

Teaching Reform of Industrial Robot Programming and Simulation Course Based on HIL Simulation

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Abstract:

Addressing the common problems in current industrial robot programming and simulation courses, such as superficial "virtual-actual integration" and students' difficulty in transitioning from standalone virtual programming to production line system practical capabilities, this paper proposes a teaching reform scheme using hardware-in-the-loop simulation as a bridging integration method. By constructing a two-stage teaching path consisting of foundational virtual simulation training and hardware-in-the-loop simulation system integration, combined with modular projects where real industrial controllers drive virtual production lines, students undergo a complete training process encompassing signal configuration, communication linkage, and production line collaborative debugging within a reconfigurable engineering environment. Practice demonstrates that this scheme effectively bridges the capability gap present in traditional teaching, significantly enhancing students' system integration abilities and complex engineering problem-solving competencies while ensuring teaching safety and economic efficiency.

Keywords: Industrial robot; Teaching reform; Hardware-in-the-loop simulation

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I. INTRODUCTION

Driven by the national strategy for intelligent manufacturing, industrial robots have become core equipment in intelligent production lines, with their application rapidly evolving from standalone operations to system integration. The course "Industrial Robot Programming and Simulation," serving as a core link bridging robot theory and engineering application, carries the crucial mission of cultivating students' transition from theory to engineering practice. However, current course teaching still faces the following prominent problems: (1) Discretized teaching content: Focused primarily on standalone, isolated tasks, lacking training in multi-device collaboration and system integration oriented towards intelligent production lines; (2) Dilemma in practice modes: Physical equipment is costly and high-risk, while purely virtual environments struggle to simulate real control logic and on-site debugging processes; (3) One-sided evaluation methods: Still dominated by knowledge assessment and single-point skill verification, failing to comprehensively evaluate students' capabilities in system design, collaborative debugging, and teamwork.

Addressing these issues, educators have explored various angles including virtual simulation platform development, hardware-in-the-loop system design, and teaching model innovation. In virtual simulation, Xu Wei et al.[1] utilized RobotStudio to construct a virtual workstation teaching platform integrating Socket communication technology, achieving multi-device collaborative simulation. Li Guang et al.[2] explored enhancing teaching efficiency and industry-education integration by constructing high-fidelity virtual models and optimizing processes. In hardware-in-the-loop simulation, Du Zhiqiang et al.[3] designed a hardware-in-the-loop simulation testing system integrating virtual commissioning technology, achieving collaborative simulation of mechanical, electrical, and control systems. Zhang Xiaofang et al. [4] constructed a hardware-in-the-loop simulation multi-robot collaborative workstation based on Profinet communication, achieving hybrid control of physical and virtual devices and flexible production line reconfiguration. Li Bo et al. [5] proposed a hardware-in-the-loop simulation experiment platform scheme for robotic aircraft assembly, aiming to cultivate students' practical abilities driven by actual engineering requirements. In teaching models, Dong Guangjie [6] guided by the integration of "posts, courses, competitions, and certificates," constructed a project-based curriculum system to address fragmented capability cultivation. Zhang Zhao et al. [7] explored a teaching model integrating "RobotStudio simulation and competition," refining teaching content through competition decomposition and virtual-actual combination. Zhang Shan [8] systematically studied curriculum reform paths oriented towards intelligent manufacturing, proposing comprehensive solutions from aspects of teaching content,

methods, practice, and assessment. Although existing research has promoted the application of the "virtual-actual integration" concept in robotics teaching, most still treat virtual simulation, hardware-in-the-loop systems, and physical operations as independent segments, lacking effective pathways for conducting full-process engineering training within a coherent, reconfigurable environment centered around real controllers.

Therefore, this paper proposes using "hardware-in-the-loop simulation" as a key bridge for system integration, reconstructing teaching content and implementation paths, and establishing a progressive teaching system of "virtual foundation, system integration." This aims to provide students with a low-cost, low-risk, repeatable system integration training environment, effectively enhancing their comprehensive ability to tackle complex engineering problems.

II. RECONSTRUCTION OF TEACHING CONTENT

To address the "virtual-actual gap" problem in traditional teaching and dismantle the discretized structure of knowledge organized by equipment functions, this reform systematically reconstructs the course content into two stages: "Foundational Virtual Simulation Training" and "Hardware-in-the-Loop Simulation System Integration." The reconstructed project-based teaching content is illustrated in Fig. 1, exemplified by Unit 3 - Scenario 3: "Machine Tool Loading and Unloading."

