

Research on Digital Twin-Based Practical Teaching for Intelligent Manufacturing

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Abstract: To address the problems of expensive equipment, limited numbers of training stations, high safety risks, and coarse-grained assessment in practical teaching for intelligent manufacturing majors, a digital twin-based practical teaching platform for intelligent manufacturing was developed. Taking a typical intelligent production line as the research object, the platform establishes a digital twin consisting of a CNC machining station, a warehousing system, a mobile manipulator, and a production control system. It forms a three-level progressive practical training model of “physical control of the virtual system, virtual control of the physical system, and virtual-physical integration.” Teaching design and implementation were carried out using four experimental projects totaling 32 class hours as examples. Teaching practice shows that this model enables risk-free, repeatable, and fault-injectable practical training, significantly improves students’ engineering practice abilities and learning outcomes, and provides a feasible pathway for practical teaching reform in emerging engineering disciplines related to intelligent manufacturing.

Keywords: Digital Twin; Intelligent Manufacturing; Practical Teaching; Virtual Commissioning; Virtual-Physical Integration.

1. Introduction

As a strategic high ground in the new round of global manufacturing competition, intelligent manufacturing is driving profound changes in manufacturing modes and promoting the transformation and upgrading of the manufacturing industry. Innovative intelligent manufacturing talent is the key to realizing this transformation. In the era of Industry 4.0, intelligent production lines are the core carriers of manufacturing. They embody the deep integration of intelligent technologies and

traditional manufacturing and constitute a critical component in cultivating students’ professional skills in intelligent manufacturing. However, the core equipment of intelligent production lines is expensive and available in limited quantities. Their operation involves safety risks, while machining processes are irreversible and consume substantial materials. As a result, students are unable to obtain sufficient hands-on opportunities or participate deeply in all stages of production, and their practical skills can hardly meet industrial needs. Digital twin technology is a key technology in the intelligent manufacturing system. It enables real-time interaction and synchronization between physical entities and virtual digital models, providing strong support for production process optimization and decision-making. The concept was first proposed by Professor Michael Grieves in 2003 and has gradually moved toward engineering application with the development of the Internet of Things, big data, cloud computing, and other technologies. By integrating information technologies such as sensing, computing, and modeling, a digital twin describes, diagnoses, and predicts the physical space, realizes interactive mapping between physical and digital spaces, and has been widely applied in intelligent manufacturing scenarios such as product lifecycle management, production process optimization, and equipment fault prediction and maintenance[1]. Applying digital twin technology to practical teaching in intelligent manufacturing courses makes it possible to establish an equivalent mapping of a production line in virtual space. Its characteristics of virtual-physical mapping, virtual control of physical systems, and virtual-physical linkage are highly compatible with the needs of engineering practical teaching. First, the virtual environment allows students to conduct repeated trial and error at zero risk, solving the problem that students “dare not operate and cannot operate” expensive equipment. Second, the digital model can

transparently present internal equipment structures, signal flows, and control logic, compensating for the shortcomings of physical training, in which students “cannot see the interior or fully understand the principles.” Third, the fault injection function can safely simulate abnormal working conditions that are difficult to reproduce on a real production line, thereby training students’ fault diagnosis and troubleshooting abilities. Fourth, process state data can be collected and traced throughout the entire process, providing a data basis for objective and refined teaching evaluation[2]. Therefore, the digital twin is not only a subject of intelligent manufacturing education, but also an important tool for reforming the methods of practical teaching in intelligent manufacturing.

In recent years, several universities in China have carried out related explorations. Li et al. established a digital twin-based intelligent workshop practical teaching platform supported by an intelligent manufacturing innovation workshop. The platform emphasizes overall workshop visualization, but its functions for student-operable virtual commissioning remain insufficient[3]. Wang et al. developed a practical course system for a digital twin intelligent production line, integrating the concepts of intelligent management, digital twins, and advanced manufacturing throughout the product lifecycle. However, its practical training still relies mainly on observation and verification-based operations, and students’ deep participation in production-line logic control programming remains limited[4]. These studies demonstrate that digital twin-enabled practical teaching is highly feasible, but further research and practice are still needed in terms of the systematic nature of platform architecture, the depth of students’ participation in programming and commissioning, and the completeness of supporting teaching resources[5]. To meet the practical teaching needs of emerging engineering majors such as intelligent manufacturing engineering and robotics engineering, this study designs and develops a digital twin-based practical teaching platform for intelligent manufacturing, and develops supporting practical training content, teaching organization methods, and an assessment and evaluation system. Teaching practice is also carried out.

