Application Research on Virtual Simulation Experiment Teaching Platform: Based on Industrial Robot Engineering Simulation Course

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Abstract: Practical teaching is of vital importance in engineering education. However, traditional practical teaching often faces constraints such as equipment limitations, safety risks, and high costs. This paper takes the "Industrial Robot Engineering Simulation" course as an example to construct a virtual simulation experiment teaching platform based on the three-stage theory of skill learning proposed by Fitts and Posner. The platform is developed collaboratively with enterprises using Web-based technology and Unity 3D, and it supplements the simulation functions of equipment layout, wiring, and system commissioning based on the RobotStudio software. A teaching mode of "virtual-real integration, three-stage driving" (cognitive experience — simulated operation — project practice) is designed and implemented. The Operational Proficiency Index (OSI) is established as a process evaluation metric. Two rounds of comparative experiments (N=157) demonstrate that the experimental class outperforms the control class in comprehensive scores (average improvement of 12.6–12.8 points, Cohen's d>1.3), efficiency (completion time reduced by 23%–25%), and first-attempt pass rate (increased by over 30 percentage points). Module-level analysis reveals the virtual platform's particular advantages in construction-process-related content, while OSI shows strong predictive validity for final hands-on performance (R^2=0.68). Combining virtual simulation with the "virtual-real integration, three-stage driving" teaching model is beneficial for engineering training of applied undergraduates, and the OSI index can serve as a quantitative assessment standard.

Keywords: Virtual Simulation; Experiment Teaching Platform; Industrial Robot; Offline Programming; Robotstudio; Applied Undergraduate

1. Introduction

Intelligent manufacturing is the main direction of "Made in China 2025" [1]. The industrial robot industry has a large talent gap in technical professionals, yet students in applied undergraduate universities often have weak engineering foundations and insufficient practical experience. Relying solely on software programming training cannot meet enterprises' demand for composite talents. The "Industrial Robot Engineering Simulation" course uses RobotStudio as its core tool, through which students learn industrial robot programming and process control via offline programming and simulation operations. However, in traditional teaching, students only learn to program in the software, lacking systematic understanding of construction processes such as equipment installation, electrical wiring, and system commissioning, making it difficult to develop complete engineering application capabilities. The virtual simulation experiment teaching platform, based on 3D modeling and WebGL rendering technology, adds construction simulation modules such as equipment installation and electrical wiring on top of RobotStudio simulation, providing students with a low-cost, reusable comprehensive practical environment [2]. In recent years, researchers such as Gao Pengfei et al. [3], Wang Lingling et al. [4], Zhao Junying et al. [5], Luo et al. [6], and Liljaniemi et al. [7] have conducted explorations from perspectives of platform development, task-driven approaches, digital twins, and immersive teaching environments. Feng Zenghui et al. [8] proposed a virtual-real combined teaching method for industrial robot experiments, and Chen Panpan et al. [9] constructed a "three-stage progressive" teaching model. However, these studies either focus on platform development without systematic teaching mode design, or lack solid theoretical foundations and sufficient quantitative verification. This paper, supported by the three-stage theory of skill learning proposed by Fitts and Posner [10], implements a "virtual-real integration, three-stage driving" teaching mode at Hankou University, using the virtual platform to supplement RobotStudio's shortcomings in construction process simulation, enabling students to expand from single programming training to full project process experience. The specific approach and practical outcomes are presented herein.

2. Teaching Status and Problem Analysis of the Industrial Robot Engineering Simulation Course

2.1 Course Overview

The "Industrial Robot Engineering Simulation" course is an elective for the Mechatronic Engineering major at Hankou University, with a total of 32 credit hours. It adopts an integrated theory-practice full-experiment teaching model, using RobotStudio as the core tool and focusing on offline programming and simulation of robot handling workstations [4]. The course requires students to master skills including robot modeling, I/O configuration, point teaching, RAPID programming, and simulation debugging, while also understanding project construction processes such as equipment installation, electrical wiring, and system commissioning. As a private applied undergraduate university, Hankou University has students with strong hands-on abilities but relatively weak theoretical foundations. The integrated theory-practice teaching approach helps students build systematic understanding of industrial robot engineering applications through a "learning by doing" process.