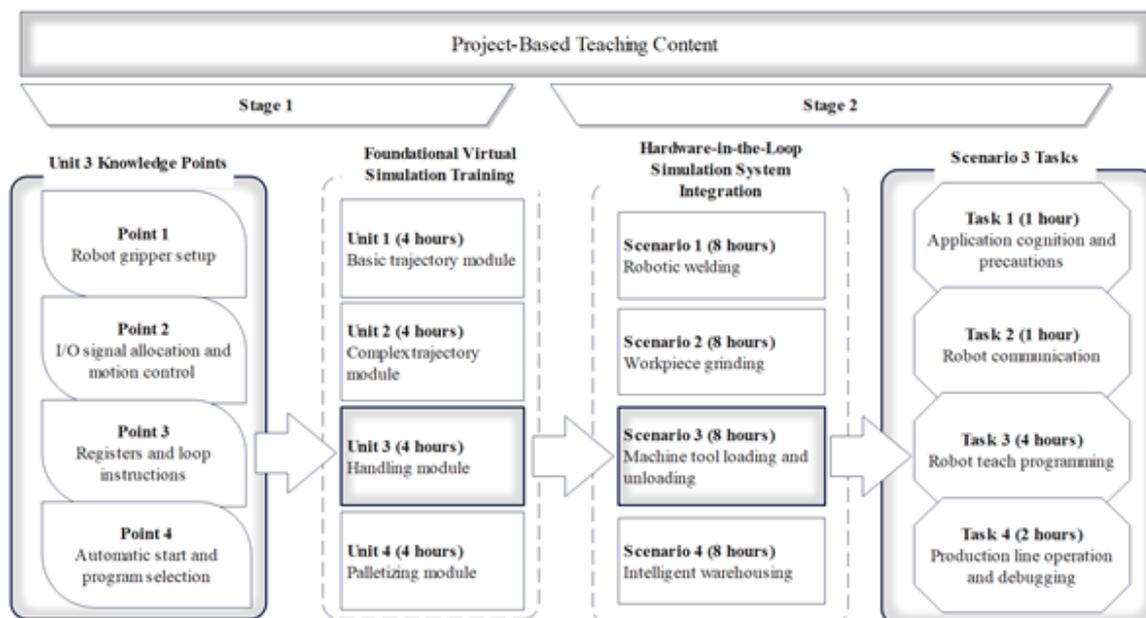


Fig.1. Project-based Teaching Content Reconstruction

Stage 1: Foundational Virtual Simulation Training (16 credit hours). Within robot simulation software such as FANUC RoboGuide, knowledge points—including robot coordinate system establishment, motion instructions, control instructions, and signal control—are integrated into project-based training covering four modules: "Basic Trajectory," "Complex Trajectory," "Handling," and "Palletizing." Each module is allocated 4 credit hours. The objective of this stage is to solidify foundational standalone virtual programming skills, with all tasks closely aligned with subsequent system integration scenarios.

Stage 2: Hardware-in-the-Loop Simulation System Integration (32 credit hours). Students rely on the hardware-in-the-loop simulation platform, as shown in Fig. 2, to complete the integration and debugging of three typical production line projects: "Robot Welding, Machine Tool Loading and Unloading, Intelligent Warehousing." Students program the virtual production line using a real FANUC teach pendant and controller, as shown in Fig. 3. They connect the controller to a real PLC (e.g., Siemens S7-1200/1500) via physical I/O, and the PLC program drives peripheral equipment in the virtual scene, forming a "perception-decision-execution" control closed loop. This stage simulates the entire process from electrical wiring, signal configuration, robot teach programming, to whole-line collaborative debugging, focusing on training system integration thinking and on-site debugging capabilities.



Fig.2. VR-TWR01 Hardware-in-the-Loop Simulation Experiment Station

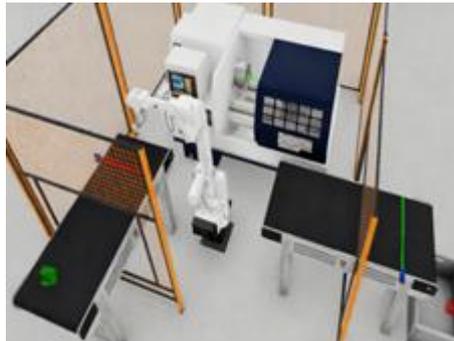


Fig.3. 3D Interface of Virtual Production Line in Hardware-in-the-Loop Simulation

Through this reconstruction, the course forms a progressive path of "virtual practice for fundamentals, hardware-in-the-loop practice for systems," achieving a natural transition from standalone skills to production line integration capabilities.