2. Current Status and Requirements of Practical Teaching in Intelligent

Manufacturing

2.1 Current Status and Problems of Practical Teaching

At present, practical teaching for intelligent manufacturing majors relies mainly on real physical equipment and generally faces the following problems. First, equipment resources are severely constrained. Intelligent production-line training equipment is expensive, occupies a large area, and is available in limited quantities. Consequently, per-student operating time is insufficient, utilization efficiency is low, and operation and maintenance costs are high. Second, safety and consumption concerns restrict deep participation. Equipment such as CNC machine tools and industrial robots poses safety risks during operation, while machining processes consume large quantities of materials. For safety and cost reasons, students can often only observe demonstrations or perform a limited set of prescribed operations, making it difficult for them to participate deeply in core activities such as production-line construction, commissioning, and troubleshooting. Third, the knowledge system is fragmented. An intelligent production line involves knowledge of machinery, numerical control, robotics, sensing and detection, electrical control, and manufacturing execution systems. Students find it difficult to integrate knowledge across disciplines, resulting in discrepancies between theoretical understanding and practical operation. Fourth, theory and practice are separated and assessment is coarse. Theoretical and practical teaching are offered separately, and theoretical knowledge cannot be verified in a timely manner. Practical training process data are difficult to collect, and assessment relies mainly on outcome-based materials and teachers’ subjective observations, lacking process-based and data-driven objective evaluation methods.

2.2 Requirements of Emerging Engineering Education for Practical Teaching

Relevant documents issued by the Ministry of Education on emerging engineering education emphasize the need to transform and upgrade traditional engineering majors and cultivate students’ ability to solve complex engineering problems and engage in engineering practice and innovation[6]. For practical teaching in intelligent manufacturing majors, these requirements are reflected in four aspects. First

is systematicity: complete production lines and authentic engineering contexts should be used as carriers to cultivate students' overall understanding of the hierarchical architecture of intelligent manufacturing systems, intelligent equipment, system integration, and intelligent management and control. Second is practicality: students should carry out genuine and substantial practical work to obtain direct experience in equipment operation, programming, commissioning, and integrated testing. Third is innovation: students should be supported in conducting open and exploratory experiments, disciplinary competitions, and innovative research activities. Fourth is adaptability: practical teaching content and methods must keep pace with industrial technological frontiers and connect with job competency requirements. The digital twin practical teaching model is an effective way to meet these requirements[7]. Virtual space breaks through the constraints of equipment, sites, and safety, making it possible to realize "one person, one machine; full participation by all students; and engagement throughout the entire process." It also supports flexible organizational forms that combine online and offline teaching, as well as centralized practice and distributed after-class practice.

3. Construction Framework and Key Technologies of the Digital Twin Practical Teaching Platform for Intelligent Manufacturing

3.1 Overall Platform Framework

The platform adopts a layered architecture consisting, from bottom to top, of a basic environment layer, a model asset layer, a platform software layer, and a teaching application layer, as shown in Figure 1. The basic environment layer is created by renovating an existing training computer room and is equipped with 40 student computers, one teacher computer, projection displays, and a gigabit local area network. It can support simultaneous practical training for a class of 40 students without the construction of a new site. The model asset layer establishes model libraries for machine tools, robotic arms, AGVs, stereoscopic racks, stackers, workpieces, and workshop fences. Models such as CNC machine tools are imported after lightweight processing, while workpieces are designed to meet the needs of

mixed-flow production of multiple product varieties. The platform software layer constructs the digital twin scenario of the production line based on the open-source simulation platform Webots R2025a. Python is used to develop five types of equipment controllers—namely, the production-line master controller, AGV, robotic arm, stacker, and CNC controllers—and functional modules such as fault injection, production-capacity statistics, and the master control panel are also developed. The teaching application layer supports teaching organization, experimental projects, assessment and evaluation, and grade management, forming a complete teaching resource system consisting of the "platform, syllabus, instruction manual, and assessment."

