Case-Based Teaching Reform in Fundamentals of Control Engineering: A Practical Exploration

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Abstract

Addressing the pain points of "theory divorced from practice," "fragmented scenarios," and "insufficient innovation capability" in traditional control engineering teaching, this study constructs a case-based teaching reform framework of "three-dimensional integration" (multi-dimensional case repository, blended teaching model, virtual simulation platform). By introducing industrial-grade real-world cases (such as heating furnace temperature control, UAV attitude control) combined with the "5E" (Engage-Explore-Explain-Elaborate-Evaluate) blended teaching methodology, deep integration of knowledge transmission and capability cultivation is achieved. Quantitative evaluation demonstrates that students' system modeling accuracy, course design innovation, and theoretical examination excellence rates have all achieved substantial improvements after the reform. Qualitative research further reveals that students have achieved qualitative transformations in engineering thinking, teamwork, and lifelong learning capabilities. The study proposes constructing a "theory-case-practice-innovation" four-dimensional integrated teaching model, forming a demand-driven closed-loop talent cultivation system through industry-education integration to develop dynamic case repositories, digital twin technology to construct virtual-real fusion experimental platforms, and graduate tracking feedback optimization mechanisms, thereby providing a replicable reform paradigm for new engineering talent cultivation.

Full Text

Preamble

Exploring Case-Based Teaching Reform in *Fundamentals of Control Engineering*

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Abstract

To address the persistent challenges in traditional control engineering education —namely, the "theory-practice disconnect," "fragmented learning scenarios," and "inadequate innovation capacity" —this study constructs a "three-dimensional integrated" case-based teaching reform framework encompassing a multi-tiered case library, hybrid teaching model, and virtual simulation platform. By integrating industrial-grade authentic cases (e.g., heating furnace temperature control, UAV attitude control) with the "5E" (Engage-Explore-Explain-Elaborate-Evaluate) hybrid instructional approach, the reform achieves a profound fusion of knowledge transfer and competency development. Quantitative evaluations demonstrate significant improvements in students' system modeling accuracy, course design innovation, and excellence rates in theoretical examinations following the reform. Qualitative research further reveals qualitative transformations in students' engineering thinking, team collaboration, and lifelong learning capabilities. The study proposes establishing a four-dimensional "Theory-Case-Practice-Innovation" integrated teaching model, leveraging industry-academia collaboration to develop dynamic case libraries, digital twin technologies to construct virtual-real experimental platforms, and alumni tracking feedback mechanisms to form a demand-driven closed-loop talent cultivation system. This provides a replicable reform paradigm for nurturing talent in emerging engineering disciplines.

Keywords: Fundamentals of Control Engineering; Case-Based Teaching; Hybrid Learning; Multi-Tiered Case Library; Engineering Thinking

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1. Introduction

Fundamentals of Control Engineering, as a core curriculum for automation, mechatronics, and other engineering majors, bears the critical responsibility of cultivating students' ability to analyze and design engineering control systems. However, with the rapid development of emerging technologies such as intelligent manufacturing and industrial internet, traditional teaching models are facing unprecedented challenges. The prevalent phenomenon of "emphasizing theoretical derivation while neglecting engineering application" has resulted in students who can proficiently perform Laplace transforms and plot root loci yet struggle to comprehend how these mathematical tools apply to practical scenarios like temperature control systems or robotic motion control. Surveys indicate that over 65% of graduates report that engineering cases encountered during their studies were overly idealized, exhibiting significant discrepancies from the nonlinear, time-varying, and multi-interference characteristics of real industrial environments. This misalignment between acquired knowledge and industry demands directly forces companies to invest 6–12 months in specialized training for new hires in areas such as control system debugging and anti-interference design, substantially increasing talent development costs.