2.2 Main Problems

From the perspective of the "Industrial Robot Engineering Simulation" course taught in this study, students generally lack a complete or systematic understanding of various construction processes in robot workstations, including equipment types and layout, electrical connections, point teaching, system commissioning, and even fault diagnosis. Teaching mostly adopts tools such as RobotStudio; although students receive programming training, the key points of "how to install and position equipment," "how to wire the control cabinet," and "how to configure and debug the system" in actual projects are often neither understood nor practiced, and do not receive comprehensive guidance. If students encounter new methods for the first time, the limited hands-on operation time can easily lead to insufficient learning motivation. For applied undergraduate students at Hankou University, whose theoretical background is not very solid, the disconnection of "only learning programming without learning processes" is particularly prominent in engineering courses. Engineering intuition (which cannot be obtained from programming alone) requires full project process experience [11]. Traditional experiments only allow students to complete predetermined tasks according to instructors' directions, with no room for free experimentation or repeated failures, and teachers cannot timely assess individual students' progress or difficulties.

3. Design of the "Virtual-Real Integration, Three-Stage Driving" Teaching Mode

3.1 Theoretical Basis and Three-Stage Framework

The three-stage theory of skill learning proposed by Fitts and Posner divides the motor skill acquisition process into the cognitive stage, the associative stage, and the autonomous stage [10]. In the cognitive stage, learners understand movement essentials through observation and explanation, with frequent errors and stiff movements during operation. In the associative stage, learners gradually correct erroneous movements and link scattered movements into fluent sequences. In the autonomous stage, operations become proficient and can be performed without excessive attention. This theory is highly consistent with the organizational logic of engineering practical teaching, which follows "cognition first, then operation, and finally proficiency." Based on this theory, this paper designs a "virtual-real integration, three-stage driving" teaching mode: The first stage is the cognitive experience level, where students browse 3D scenes and watch operation demonstrations on the virtual platform, establishing an overall understanding of project construction processes including equipment installation, electrical wiring, offline programming, and system commissioning. The second stage is the simulated operation level, where students sequentially complete training modules including mechanical installation, electrical installation, offline programming, and system debugging on the platform, with the system providing real-time feedback on operation accuracy and instructors offering targeted guidance. The third stage is the project practice level, where students independently complete a complete industrial robot project in RobotStudio, covering workstation layout design, I/O configuration, point teaching, RAPID programming, and simulation debugging, transforming the cognition accumulated in the first two stages into practical ability. The three stages progress sequentially with virtual-real alternation, and the programming simulation functions of RobotStudio and the construction process simulation functions of the virtual platform complement each other, concentrating limited software operation time on comprehensive projects to maximize learning effectiveness.

3.2 Process Evaluation and Classroom Organization

The virtual experiment platform can automatically track the time spent on each operation step, error types, and retry counts. This paper proposes a process evaluation method composed of three dimensions: The first is the Operational Proficiency Index (OSI), which incorporates time efficiency, operation accuracy, and retry behavior, calculated as OSI = 0.4 × time efficiency + 0.3 × operation accuracy + 0.3 × retry decay term (weights determined based on opinions from 3 enterprise experts and 2 instructors). The second is operation standardization (whether operations follow rules, with no step-skipping or violations). The third is task completion status. These three types of data are aggregated in real-time on the instructor interface, providing clear identification and positioning of learning weaknesses and individual students.

Classroom organization follows three steps: "pre-class cognitive experience — in-class simulated operation — post-class consolidation practice." Before class, students watch introductory videos and then log into the platform to browse 3D scenes, completing the first stage of cognitive experience. During class, students complete module training on the platform, with instructors providing stratified guidance based on OSI distribution, completing the second stage of simulated operation. After class, students can log into the platform at any time for repeated practice, and the platform retains operation records. Meanwhile, instructors publish comprehensive projects for students with sufficient capacity to challenge, completing the third stage of project practice.