The layers interact through standardized data interfaces in a two-way closed loop. The basic environment layer provides computing and rendering resource support for the model asset layer. The model asset layer provides callable equipment entities to the platform software layer in the form of lightweight model libraries. The platform software layer drives the motion of virtual equipment through a control bus based on Webots ROS/PLC interfaces and feeds operating states back to the teaching application layer in real time. Student operation commands from the teaching application layer are parsed by the platform software layer and then issued to the model layer for execution. Execution results are synchronously returned to the teaching application layer for process recording and evaluation, thereby forming a closed loop of "command issuance → virtual execution → state feedback → data retention"[8]. This layered design directly addresses the four types of problems described in Chapter 2. Virtualized model assets break through constraints on equipment quantity and site space; the zero-risk execution environment eliminates safety hazards; the integrated multi-equipment linkage scenario helps bridge fragmented knowledge; and the full-process data acquisition function provides a technical basis for overcoming coarse-grained assessment.

3.2 Digital Twin of the Intelligent Production Line

A 1:1 digital twin is established for a typical intelligent production line and consists of four major units, as shown in Figure 2. The CNC machining station, comprising a CNC lathe and

a machining center, performs turning and milling operations on blanks. The warehousing system, comprising stereoscopic racks and a stacker, realizes automated storage and retrieval of blanks and finished products as well as first-in, first-out (FIFO) inventory management. The mobile manipulator, consisting of a six-axis robotic arm mounted on an AGV chassis and equipped with a gripper and a vision camera at the end effector, is responsible for machine loading and unloading, vision-based sorting, and material transfer. The production control system, comprising a manufacturing execution system (MES), a warehouse management system (WMS), and a virtual PLC, is responsible for order management, inventory management, process logic control, and equipment scheduling. This digital twin can synchronize the actions and information of CNC machine tool control, industrial robot control, PLC control, AGV control, stacker control, and warehouse management in a real production line. Parameters, logic, and programs modified by students in the digital model receive immediate feedback in the virtual world and can also be imported into real equipment for operation. Thus, students can readily learn the composition, motion principles, and programming operations of intelligent manufacturing equipment[9]. In addition to the intelligent production line, the platform also supports the construction of digital twins for other production units and even an entire workshop.

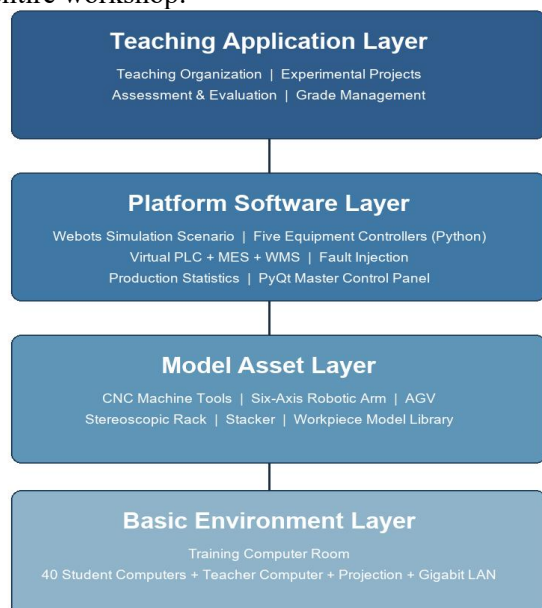


Figure 1. Overall Architecture of the Digital Twin Practical Teaching Platform for Intelligent Manufacturing

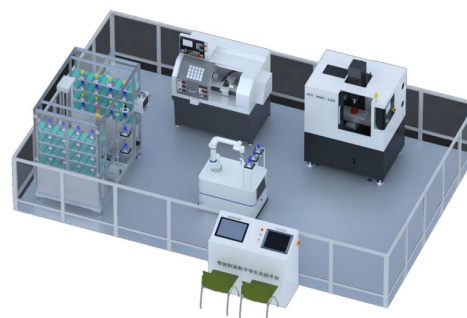


Figure 2. Digital Twin of the Intelligent Production Line

3.3 Key Technologies

(1) Multidomain unified modeling and scenario construction technology. Geometric modeling, kinematic and dynamic modeling, and behavioral logic modeling methods are integrated to provide multidimensional digital representations of electromechanical equipment. The platform uses SolidWorks for precise geometric modeling. Models are exported in URDF format and imported into Webots, and kinematic modeling is realized by defining joint constraints and collision body properties. Equipment behavioral logic is encapsulated using Python state-machine scripts to realize sequential control of action sequences and exception handling. The models are lightweighted, with the number of faces controlled within 500,000, to ensure that the simulation frame rate remains no lower than 30 FPS when 40 student computers run concurrently.