Further analysis reveals three deep-seated contradictions in traditional teaching models. First, the high abstraction of control theory contrasts sharply with the concreteness of engineering problems. Instruction on core topics such as frequency-domain analysis and state-space methods often remains detached from specific physical systems, plunging students into a learning dilemma of "studying mathematics for mathematics' sake." Second, knowledge delivery exhibits fragmented characteristics, with classical control theory, modern control methods, continuous systems, and discrete systems taught in isolation without engineering scenarios to connect them, preventing students from constructing a holistic cognitive framework of control systems. Third, one-way didactic teaching methods stifle innovative potential, with instructor-led derivations and software demonstrations dominating the classroom while students passively receive knowledge without opportunities for active inquiry. Consequently, students often demonstrate a lack of systematic thinking and insufficient innovation capacity when confronted with complex engineering problems.

In this context, case-based teaching, with its unique advantage of "using cases as carriers and problems as guides," has gradually emerged as a crucial direction for control engineering education reform. By introducing industrial-grade authentic cases, case-based teaching situates core components such as control system modeling, controller design, and performance optimization within specific engineering contexts, enabling students to naturally grasp the engineering significance of control theory through problem-solving processes. Assessment reports from the U.S. Accreditation Board for Engineering and Technology (ABET) reveal that graduates from control courses employing case-based teaching demonstrate significantly superior system-level problem-solving and interdisciplinary collaboration abilities compared to those from traditional teaching models. China' s "Emerging Engineering Education" construction guidelines also explicitly advocate for transforming engineering education from knowledge transmission to competency cultivation, building a deeply integrated "theory-practice-innovation" talent development system. Therefore, exploring case-based teaching reform in *Fundamentals of Control Engineering* represents not only a breakthrough innovation in traditional teaching models but also an inevitable choice for responding to national strategic needs and cultivating outstanding engineering talent.

2. Implementation Framework for Case-Based Teaching Reform

Based on the above problem analysis, this study constructs a "three-dimensional integrated" case-based teaching reform implementation framework (Figure 1 [Figure 1: see original paper]) centered on the core philosophy of "engineering problem orientation and progressive competency cultivation." This framework uses multi-level case library construction as its foundational support, achieves deep integration of theoretical teaching and engineering practice through a hybrid teaching model, and overcomes the spatiotemporal limitations of traditional experiments via a virtual simulation platform, forming a reform path of "case-driven, virtual-real integration, and competency advancement." Specific implementation strategies unfold across three dimensions—case resource development, teaching method innovation, and technology platform empowerment—to systematically address pain points such as case scarcity, fragmented scenarios, and limited verification methods in traditional teaching.

2.1 Multi-Dimensional Case Library Construction

Figure 1. "Three-Dimensional Integrated" Case-Based Teaching Reform Framework

In exploring case-based teaching reform for *Fundamentals of Control Engineering*, constructing a multi-dimensional and hierarchically structured case library proves essential for enhancing teaching quality and stimulating student interest and innovation. This case library design emphasizes not only diversity and representativeness but also applicability and heuristic value in the teaching process, aiming to guide students toward comprehensive mastery from fundamental theory to practical application, thereby cultivating their ability to solve complex engineering problems. Specifically, the case library is meticulously categorized into three types—basic verification, comprehensive application, and innovative research—based on case complexity, application domain, and innovation level, forming an organic whole that is both independent and interconnected.

Basic verification cases serve as the cornerstone of the case library, primarily selecting classic, easily understandable examples that intuitively reflect fundamental control principles, such as single pendulum systems and DC motor speed regulation. These cases typically feature simple structures and clear parameters, enabling students to experience firsthand the processes of control system construction, parameter adjustment, and performance analysis through experimental operations or simulation. This deepens their understanding and mastery of fundamental concepts, principles, and methods in control theory, establishing a solid theoretical foundation for subsequent study of more complex cases.

Comprehensive application cases focus on interdisciplinary knowledge integration and application, selecting complex systems spanning multiple engineering domains—such as UAV attitude control and intelligent greenhouse environmental regulation—as research objects. These cases demand not only solid control theory foundations but also mastery of multidisciplinary knowledge in mechanics, electronics, and computer science, requiring students to comprehensively apply various technical means to solve practical problems. Through engagement with comprehensive application cases and project practices, students develop interdisciplinary thinking and teamwork capabilities, learning how to design and implement efficient, stable control systems using system integration approaches in complex and dynamic environments, thereby enhancing their comprehensive ability to solve real engineering problems.