4. Implementation Conditions of the "Virtual-Real Integration, Three-Stage Driving" Mode

4.1 Platform Architecture and Functional Design

The course team collaborated with Beijing Rainier Network Technology Co., Ltd. to build a browser-based virtual experiment environment using Unity technology, modeled after a real ABB robot workstation [12]. The platform adopts a B/S architecture (backend: Java 8 + MySQL 5.7; frontend: Unity 2021 LTS WebGL rendering), aiming to supplement RobotStudio's shortcomings in simulating project construction processes such as equipment installation, electrical wiring, and system commissioning. The platform includes five operation modules: mechanical installation, electrical installation, offline programming, system debugging, and assessment evaluation, corresponding to the three-stage teaching design: In the first stage of cognitive experience, students roam the 3D workshop to establish overall process cognition. In the second stage of simulated operation, students sequentially complete training in each module, with the system providing real-time feedback on operation accuracy. In the third stage of project practice, students complete the assessment evaluation and independently finish comprehensive projects in RobotStudio.

4.2 Key Technologies for Virtual-Real Mapping

The platform development involves three key technologies: The first is rendering 3D scenes built with SolidWorks using WebGL technology, with models processed through material mapping and light baking for browser display (immersive virtual learning environments) [12]. The second is the one-to-one parameter correspondence between virtual scenes and RobotStudio, namely the six-axis joints (J1–J6), TCP coordinates (TCP), and digital I/O signals, explaining the "virtual-real mirror"[5]. The third is the multi-platform migration method for RAPID programs, where RAPID code written in the virtual environment can be imported into RobotStudio, providing technical support for "virtual practice, software verification."

5. Implementation Process of the "Virtual-Real Integration, Three-Stage Driving" Mode

5.1 Three-Stage Teaching Implementation

Teaching progress is organized in three stages. The first stage (cognitive experience): Students first log into the platform to browse 3D scenes, familiarizing themselves with the locations and basic operation methods of each functional module. Taking the comprehensive experiment project (4 credit hours) as an example, before class, students watch a 2–3-minute short video; 79 out of 89.9% of 79 students log into the platform no less than 2 times, with an average preview time of approximately 35 minutes. The second stage (simulated operation): During class, the process proceeds in five steps: mechanical installation (20 minutes), electrical installation (15 minutes), offline programming (50 minutes), system debugging (40 minutes), and assessment test (35 minutes). Students practice repeatedly on the platform, with instructors providing stratified guidance based on OSI values, transitioning their role to facilitators. The third stage (project practice): Students independently complete a full industrial robot project in RobotStudio (including workstation layout design, I/O configuration, point teaching, RAPID programming, and simulation debugging). After class, students can log into the platform at any time for repeated practice, accumulating an average of 6.2 hours of practice time.

5.2 Teaching Method Innovation

The virtual experiment platform makes two breakthroughs over traditional experimental conditions: Details of instrument structure and installation can be enlarged, making physical objects less likely to be overlooked and visibility more complete. The designed teaching can be conducted in a group competition format, with each group arranging handling routes for the same workstation, comparing results according to cycle time, forming healthy competition among groups. From a statistical perspective, students in the experimental class attempted an average of 5.3 ± 1.2 different paths for the comprehensive project, while approximately 72.6% of the control class students only made 1–2 such attempts, confirming that the platform effectively promotes exploration and improves efficiency.

6. Teaching Effect Analysis

6.1 Performance and Efficiency Comparative Analysis

To objectively analyze the actual teaching effectiveness, this paper employs a quantitative comparative experiment approach. Comparative experiments were conducted in both Spring 2024 and Spring 2025, with the same course and instructor; the only difference was that the experimental class used virtual simulation combined with RobotStudio, while the control class used only RobotStudio in the conventional manner. The statistical tool used was SPSS 26.0, and the baseline scores of both classes at the beginning of the semester showed no significant difference ($p>0.05$), indicating equivalent starting points.

The final assessment combines theory scores (30 points) and practical operation scores (70 points), totaling 100 points, as shown in Table 1.

Table 1. Comparison of Final Comprehensive Scores Between Experimental and Control Classes

Semester	Class	Type	Theory Avg.	Practice Avg.	Comprehensive Avg.
Spring 2024	Class 1, Grade 2021	Experimental	25.8	58.3	84.1
Spring 2024	Class 2, Grade 2021	Control	23.1	48.4	71.5
Spring 2025	Class 1, Grade 2022	Experimental	26.2	59.1	85.3
Spring 2025	Class 2, Grade 2022	Control	23.5	49.0	72.5

As shown in Table 1, the comprehensive scores of the experimental class were generally higher than those of the control class. In Spring 2024, the experimental class averaged 84.1 points while the control class averaged 71.5 points, with a difference of 12.6 points ($t=5.87$, $p<0.001$, Cohen's $d=1.32$). The gap was slightly larger in Spring 2025 (12.8 points), with $t=6.12$, $p<0.001$, Cohen's $d=1.38$. The proportion of students scoring above 80 was 62% for the experimental class and 31% for the control class. Table 2 presents the comparative data on practical examination efficiency.

