Development of a digital twin management system for extrusion molding experimental equipment

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Abstract: This paper introduces the concept of digital twins into the field of laboratory management, taking the twin-screw extrusion experimental device as an example, developed a digital twin management system for experimental devices. Starting from the informatization transformation of traditional equipment, the development process of the digital twin management system is introduced from the aspects of on-site data network transmission, laboratory network redundancy configuration, data management, and application management system development. The advantages of the digital twin management system are elaborated from the aspects of experimental safety, operation and maintenance costs, and experimental efficiency. The content covered in this article has certain guiding significance for the application of digital twin technology in laboratory management in colleges and universities and the informatization upgrade of equipment in small and medium-sized enterprises.

Key words: digital twin; laboratory management; extrusion unit

Classification number: TQ330.493 **Article number:** 1009-797X(2026)01-0010-05

Document code: B **DOI:**10.13520/j.cnki.rpte.2026.01.004

0 Introduction

Digital twin refers to the integration of multidisciplinary and multiscale simulation processes, leveraging data such as physical models, sensors, and operational history. As a mirror image of physical products in virtual space, it reflects the entire lifecycle process of the corresponding physical entity. Introducing the concept of digital twin into the field of laboratory management requires starting with the informatization of experimental device operation data, selecting a series of real-time data that can represent the operating state of the experimental device. Under the framework of constructing a mathematical model based on data, a complete mirror image of the experimental equipment in virtual space is formed. It can not only represent the real-time operating state of the equipment but also anticipate and predict the trend of changes in equipment operating state. This article takes the informatization transformation of traditional equipment as a starting point, introducing the development process of the digital twin management system from aspects such as on-site data network transmission, laboratory network redundancy configuration, data management, and application management system development. It also elaborates on the advantages of the digital twin management system from aspects such as experimental safety, operation and maintenance costs, and experimental efficiency. The content covered in this article provides certain guiding significance for the application of digital twin technology in laboratory management in colleges and universities, as well as in the informatization upgrade of equipment in small and medium-sized enterprises.

1 Technical upgrading of extrusion molding experimental device

Biography: Bi Chao (1981-), male, is the laboratory director of the Mechanical Design, Manufacturing and Automation Major at the School of Mechanical and Electrical Engineering, Beijing University of Chemical Technology. He is primarily engaged in research and development related to the development of polymer material processing equipment and its informatization construction.

1.1 Digitization and informatization of equipment

1.1.1 Equipment introduction

As shown in Figure 1, it is a photo of the existing CHT-30B/600-11-48 twin-screw extruder in the laboratory. This unit consists of a host machine, a feeding system, a cooling water tank, a dryer, and a granulator. Its control electrical system adopts a traditional electrical control scheme primarily relying on relays, which does not meet the basic conditions for device information management.

Figure 1 Twin-screw extrusion unit

1.1.2 Data and collection methods

To equip the unit with information management capabilities, a digital upgrade of its existing control system is required. Without affecting the normal operation of the unit for experiments, hardware devices such as data acquisition modules, PLC controllers, and communication gateways were added to enable the collection, storage, monitoring, and real-time analysis of core operational data. The operating parameters of the unit are shown in Table 1, encompassing two parts: heating and cooling, and motor operation. There are four categories: current, voltage, switch status, and temperature, totaling 59 characteristic data points. Among them, real-time temperature and set temperature are directly collected to the PLC controller via 485 communication. Motor and heater current, as well as system voltage, are collected through 4~20 mA analog conversion. The on/off status of the cooling solenoid valve is indirectly connected to the digital input port of the PLC via an intermediate relay, using the output signal from the temperature controller. All collected data is aggregated into the PLC controller.

Table 1 Unit operation data collection

Data category	Data source	Collection Method	Signal type
Set temperature, actual temperature	Machine barrel and head of Zone 11	Temperature sensor	Digital quantity
Cooling state	Machine barrel in Zone 11	Thermometer output	Discrete signal
Current	Main motor, feeding motors, water pump, vacuum pump, dryer, granulator	Current transducer	4~20 mA analog quantity
Voltage	Main motor, main feeding motor, upper-stage side feeding motor, pelletizer	Voltage transmitter	4~20 mA analog quantity

1.1.3 Informatization transmission

After completing data acquisition, the PLC controller transmits data through both on-site and remote channels. On the one hand, the data is integrated into the on-site data management system, enabling real-time monitoring of on-site data. On the other hand, the data is uploaded to the server cloud platform via an intelligent gateway, facilitating data storage and remote monitoring. Additionally, through the analysis and processing by a real-time fault analysis application, fault diagnosis is achieved.

1.2 On-site and external network configuration

1.2.1 On-site network

The laboratory site is equipped with both wired and wireless network access methods. Since the on-site access devices are within the network range of the same high-speed router, the on-site equipment enjoys high-speed data transmission bandwidth, enabling real-time data visualization display and sensitive fault warning response. Specifically, within the laboratory's on-site network environment, data transfer between the PLC controller and the single-board computer is achieved using the Node-RED open-source IoT platform. Furthermore, a real-time data visualization system has been developed using its control panel tool, as illustrated in Figure 2.