Innovative research cases represent the highlights and frontiers of the case library, focusing on cutting-edge domains such as industrial robot trajectory planning and intelligent manufacturing system optimization based on emerging technologies like digital twins and artificial intelligence. These cases are highly innovative and challenging, requiring students to possess not only profound theoretical foundations but also keen research insight and innovation capacity. Students must propose novel research ideas and methods while exploring unknown territories to solve technical challenges that traditional approaches cannot overcome. Through participation in innovative research cases, students can keep pace with technological development, cultivate a scientific spirit of exploration and innovation, and lay a solid foundation for becoming future leaders in control engineering.

2.2 Case Design Principles

In the practice of case-based teaching reform for *Fundamentals of Control Engineering*, case design constitutes the core element of the teaching system, with its quality directly determining students' ability to transfer theoretical knowledge and develop practical innovation literacy. To ensure that case teaching both carries the systematic nature of control theory and stimulates student initiative, we follow the integrated design principle of "authenticity-gradation-openness" to construct a case matrix with engineering depth.

Authenticity in cases is key to breaking the barrier between theory and practice. Using a steel plant heating furnace temperature control system as a prototype, we completely transplanted multi-source heterogeneous data from actual production: real-time furnace temperature curves measured by thermocouples (including raw fluctuation data at 200Hz sampling frequency), PID control loop parameters for fuel and air flow (including implementation code for integral separation and anti-windup mechanisms), and temperature-time curves required by workpiece heat treatment processes (including piecewise control strategies for phase transformation critical points). This data not only retains noise interference and nonlinear characteristics from industrial sites but also, by reconstructing real production accident scenarios such as "temperature overshoot causing steel plate grain coarsening," enables students to intuitively understand the quantitative relationship between control precision and product quality. For instance, when analyzing the heating furnace regenerator temperature control case, students must handle dynamic models containing 12 types of disturbance factors, including fuel calorific value fluctuations, reversing valve action delays, and flue gas waste heat recovery efficiency variations. This complexity far exceeds the simplified "ideal sensor + linear object"assumptions in traditional teaching cases, forcing students to apply advanced theories such as frequency-domain analysis and robust control for system decoupling and compensation design.

Gradation design constructs a cognitive ladder from basic understanding to comprehensive innovation. The case system begins with single-input single-output (SISO) control systems, using typical cases such as heating furnace gas pressure control and cooling water flow regulation to help students master core skills like PID parameter tuning and stability criterion application. It then gradually introduces multi-input multi-output (MIMO) systems—for example, heating furnace combustion control systems require simultaneous coordination of gas/air flow ratio and furnace pressure, where students must analyze coupling relationships between variables using relative gain arrays and achieve multi-loop coordination through feedforward compensation and decoupling control strategies. Finally, at the comprehensive case stage, using heating furnace full-process optimization as an example, students are required to integrate multiple subsystems including temperature, pressure, and flow, and design hierarchical control systems under multi-objective constraints such as energy consumption, equipment lifespan, and production rhythm. This spiral case arrangement conforms to cognitive patterns while forcing students to transition from "parameter tuners" to "system architects" through exponentially increasing problem complexity.

Openness design provides flexible space for personalized learning. Each case reserves multi-dimensional parameter adjustment interfaces: at the model level, students can modify time constants and gain coefficients in object transfer functions to observe changes in system dynamic characteristics; at the algorithm level, they can replace PID controllers with intelligent algorithms such as fuzzy control or neural network control to verify the adaptability of different control strategies through comparative experiments; at the engineering constraint level, they can adjust hardware parameters such as sensor accuracy and actuator dead zones to analyze their impact on system robustness. For example, in the heating furnace temperature control case, students discovered that when thermocouple measurement delay increased from 5 seconds to 15 seconds, the overshoot of traditional PID control surged by 47%, while introducing a predictor could suppress overshoot to within 8%. This inquiry-based learning model of "parameter perturbation-phenomenon observation-theoretical verification" not only deepens students' understanding of control theory fundamentals but also cultivates their ability to abstract and model engineering problems. Through open case design, the teaching team observed student-initiated innovative solutions such as "variable-parameter PID control based on furnace temperature prediction" and "adaptive compensation strategies considering fuel calorific value fluctuations," fully validating the stimulating effect of open architecture on innovative thinking.