(2) Virtual-physical mapping and signal interaction technology. Binding relationships between virtual equipment objects and controller programs and an I/O signal mapping table are established. Through the encapsulation of object containers and program containers, sensor signal configuration, equipment data communication, and interlocking control are realized. The platform defines a standard I/O signal dictionary for each virtual device, including digital input and output signals and analog register addresses. The supervisor interface of Webots is used to read and write virtual sensor values in real time and map them to the PLC address space, thereby ensuring a consistent interface between virtual signal interaction and physical PLC commissioning.

(3) Virtual commissioning technology for control programs. With a virtual PLC as the core, sequential process control programs can be written and verified. The platform supports full-

element commissioning, including CNC machine tool program calling, robot point teaching and loading/unloading programming, stacker addressing, AGV path planning and scheduling, and vision recognition and guided sorting. The platform adopts the open-source OpenPLC as the virtual PLC kernel and supports ladder diagram and structured text programming under the IEC 61131-3 standard. PLC programs written by students communicate with virtual equipment in Webots through the Modbus TCP protocol, enabling the invocation of machine tool M codes and the issuance of robot point coordinates. Programs that pass commissioning can be exported with one click and migrated to real controllers for operation.

(4) Fault injection and error-proof interlocking technology. Typical faults, such as conveyor jamming, stacker overtravel, AGV positioning deviation, and camera occlusion, are preset and can also be randomly injected to train students' engineering standard awareness and troubleshooting abilities. The platform reserves fault-injection hook functions in the state machines of the equipment controllers. Through the master control panel, teachers can set the occurrence time, duration, and triggering conditions of faults. The system automatically triggers interlocked shutdown and displays an error log, which students can consult and analyze to locate the fault source.

(5) Process data acquisition and evaluation support technology. Process state data at key nodes are collected and traced throughout the entire process, and statistical results can be exported, providing a basis for data-driven objective assessment and continuous teaching improvement[10]. Through Python scripts, the platform samples key indicators such as cycle counts, confidence values of visual recognition, and material inventory differences at the end of each control cycle. The sampled results are appended in real time to a local database in CSV format and can be exported as Excel reports with one click after the course for grading and teaching review.

4. Teaching Design of the Digital Twin Practical Teaching Platform for Intelligent Manufacturing

4.1 Three-Level Progressive Practical Training Model of “Physical Control of the Virtual System-Virtual Control of the

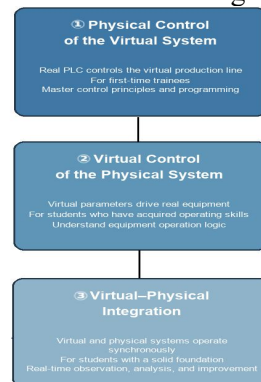
Physical Integration”

As students' practical skills improve, practical training based on the digital twin of the intelligent production line is progressively carried out in three modes, as shown in Figure 3: (1) Physical control of the virtual system. For students participating in practical training for the first time, the digital twin is set to PLC control mode. This mode does not require real on-site equipment. Instead, a real hardware PLC is used to drive the operation of the virtual production line. By debugging PLC logic programs and verifying them in the virtual scenario, students master control principles and programming methods.

(2) Virtual control of the physical system. For students who have mastered equipment operating principles and basic operational skills, the digital twin is set to teaching mode. Students drive the operation of real equipment by setting intelligent production-line parameters in the virtual environment, thereby deepening their understanding of equipment operating logic.

(3) Virtual-physical integration. For students with a stronger foundation, access to demonstration-mode practical training is enabled. The virtual scenario and real equipment move synchronously, while students observe motion control effects in real time, consult system logs, analyze the practical training process, and identify and improve deficiencies.

