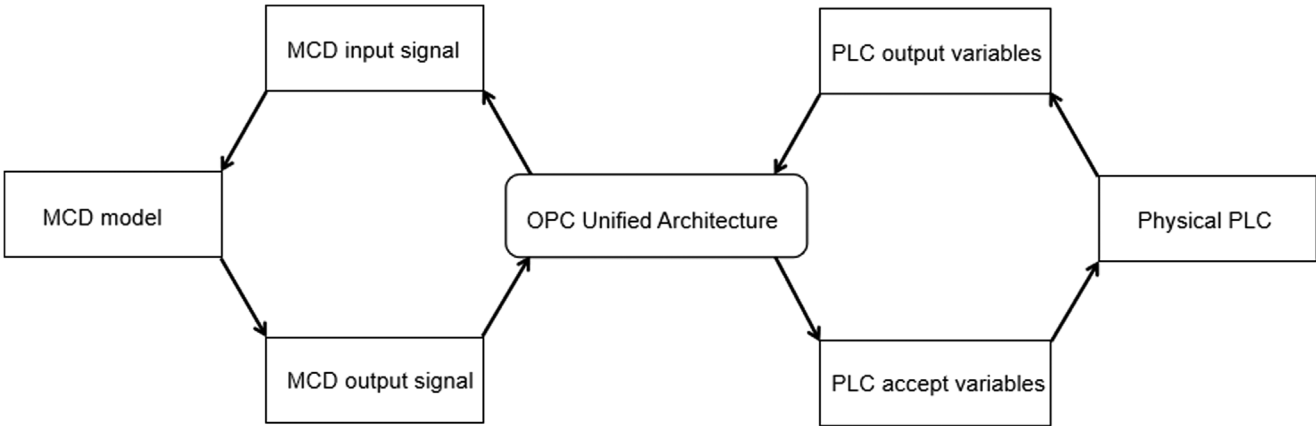


Fig. 16. Online-offline data interaction structure.

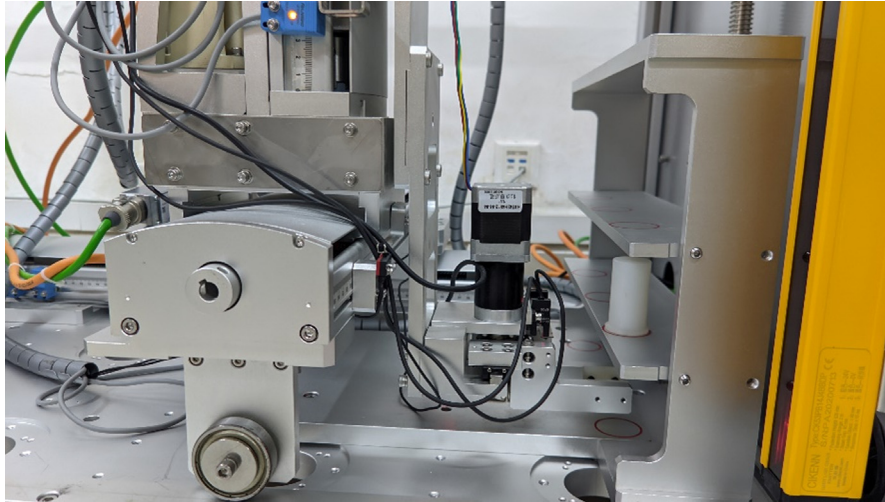


Fig. 17. Physical operation diagram.

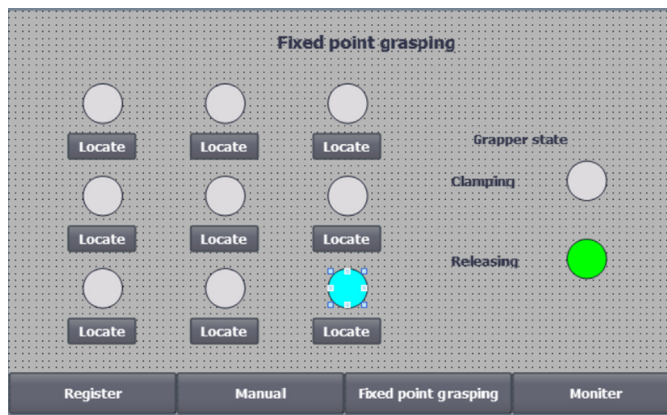


Fig. 18. HMI interface operation.

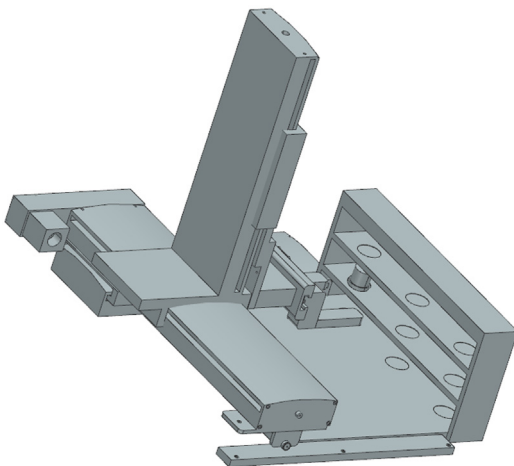


Fig. 19. Virtual model running result.

the virtual model by the PLC is achieved, enabling the interaction of virtuality with reality and the use of virtual models to control real objects.

After the operator presses the button for shelf positioning, as shown in Figure 17, the circle (representing the placement area) on the HMI interface button flashes to indicate that the positioning is complete. Simultaneously, the virtual model moves to the corresponding position and is ready for subsequent operations as shown in Figure 18 and Figure 19.

7 Conclusions

During the model establishment process, issues such as poor data quality and the insufficient diversity of data sources may lead to inaccuracies in the model. To address these issues, this study adopts the D-H algorithm to ensure data quality and conducts multiple repeated validation experiments to increase the diversity of data sources. It integrates various data sources to enhance the comprehensiveness and accuracy of the model. In the early stage of the research, the model was unable to reflect real-time changes in the actual system, resulting in discrepancies between the debugging results and reality. The study introduced real-time data monitoring variables to promptly update model parameters and established a feedback mechanism to continuously improve and adjust the model based on real-time data.

Through the simulation platform, the study not only designs the three-axis system but also focuses on designing assembly equipment for mechanization, modularization, and automation. By building a program-controlled environment through the TIA Portal, the study aims to design and verify the configuration and programming for physical devices, PLC programs, and HMI interfaces. All these efforts ultimately lead to successful control by the PLC, co-simulation, and debugging with NX MCD, and synchronization between physical platforms and virtual models.

Debugging on the virtual platform effectively reduces both the cost and the risk of field testing in the early stages of factory design. The collaboration between virtual systems and real models significantly enhances the intelligence of material grabbing and sorting, as well as greatly improving production efficiency. These advancements offer valuable

references and have practical significance for enterprises looking to further improve their industrial automation, intelligence, and efficiency.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability statement

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Author contribution statement

M.L. wrote the main manuscript text and prepared all figures. D.Y. reviewed the manuscript.

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