III. COURSE IMPLEMENTATION PROCESS

To effectively cultivate students' system integration capabilities, the course establishes a teaching model of "Pre-class Guidance - In-class Implementation - Post-class Extension," as shown in Fig. 4. This model is driven by production line projects as tasks, centered around the hardware-in-the-loop simulation platform, and integrates online and offline methods, forming a closed-loop capability cultivation cycle of "problem guidance, virtual-actual progression, practical challenge tackling."

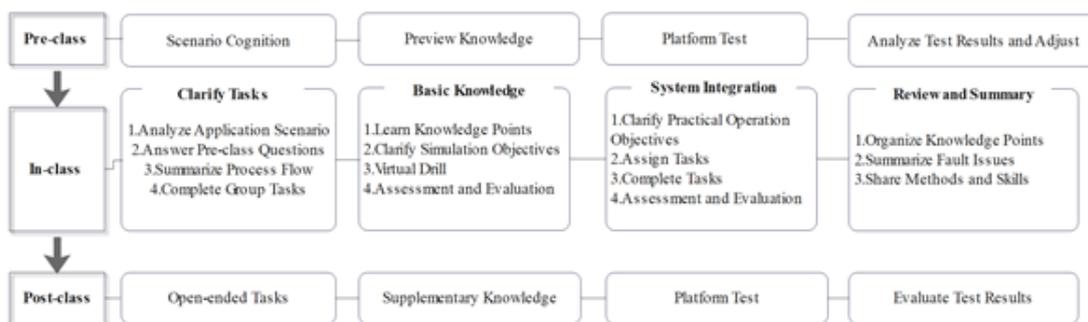


Fig.4. Course Reform Implementation Flow

Pre-class Guidance: Teachers release project resource packages (including case videos, simulation models, micro-lectures, and pre-class questions) via the online platform, guiding students to autonomously complete scenario cognition, knowledge preview, and online diagnostics. After analyzing the process, students submit preliminary plans and questions, transforming from passive recipients to learners entering the classroom with problems, thus preparing cognitively and goal-wise for in-depth classroom practice.

In-class Implementation: Focusing on pre-class questions through in-depth discussion and clarifying task objectives, students first engage in the simulation software learning segment. They perform hands-on operation and practice of theoretical knowledge in the virtual environment, complete robot programming and process optimization, and pass fundamental theory assessments. Subsequently, they proceed to the hardware-in-the-loop simulation platform learning segment. Students conduct physical wiring and signal configuration using real

controllers and PLC, program and debug the virtual robot and production line using the actual teach pendant, solve typical engineering problems such as timing coordination and communication connection, and undergo systematic fault diagnosis training. After debugging, centralized reviews are organized to summarize common fault types and resolution strategies, strengthening students' system debugging and problem backtracking abilities.

Post-class Extension: To promote knowledge transfer and innovation, open-ended challenge tasks (e.g., integrating vision systems, optimizing cycle time) are released after class, encouraging students to engage in extended learning. The teaching platform simultaneously integrates excellent past design cases, providing continuous improvement feedback and guiding students' transition from skill mastery to engineering innovation.

This model, through the spiral design of "online preparation - offline challenge tackling - post-class," enables students to undergo complete training from cognition, simulation, practice, to innovation within a safe and economical hardware-in-the-loop simulation environment, thereby enhancing their comprehensive practical ability to address complex engineering problems.

IV. REFORM OF THE ASSESSMENT SYSTEM

To scientifically evaluate the teaching effectiveness of the curriculum reconstruction and replace the previous assessment method dominated by final exams and isolated practical operations, this reform constructs a multi-dimensional process assessment system centered on hardware-in-the-loop simulation projects, integrating online and offline components. The final overall score comprises virtual foundational capabilities and system integration capabilities, with the specific framework shown in Fig. 5.