The three modes run throughout the entire course and are progressively connected with the four experimental projects. Students' competency development path thus moves from “control principles” to “equipment logic” and then to “comprehensive system analysis,” which is consistent with the laws of cognition.



Progressive skill development:

Control Principles → Equipment Logic → Comprehensive Analysis

Figure 3. Three-Level Progressive Practical Training Model

4.2 Teaching Objectives and Content Design

The course Practical Training in Digital Twins for Intelligent Manufacturing, offered on the basis of the platform, is a comprehensive practical component for majors related to intelligent manufacturing. Course objectives are set in three dimensions: knowledge, ability, and professional quality. In terms of knowledge, students are expected to master the composition and functions of each unit of an intelligent production line and understand the concept of the digital twin and the virtual–physical mapping relationship. In terms of ability, students should be able to construct production-line scenarios, invoke machine tool programs, carry out robot teaching and programming, conduct visual recognition commissioning, perform PLC process control programming, and complete mixed-flow integrated commissioning of the

entire production line. In terms of professional quality, students should develop an engineering standard awareness of “inspection before power-on and single-step operation before linked operation.” In view of students’ fragmented knowledge and substantial differences in programming proficiency, the course is organized progressively around a complete production line, moving from “units” to the “system,” and code frameworks and layered tasks are provided to accommodate individual differences.

The teaching content covers four components: CNC machine tool operation, industrial robot operation, AGV operation, and system-integrated commissioning. Four experimental projects are arranged over 32 class hours, as shown in Table 1. The four projects progress step by step from units to the system and from individual skills to comprehensive abilities.

Table 1. Experimental Project Arrangement and Class-Hour Allocation

Project	Title	Hours	Main content	Organization mode
Project 1	Virtual commissioning training for the cutting unit	8	Scenario construction, machine tool program invocation, robot loading/unloading teaching and programming, and unit-integrated commissioning	Mainly physical control of the virtual system
Project 2	Virtual commissioning training for the machine vision unit	8	Camera calibration, workpiece recognition and commissioning, and vision-guided sorting integrated commissioning	Mainly physical control of the virtual system
Project 3	Integrated commissioning training for the logistics–storage unit	8	Stacker addressing, FIFO storage and retrieval, AGV transfer commissioning, and unit-integrated commissioning	Mainly virtual control of the physical system
Project 4	Integrated commissioning training for the production control system	8	WMS/MES operation, PLC programming for storage and retrieval, and mixed-flow integrated commissioning of the entire production line	Mainly virtual–physical integration

4.3 Teaching Methods and Organization

The course integrates multiple teaching methods. First, task-driven teaching is adopted. The four projects are decomposed into 24 numbered tasks, each with clear inputs (task sheets), operating procedures, and deliverables. Second, virtual–physical integration and theory–practice integration are implemented. Theoretical explanation is controlled within 15 minutes and immediately followed by hands-on operation on the platform, while online and offline learning as well as centralized and distributed after-class practice are organically combined. Third, layered teaching is adopted, with compulsory and optional tasks designed to accommodate differences among students. Fourth, fault-based teaching is used to train troubleshooting abilities through preset or randomly injected faults. Fifth, assessment is used to promote learning by making the evaluation criteria publicly available in advance.

The teaching process is organized according to the sequence of “contextual introduction → theoretical explanation → operational practice → task commissioning → integrated commissioning and acceptance → summary and evaluation.” Students complete the entire practical chain from scenario construction to unit-integrated commissioning. In the first stage, the unit projects are conducted mainly in the mode of physical control of the virtual system. Students use real PLC hardware to write logic control programs that drive corresponding units in the virtual production line. In a zero-risk environment, they repeatedly debug programs and observe execution results. After the programs are mature, teachers arrange for students to download them to real laboratory equipment for trial operation, forming the first “virtual–physical comparison.” In the second stage, the integrated commissioning project for the logistics and storage unit is carried out mainly in the mode of virtual control of the

physical system. After completing parameter configuration and integrated commissioning verification for mixed-flow production of the entire line in the virtual environment, students import the verified production-line parameters and programs into the real production-line equipment. They then drive the real equipment according to the virtual solution and compare differences between virtual and physical execution, thereby deepening their understanding of equipment operating logic. In the third stage, the production control system commissioning project is carried out in virtual–physical integration mode. The virtual scenario and real equipment operate synchronously, while students observe motion control effects in real time, consult system logs, and complete data analysis and scheme optimization.