2.3 Hybrid Case Teaching Model

In the pre-class phase of the hybrid case teaching model, the instructor team constructs a multi-dimensional preview resource system based on a smart teaching platform. The digital case manual released includes not only three-dimensional interactive models of inverted pendulum systems (such as the gyroscope model in inertial navigation systems shown in Figure 2 [Figure 2: see original paper]), which support multi-angle rotation and cross-sectional observation of mechanical structure details, but also dynamic simulation modules developed based on MATLAB/Simulink. Students can independently adjust PID parameter combinations and observe real-time changes in system response curves, intuitively experiencing the nonlinear relationships between key indicators such as overshoot and settling time and control parameters.

Figure 2. Example of 3D Interactive Model

Combined with the pre-research question chain pushed through the teaching platform, instructors assign the core task of "analyzing influencing factors of slider-pendulum systems" (as shown in Figure 3 [Figure 3: see original paper]), decomposing it layer by layer into sub-problems covering mechanical parameters (e.g., pendulum rod length, moment of inertia), actuator characteristics (motor response bandwidth, output torque), and sensor precision (encoder resolution, sampling frequency). Each question is equipped with theoretical hint cards to guide students in conducting preliminary analyses using tools such as the Routh criterion and root locus method, and submitting mind maps through the platform discussion area. The system automatically collects behavioral data including model operation frequency and simulation parameter adjustment ranges, generating cognitive heatmaps that help instructors accurately identify common misconceptions and provide a basis for differentiated in-class instruction.

Figure 3 [Figure 3: see original paper]. Slider-Pendulum Case

The in-class phase employs the "5E" teaching model to construct an immersive learning environment. For example, during the Engage phase, instructors play real-world test videos of Tesla' s Autopilot system failing to maintain lane position under strong crosswind conditions, presenting engineering details such as sudden lateral displacement and control output saturation through first-person perspective footage to provoke deep reflection on "robust control boundaries." Subsequently, in the Explore phase, students work in groups to operate physical inverted pendulum experimental platforms, applying classical tuning strategies such as trial-and-error and Ziegler-Nichols methods for parameter optimization. Each group uploads experimental data in real-time via wireless sensors to a central monitoring system, with large screens dynamically displaying comparative control effect curves from all groups to create a healthy competitive mechanism. In the Explain phase, instructors systematically elaborate on the engineering significance of frequency-domain analysis in control system design, using student experimental data to plot open-loop Bode diagrams, explain the quantitative relationship between phase margin, gain margin, and system stability, and contrast the intrinsic correlations between time-domain indicators (e.g., overshoot) and frequency-domain indicators (e.g., resonant peak). The Elaborate phase introduces Model Predictive Control (MPC) for comparative analysis, demonstrating how MPC algorithms overcome traditional PID control' s sensitivity to model errors through rolling optimization with multi-step prediction, and guiding students to compare robustness differences between the two control strategies under parameter perturbations through simulation. Finally, in the

Evaluate phase, students use smart terminals to log into a real-time voting system, quantitatively scoring each group' s solution across three dimensions: stability, rapidity, and robustness. The system automatically generates radar charts displaying comprehensive solution performance, and instructors provide targeted feedback based on voting results to reinforce students' engineering cognition regarding trade-offs among control performance metrics.

The post-class phase constructs a closed-loop improvement mechanism of "practice-feedback-iteration." Instructors assign engineering-open-ended modification tasks, such as adding anti-interference modules to existing inverted pendulum cases, requiring students to comprehensively apply advanced control strategies including feedforward compensation and disturbance observers for system upgrades. Students can upload multimedia materials including solution documents, simulation model files, and experimental videos. Instructors regularly organize online defense sessions, awarding honors such as "Best Innovation Award" and "Most Engineering Value Award," with outstanding works being incorporated into the case library and credited to creators, forming a continuously motivating innovation ecosystem.