1.2.2 External network

The external network primarily serves remote data monitoring. Specifically, the intelligent gateway accesses the laboratory network environment via Ethernet and provides external network data services. To ensure stable data collection and provide necessary redundant network resources, the gateway can also access the mobile 4G network through cellular network.

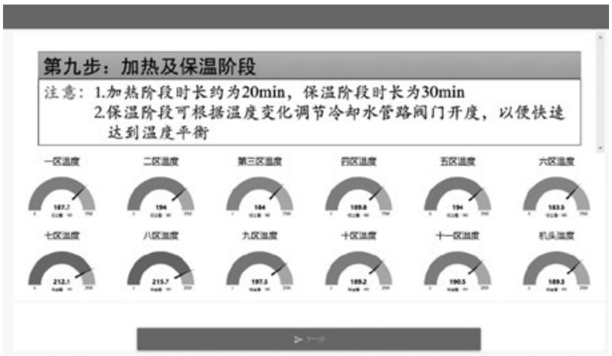


Figure 2 On-site real-time monitoring system

1.3 Data management

1.3.1 Data storage

Second-level data storage can be achieved through the on-site network. Relying on this data, edge computing can be utilized to achieve rapid fault analysis and early warning response. Considering the operation and maintenance costs of data storage, data storage servers will not be established in the laboratory. Therefore, the amount of data stored through the on-site network will only be based on the data required for short-cycle data analysis mathematical models.

Through the external network, not only is the equipment operation data connected to the IoT cloud platform, but it is also stored in the cloud server database. These data will not only be used for analysis models with longer cycles but also serve as the basis for tracing the operation management process of laboratory equipment. Considering factors such as data synchronization lag and data transmission stability limitations, the interval between data being connected to the IoT cloud platform and stored in the cloud server database is calculated as 20 seconds.

Although connecting data to the IoT cloud platform and storing it in the cloud server database incurs certain operational costs, this approach avoids the expenses and maintenance costs associated with setting up servers in the laboratory. In fact, this model is of great help to small and medium-sized enterprises in achieving equipment information management. The related technology upgrade costs can be concentrated on the information upgrade of in-house equipment, greatly avoiding the need to set up private servers. At the same time, adopting cloud services can also greatly reduce the labor and maintenance costs at the data level.

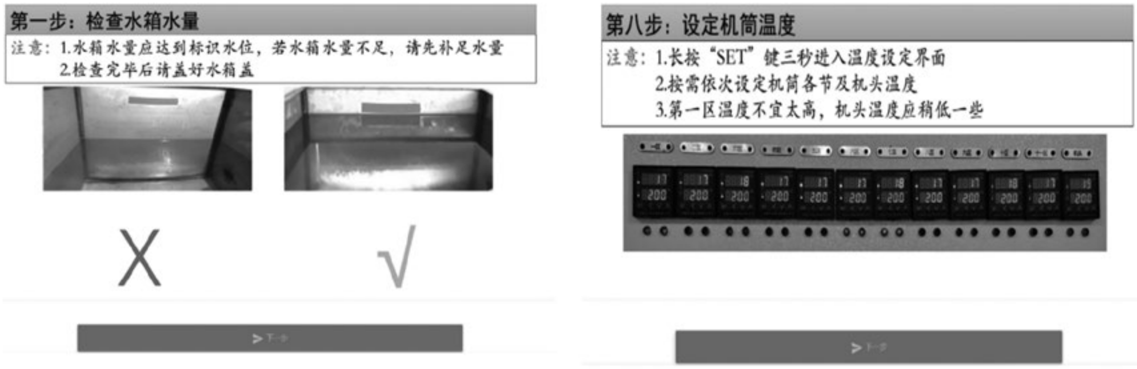
1.3.2 Mathematical model

Utilizing the timing trigger function of the network server, not only is the timing collection of data achieved, but also real-time analysis of data can be conducted. The true value of equipment informatization lies in data-driven services and decision-making. The way to achieve services and decision-making is to establish mathematical models based on data. After the informatization upgrade of the current extrusion laboratory experimental equipment, various targeted mathematical models have been developed based on data such as current and temperature during equipment operation, including system operation energy consumption analysis, heating and cooling system fault analysis, host machine fault warning analysis, feeding system adjustment warning, and pelletizer anti-blocking rotation analysis.

1.4 Application and management

1.4.1 On/off guidance system

From the perspective of the characteristics of laboratory operating personnel, the majority of those operating experimental equipment are students. Although students have acquired certain professional theoretical knowledge before entering the laboratory, there is still a significant deficiency in their proficiency in equipment operation. In order to enhance students' active participation in the experimental process and ensure the safe and reliable operation of equipment, a startup and shutdown guidance system for the extrusion unit has been developed based on the digital twin system of the extrusion unit that we have developed. During the operation of this system, the prompts for startup and shutdown steps are provided based on the real-time status of the equipment. During the startup process, the system divides the startup process into 10 steps. If any previous step is not executed properly, the system will not provide prompts for the subsequent steps. For example, if the real-time temperature of the barrel is lower than the set temperature, the system will not proceed to the heat preservation stage; if the heat preservation time is shorter than the specified time, the system will disable the host machine startup function. In this way, after conducting necessary safety checks on the unit according to the startup system prompts, operators can follow the on-screen prompts to perform the startup steps in order. During the shutdown process, following the system prompts and based on the completion of experimental material cleaning, it can also ensure that the machine's shutdown state is optimal for the next experimental startup. The shutdown process ends with the final disconnection of all power supplies to the unit, avoiding potential safety hazards. The guidance interface for some steps of the startup guidance system is shown in Figure 3.