5. Teaching Implementation and Effect Analysis

After its completion, the platform was used in a controlled teaching experiment involving two parallel classes of the intelligent manufacturing engineering major. The experimental class adopted the digital twin practical teaching model, while the control class adopted the traditional physical-equipment training model. The two classes had the same instructors, teaching objectives, and assessment standards. At the end of the course, the average overall score of the experimental class was 86.4, significantly higher than the 78.2 of the control class. The percentage of students receiving excellent grades (≥ 90) in the experimental class was 42.5%, the percentage receiving good or higher grades was 80.0%, and the pass rate was 100%. These figures were higher than the corresponding values of 20.0%, 52.5%, and 92.5% in the control class, as shown in Figure 4. The assessment pass rates for the four experimental projects, based on achievement of the quantitative acceptance indicators, were 97.5%, 92.5%, 95.0%, and 90.0%, respectively. All rates exceeded 90%, indicating that the progressive teaching design from “units” to the “system” is reasonable and feasible.

After the course, a questionnaire survey was conducted among the 40 students in the experimental class, and 40 valid questionnaires were collected. The results show that 95.0% of the students believed that the practical training platform helped them understand the composition and operating principles of the

intelligent production line; 90.0% believed that virtual commissioning improved their hands-on operating ability; 87.5% believed that fault-injection training enhanced their troubleshooting ability; 92.5% were willing to participate in subsequent virtual–physical integrated practical training; and 95.0% were satisfied with the course overall. In addition, students in the experimental class independently logged into the platform for after-class practice an average of 6.8 times per person, and the submission rate of practical training materials reached 100%. These results indicate that students’ learning engagement increased significantly compared with traditional practical training.

Several shortcomings remain. There are still gaps between the virtual environment and real equipment in terms of operating feel and on-site immersion. Some students with weak programming foundations found the comprehensive projects challenging. The fault type library and process cases also need to be enriched. Future improvements will be made through semi-physical integrated commissioning combining virtual and physical systems, as well as through the optimization of layered tasks.

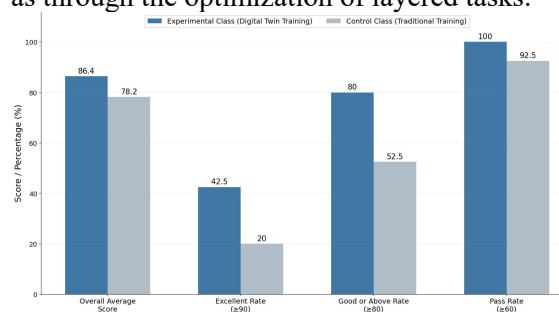


Figure 4. Comparison of Assessment Results between the Experimental and Control Classes

6. Conclusions and Prospects

To address the problems of limited equipment, high risks, fragmented systems, and coarse-grained assessment in practical teaching for intelligent manufacturing majors, this study introduces digital twin technology into practical teaching and develops a digital twin–based practical teaching platform for intelligent manufacturing. A digital twin of an intelligent production line covering a CNC machining station, a warehousing system, a mobile manipulator, and a production control system is established, and a four-layer platform architecture is formed. A three-level progressive practical training model of “physical control of

the virtual system, virtual control of the physical system, and virtual-physical integration” is proposed and implemented in teaching. A teaching content system consisting of four experimental projects over 32 class hours and a data-driven assessment and evaluation method are designed. The controlled teaching experiment shows that this model enables practical training with zero material loss, zero risk, repeatability, and fault injection. It significantly improves students’ engineering practice abilities and learning outcomes. Moreover, the platform is built on open-source software, has low construction costs, and therefore has strong value for wider application. Future work will expand scenarios such as multi-AGV scheduling and AI-based visual inspection and will explore precise evaluation based on learning behavior data, thereby promoting continuous improvement in practical teaching quality.

Acknowledgments

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