This three-stage progressive model of "pre-class precise preview—in-class deep exploration—post-class iterative optimization" effectively addresses core issues in traditional case teaching, including "theory divorced from engineering practice, insufficient student engagement, and discontinuous innovation capacity cultivation," providing a replicable hybrid teaching paradigm for control engineering talent development.

3. Analysis of Teaching Reform Effectiveness

3.1 Quantitative Evaluation Data

To systematically verify the actual effectiveness of the hybrid case teaching model, the research team conducted comparative experiments across four consecutive cohorts of control engineering students from 2019 to 2022. The 2019–2020 cohorts served as the traditional teaching control group (using classroom lectures + verification experiments), while the 2021–2022 cohorts constituted the case teaching reform experimental group (implementing the "three-dimensional case library + 5E hybrid teaching" system). A multi-dimensional evaluation index system was constructed for quantitative comparative analysis across three dimensions: knowledge mastery, competency enhancement, and innovation literacy.

Table 1 . Quantitative Data from 2019-2022 Cohorts

Metric	Traditional Class	Case-Based Class
System Modeling Accuracy	68%	89.7%
Course Design Innovation Score	2.1/5	3.8/5
Theoretical Exam Excellence Rate	15%	28%

In system modeling competency assessment, the experimental group achieved 89.7% accuracy in mathematical modeling of complex systems, representing a 32% improvement over the control group' s 68%. Specifically, in inverted pendulum system modeling tasks, experimental group students more accurately identified nonlinear elements (e.g., friction dead zones, motor saturation characteristics) and reasonably applied small-disturbance linearization methods for simplification. In the heating furnace temperature control case, experimental group students' dynamic models incorporated 12 types of practical disturbance factors including fuel calorific value fluctuations and reversing valve action delays, whereas control group models averaged only 4 simplified disturbances. This difference directly reflected in course design quality—the experimental group' s mean innovation score reached 3.8/5, an 81% improvement over the control group' s 2.1/5, yielding numerous innovative achievements in university innovation programs and competitions.

Comparative data on theoretical assessment scores further confirmed the deep effects of the teaching model reform. The experimental group's theoretical exam excellence rate ($ $85 points) increased from 15% in the control group to 28%, a remarkable 87% improvement. More notably, the score distribution pattern changed significantly: the control group exhibited a typical normal distribution with 62% of students in the middle range, while the experimental group showed a "left-skewed heavy-tail" characteristic, with 54% of students scoring above 80 points and a 41% reduction in low-scoring (<60) students. This transformation stems from case teaching' s cultivation of higher-order thinking skills—in frequency-domain analysis assessments, experimental group students more flexibly applied Nyquist criteria to analyze stability of systems with delay elements, with phase margin calculation errors in their Bode plots controlled within $±$3° (compared to $±$8° average error in the control group). In optimal control theory application problems, 37% of experimental group students considered actuator saturation constraints in their solutions, versus only 8% in the control group.

The data reflects a profound paradigm shift: the "problem-driven—theoretical verification—engineering iteration" cognitive mode formed by experimental group students through case discussions enables them to more actively transform control theory into tools for solving practical problems. For example, in the UAV attitude control case, experimental group students spontaneously proposed upgrading traditional PID control to adaptive fuzzy-PID composite control by introducing air density sensors for real-time parameter correction. This transformation from "passive acceptance" to "active creation" represents the core educational achievement of the hybrid case teaching model through reconstruction of authentic engineering scenarios and construction of multi-dimensional cognitive scaffolds.

3.2 Student Interview Analysis

To further reveal the deep educational value behind the quantitative data, the research team conducted in-depth interviews with 28 stratified sampled students from the experimental group, covering different academic performance levels (top 25%, middle 50%, bottom 25%) and gender ratios. Interview content focused on three dimensions: "knowledge transfer ability," "engineering thinking development," and "learning motivation transformation."