（a）为水箱检查指导　　（b）为温度设定指导

Figure 3 Guidance Interface

1.4.2 Fault monitoring and alarm expert system

The development purpose of the fault monitoring and alarm system is to: ① reduce the number of equipment interlock shutdowns; ② indicate the location of the fault point when an interlock shutdown occurs; ③ provide guidance on troubleshooting. Taking the monitoring of the current of the host machine's screw drive motor as an example, the functions of this system are analyzed. In the experiment, when the main feeding amount is increased, the current of the host machine will show a rapid increase with the increase of the feeding amount and then stabilize. For inexperienced student operators, if they adjust the main feeding speed too quickly, there is a high risk of the host machine current being momentarily overloaded, leading to an interlock shutdown. Therefore, the system will provide necessary guidance to the operators based on changes in the main feeding speed, main feeding current, and host machine current. If the main feeding speed is adjusted too quickly, the system will prompt the operator to stop the operation and adjust the feeding speed in the opposite direction. This can effectively avoid interlock shutdowns caused by host machine current overload. For another example, by analyzing historical data on the barrel temperature and using real-time data on the current of the corresponding barrel heater, it is possible to determine possible faults in the barrel heater. Because the occurrence of certain equipment faults may correspond to multiple reasons, it is more important for inexperienced student operators to quickly formulate a troubleshooting approach. Taking the fault of the heater not working properly as an example, the expert system will provide maintenance guidance on checking whether the line terminals are loose, whether the line electrical components (fuses) are open-circuited, and whether the temperature control instrument is working properly.

2 Benefits brought by digital twins

2.1 Improved safety level

A device management system based on digital twins can effectively enhance the safety of equipment operation. Taking the boot guidance system as an example, while operators follow the system's instructions to carry out various startup procedures, the system monitors the progress of the boot process, minimizing potential risks and failures of the equipment caused by inexperienced operators due to oversights. At the same time, the digital twin system can also standardize the operation procedures for inexperienced operators based on the real-time status of the equipment, preventing interlock shutdowns caused by improper operations. According to incomplete statistics, the number of interlock shutdowns of equipment operation has decreased by 50% before and after using this system.

2.2 Reduction in equipment operation and maintenance costs

Equipment electricity consumption is one of the main components of the operation and maintenance costs of laboratory equipment. Taking the equipment insulation process during startup as an example, after adopting a digital twin management system, the system determines the end point of the insulation time based on the actual temperature changes of the barrel. This not only ensures that the equipment is heated thoroughly, but also provides a prompt for terminating the insulation stage, allowing the equipment to be started with the shortest insulation time, thus avoiding energy loss caused by excessive insulation. At the same time, the digital twin system can ensure that the equipment is always in an efficient and stable working state. While ensuring optimal energy efficiency, it also ensures that the equipment is in a good health and operational state. This effectively reduces the frequency of equipment maintenance, improves the lifespan of vulnerable parts, and reduces operation and maintenance costs.

In addition, the use of a digital twin management system can effectively reduce the number of interlocking shutdowns during equipment operation, thereby avoiding unnecessary material wastage from the perspective of material usage, and ultimately reducing operational and maintenance costs related to material consumption.

2.3 Improvement of experimental efficiency

Given the ever-increasing demand for laboratory equipment for course delivery and the uncertainty surrounding the duration of open teaching experiments, addressing the contradiction between insufficient teaching resources and the high dependence of experimental setups on equipment requires improving equipment operational efficiency. On the one hand, a digital twin management system can assist operators in quickly adjusting the equipment to its optimal working state, effectively saving experimental time. On the other hand, the use of a digital twin management system allows for real-time assessment of equipment conditions, enabling early warning of faults and preventing potential issues, thereby ensuring the continuity of experiments. In the event of a fault, the system can quickly locate the fault point and provide maintenance guidance, reducing unnecessary experimental time.

3 Summary

Based on real-time data from the extrusion molding experimental device, this article constructs a complete virtual mirror image of the experimental device and develops a digital twin management system for the extrusion molding experimental device. In the informationization transformation of traditional equipment, 60 characteristic data are exposed for the twin-screw extrusion unit. The development process of the digital twin management system is introduced from the aspects of on-site data network transmission, laboratory network redundancy configuration, data management, and application management system development. The advantages of the digital twin management system are elaborated from the aspects of experimental safety, operation and maintenance costs, and experimental efficiency. The content involved in this article has certain guiding significance for the application of digital twin technology in laboratory management in colleges and universities and equipment informationization upgrading in small and medium-sized enterprises.