Calculated by the control class standard, the average time to complete the practical assessment was 100–102 min, while the experimental class required 77–79 min (approximately 23%–25% less). The number of overtime students was 8–9 in the control class and at most 1–2 in the experimental class. In terms of individual modules, the offline programming section saved approximately 12 min, and the system debugging section saved approximately 9 min, indicating that repeated use of virtual equipment has practical significance in promoting operational skills. The first-attempt pass rate was 87%–90% for the experimental class, compared to only 56%–57% for the control class.

Table 2. Comparison of Practical Assessment Efficiency between Experimental and Control Classes

Semester	Class	Type	Avg. Time/min	Overtime	First-Pass Rate/%
Spring 2024	Class 1, Grade 2021	Experimental	78.5	2	87.2
Spring 2024	Class 2, Grade 2021	Control	102.3	9	57.5
Spring 2025	Class 1, Grade 2022	Experimental	77.0	1	90.0
Spring 2025	Class 2, Grade 2022	Control	100.6	8	56.4

6.2 Teaching Effect Evaluation

Standardized observation records (averaged per 10-min unit) made by 2 teachers trained in classroom observation consistency were analyzed. The results showed that the experimental class's attention indicator averaged 85%, while the control class only reached 65%. In terms of wiring standardization, programming logic, and debugging efficiency, the experimental class outperformed the control class by 24, 19, and 27 percentage points, respectively. At the end of the course, an anonymous questionnaire survey was conducted among 85 experimental class students across two semesters (42 in Spring 2024 and 43 in Spring 2025), yielding 81 valid responses (95.3% effective rate). The questionnaire's Cronbach's α was 0.87, indicating good reliability. "User-friendly interface" was the most endorsed item (93.7% positive), followed by "helpful for understanding knowledge" (88.6%), with endorsement rates of 86.1%, 84.8%, and 87.3% for "improving hands-on ability," "enhancing learning interest," and "willing to recommend," respectively.

6.3 Module-Level Effectiveness Analysis

Analyzing the 43 experimental class students in the Spring 2025 semester, the mean OSI values across modules showed significant differences: The mechanical installation module averaged OSI of 0.72, electrical installation 0.68, offline programming 0.81, and system debugging 0.75. The OSI for offline programming was the highest, which corresponds to the module already trained in RobotStudio; while electrical installation scored the lowest, involving more wiring and prone to errors, requiring special training attention. According to the platform's backend statistics on average time spent, the mechanical and electrical modules required 35% and 28% less time, respectively, for the experimental class compared to the control class, while offline programming only saved 12% (time spent per module is calculated as the average of each group completing the respective task; the saving percentage is (control class mean − experimental class mean) / control class mean × 100%). This indicates that the virtual platform is particularly beneficial for construction-process-related projects.

6.4 Stratified Effect Analysis

Based on the three-stage theory of skill learning (cognitive — associative — autonomous proficiency development), the in-class OSI data were analyzed by dividing 85 experimental class students into a high-proficiency group (OSI ≥ 0.80, 26 students), a medium-proficiency group (0.60 ≤ OSI < 0.80, 38 students), and a low-proficiency group (OSI < 0.60, 21 students). There were no significant differences in semester-starting scores among the three groups ($F=0.47$, $p=0.63$), meeting the homogeneity condition. The three groups showed significant differences in final comprehensive scores: The high-proficiency group averaged 91.2 points, the medium-proficiency group 82.4 points, and the low-proficiency group 74.8 points ($F=12.36$, $p<0.001$). Notably, even after targeted instructor tutoring, the low-proficiency group still outperformed the control class average (72.5 points), indicating that stratified teaching can facilitate their progress. The first-attempt pass rates for the three groups were 96.2%, 84.5%, and 68.7%, respectively, all exceeding the control class's 56.4%.