1. Knowledge Structure Transition from Fragmented to Systematic

The majority of students (21/28) noted that the dynamic simulation models and physical experimental platforms in the three-dimensional case library formed a "virtual-real integrated" cognitive closed loop. For example, when analyzing inverted pendulum system stability, one student stated: "The Routh criterion I used to memorize by rote now comes alive when I adjust the pendulum rod length parameters in the 3D model and visually observe the trajectory of characteristic roots moving across the complex plane." This cognitive shift becomes particularly significant when solving complex engineering problems—when asked to design a boiler liquid-level control system, experimental group students proactively constructed complete models incorporating 8 subsystems including steam flow disturbances and water supply valve nonlinearities, whereas control group students mostly remained at the simplified level of single-input single-output analysis.

2. Engineering Thinking Transformation from "Problem-Solving" to "Problem Resolution"

Interviews revealed that the "5E" inquiry segments in case teaching effectively cultivated students' systematic engineering thinking. After discussing the "Tesla Autopilot failure case," 75% of students spontaneously attempted to apply "fault tree analysis" to decompose problems: deriving from sensor noise (root node) through intermediate nodes such as insufficient control algorithm robustness to propose composite solutions. More notably, when asked "what if parameter tuning fails," experimental group students demonstrated stronger engineering fault tolerance awareness—19 proposed adopting a "progressive parameter debugging method" that first ensures system stability before optimizing dynamic performance, while only 5 control group students offered similar strategies, with most others trapped in trial-and-error cycles of "tuning—crash—retuning."

3. Learning Motivation Shift from External to Internal Value Recognition

Online case community interaction data strongly corroborates interview findings: experimental group students logged into the community an average of 3.2 times per week, with 63% actively sharing technical documents, far exceeding the control group' s passive downloading frequency of 0.8 times per week. When asked why they were willing to invest extra time optimizing cases, students commonly responded: "The sense of achievement when seeing my improved PID algorithm reduce the inverted pendulum' s swing amplitude by 40% is more lasting than high exam scores," and "When receiving improvement suggestions from students at other schools in the community, I suddenly realized that control engineering isn' t isolated formulas but technology that can truly change reality." This value recognition directly translates into sustained learning motivation—experimental group students' self-directed post-class learning covers frontier areas including reinforcement learning control (14 students) and industrial network communications (9 students), whereas control group students' post-class learning remained focused on textbook chapter review.

4. Conclusion

The case-based teaching reform in control engineering effectively promotes the transformation of knowledge into competency through immersive experiences in authentic engineering contexts. This transformation manifests not only in students' deep understanding and flexible application of core theories such as system modeling and frequency-domain analysis but more significantly in the migration of their engineering thinking from a "textbook paradigm" to a "field paradigm"—students begin actively focusing on practical engineering details like sensor noise suppression and actuator saturation constraints, and can apply the engineering methodology of "problem decomposition—theoretical mapping—solution iteration" to solve complex control problems. Simultaneously, the hybrid teaching model reconstructs the learning ecology from "instructor-dominated" to "student-centered," with the continuous operation of online case communities and cross-institutional collaboration mechanisms fostering a new learning culture of "self-organized learning—collective wisdom co-creation," systematically enhancing students' teamwork and technical communication abilities.

Future efforts must continuously improve the case ecosystem by constructing a four-dimensional "Theory-Case-Practice-Innovation" integrated teaching model. On one hand, we must deepen industry-academia integration, collaborating with leading enterprises to develop "living cases" that incorporate new technologies such as 5G communications and industrial internet into the case library, ensuring teaching content resonates with industry needs. On the other hand, we must strengthen digital technology empowerment, utilizing digital twin technology to construct virtual-real integrated experimental platforms that enable full-process digitization of "case design—simulation verification—physical debugging," lowering technical barriers for student exploration and innovation. Additionally, we should establish long-term feedback mechanisms, dynamically optimizing case design through graduate tracking surveys and enterprise satisfaction evaluations, ultimately forming a demand-driven, case-supported, competency-oriented closed-loop talent cultivation system that provides a replicable and scalable reform paradigm for emerging engineering talent development.

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Note: Figure translations are in progress. See original paper for figures.