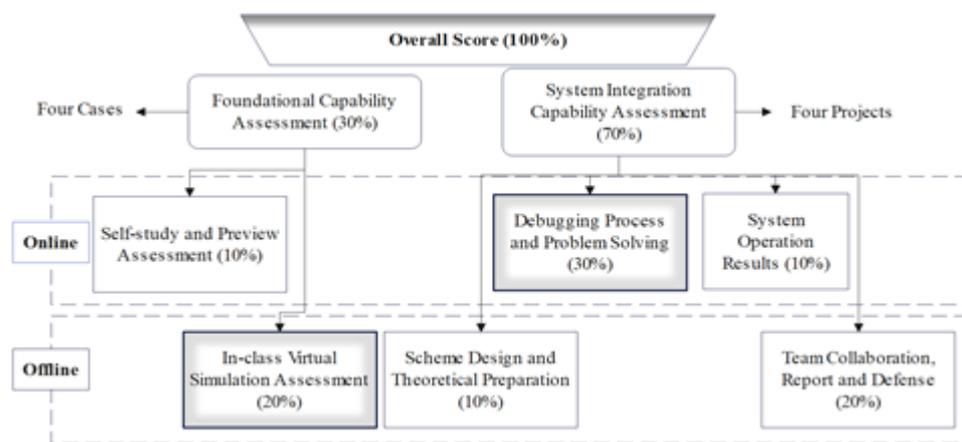


Fig.5. Multi-dimensional Process Assessment System for the Course

The virtual foundational capability assessment evaluates knowledge mastery from the first stage, employing a combination of automatic evaluation via the online platform and teacher assessment. By recording and analyzing students' pre-class resource study duration, pre-class test completion rates and accuracy through the teaching management platform, their autonomous learning habits and knowledge preview effectiveness are evaluated. In-class teaching assessment is based on time-limited assessments of four cases within the RoboGuide virtual environment, automatically scoring based on trajectory accuracy and task completion, achieving objective evaluation of basic programming skills.

System integration capability assessment forms the core of the reform, comprehensively evaluating students' comprehensive engineering practice abilities during the second stage (Hardware-in-the-Loop Simulation System Integration). This assessment component runs throughout the entire project, covering the following aspects: (1) Evaluating students' preliminary analysis and engineering design capabilities by assessing the standardization, process rationality, and system planning ideas presented in their submitted "Project Proposal"; (2) Utilizing the data acquisition functions of the hardware-in-the-loop simulation platform to comprehensively record students' operation logs, debugging steps, fault diagnosis paths, and resolution efficiency. Based on these records, teachers comprehensively evaluate the standardization of their hardware connection and signal configuration, the logic of their program programming and debugging, and the timeliness of their problem analysis and resolution when encountering technical difficulties. (3) Evaluating teamwork division, collaboration, and communication skills through project group defenses and peer evaluations; Teachers assess students' engineering summarization, technical reflection, and documentation writing abilities based on their submitted "Project Summary Report."

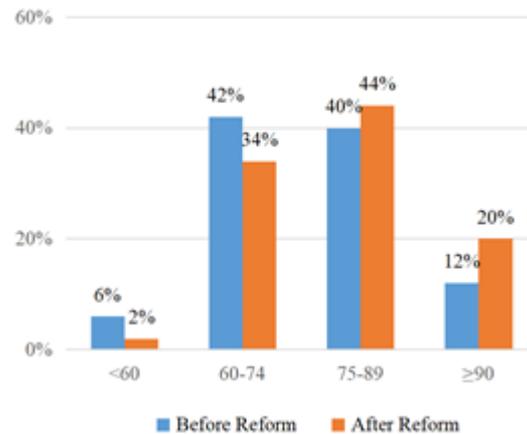


Fig.6. Comparison of Student Performance Distribution Before and After Teaching Reform

To intuitively demonstrate the improvement effect of the teaching reform on student abilities, an analysis of teaching data before and after the reform is presented, as shown in Figure 6. The figure reveals a clear upward trend in performance after the reform, with a significant increase in the proportion of students in the high-score segment. Practice indicates that this system can comprehensively and authentically reflect students' comprehensive literacy in engineering thinking, technical practice, and teamwork, achieving the reform objectives of "promoting learning through assessment and promoting improvement through assessment."

V. CONCLUSION

This paper proposes a reform scheme centered on hardware-in-the-loop simulation, reconstructing teaching content and pathways, forming a progressive capability cultivation system of "virtual simulation foundation - hardware-in-the-loop system integration." Through project-based training where real controllers drive virtual production lines, students undergo a complete practical process from design, linkage debugging to commissioning within a reconfigurable engineering environment. Teaching practice proves that this reform effectively bridges the gap between "virtual" and "real," significantly enhances students' system integration capabilities and complex engineering problem-solving competencies while ensuring teaching safety and economic efficiency, providing a referable implementation path for cultivating industrial robot talent in the context of intelligent manufacturing.

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