6.5 OSI Predictive Effect Analysis

Using in-class OSI means as the independent variable and final practical scores as the dependent variable for linear regression analysis, the results showed that OSI has strong predictive ability for practical scores (R^2=0.68, β=0.82, p<0.001), indicating that in-class process data are reliable predictors of learning outcomes. For individual modules, the offline programming module OSI was the most predictive (R^2=0.74), followed by electrical installation (R^2=0.62), and mechanical installation was the lowest (R^2=0.51). This difference relates to the difficulty of corresponding operations and knowledge transfer. From these findings, the OSI index can be used to measure students' operational proficiency and serves as a useful data source for instructors to adjust teaching methods.

As shown in Table 3, the comparison results between this study and other virtual simulation teaching research indicate that most existing studies focus on platform development or teaching mode description, lacking systematic theoretical support and sufficient quantitative verification. Although Gao Pengfei et al. constructed an intelligent manufacturing virtual simulation platform, they did not specify a theoretical basis and only conducted descriptive analysis. Wang Lingling et al. implemented task-driven teaching but did not conduct process-oriented quantitative evaluation. Feng Zenghui et al. proposed a virtual-real combined experimental teaching method but only conducted single-round experimental verification. Chen Panpan et al. constructed a progressive teaching model but also lacked quantitative data support.

6.6 Comparison with Existing Research

Table 3. Comparison of This Study with Other Virtual Simulation Teaching Research

Dimension	Gao et al. [3]	Wang et al. [4]	Feng et al. [8]	Chen et al. [9]	This Study
Theoretical Basis	Not specified	Task-driven	Virtual-real combination	Three-stage progressive	Fitts-Posner three-stage
Teaching Mode	Platform demonstration	Task-driven	Virtual-real complementation	Progressive	Virtual-real integration, three-stage driving
Process Evaluation	None	None	None	None	OSI three-dimensional quantification
Quantitative Verification	Descriptive	Descriptive	Single-round experiment	Descriptive	Two-round comparative experiment
Effect Size Report	None	None	None	None	Cohen's d=1.32
Construction Process Coverage	Partial	None	Partial	None	Full process

In comparison, this study has the following significant advantages: First, it uses the Fitts-Posner three-stage skill learning theory as its theoretical foundation, providing a well-grounded teaching mode design. Second, it proposes an OSI three-dimensional quantitative evaluation system, achieving refined evaluation of the teaching process. Third, it conducts sufficient quantitative verification through two rounds of comparative experiments, with an effect size of Cohen's d reaching 1.32, significantly stronger than existing studies. Fourth, it covers full-process construction aspects including equipment installation, electrical wiring, and system commissioning, filling the gap in existing research on construction process simulation.

7. Conclusion

Hankou University, following the applied undergraduate education approach, incorporates five functional modules into virtual simulation experiment teaching through the "Industrial Robot Engineering Simulation" course, effectively addressing the shortcomings of traditional teaching regarding industrial robot workstation construction. Starting from the three-stage theory of skill learning proposed by Fitts and Posner, the teaching problems are analyzed, and a "virtual-real integration, three-stage driving" organizational form is proposed, with the OSI operational proficiency index used to quantify operational process progress. Results from two rounds of comparative experiments show that the experimental class demonstrates significant improvements across all indicators (scores, efficiency, satisfaction) compared to the control class (Cohen's d>1.3). Module-level analysis reveals that the virtual platform is particularly beneficial for construction-process-related tasks, and the OSI index shows strong predictive power for final practical performance (R^2=0.68). Therefore, the effectiveness of this method in promoting teaching quality is credible. Compared to existing literature, the innovations of this paper are as follows: designing a virtual-real combined teaching plan based on Fitts-Posner theory, proposing the OSI three-level quantitative standard, and providing comprehensive empirical evidence through two rounds of comparative experiments and effect size data. Limitations should also be acknowledged: The current platform only handles robot scenarios for handling tasks, with no corresponding modules for welding or spraying. Both rounds of experiments were limited to a single university, and the sample may not be broadly representative. Future plans include expanding workstation types, conducting multi-center comparative analysis with other universities, and providing more refined definitions for OSI weight parameters.

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