An Educational Platform for Real-Time Control and Reinforcement Learning Experiments Using Rotary Inverted Pendulum and LW-RCP

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Abstract: This paper presents an integrated experimental platform for hands-on education in control engineering, built around a compact rotary inverted pendulum system based on a stepper motor and a Simulink-based Light Weight Rapid Control Prototyping (LW-RCP) environment. The proposed platform supports real-time implementation of a wide range of control experiments, including current-based vector control, nonlinear swing-up control, linear stabilization, and reinforcement learning-based control. The hardware consists of a rotary inverted pendulum made with 3D-printed components and a hollow-shaft stepper motor, incorporating a compact inverter realized through an L6234 motor driver. Its compact and lightweight design allows for tabletop experimentation, enabling one-device-per-student operation and enhancing scalability in education. On the software side, users can design controllers and collect real-time data through Simulink's block-based modeling interface without coding. Moreover, Python integration enables sim-to-real experiments with reinforcement learning controllers. This platform complements traditional theory-centric control engineering education by offering rich hands-on experiences, thereby increasing student motivation and fostering a deeper conceptual understanding through the full process of controller design and system response analysis.

1 INTRODUCTION

Control engineering has long been a fundamental discipline in engineering education, traditionally focusing on theory-oriented curricula such as mathematical modeling of systems, frequency response analysis, and controller design using state-space methods. These conventional approaches often rely on simulation environments to help students understand controller behavior indirectly. However, in modern industrial applications, engineers are expected to possess practical capabilities to control complex and nonlinear systems in real-time (Iqbal et al., 2017; Faulwasser et al., 2017; Han and Qiao, 2014). Fields such as drones, autonomous vehicles, and industrial robotics demand not only theoretical knowledge but also the ability to implement controllers that account for real-world constraints. Consequently, the direction of engineering education has been shifting from passive theoretical instruction to hands-on, experiment-driven learning, where students actively design controllers and validate their performance through experiments (Lei et al., 2022; Framing et al., 2020; Precup et al., 2011).

However, to effectively implement hands-on education in real-world control engineering classrooms, it is essential to provide students with a hardware-based experimental environment that enables direct physical interaction with control targets. Despite its importance, the widespread adoption of such environments is hindered by the high cost of experimental equipment and limited infrastructure. For instance, some universities utilize advanced instructional systems such as the Rotary Inverted Pendulum from Quanser (Quanser Consulting Inc., 1990) or the MicroAutoBox from dSPACE (dSPACE Inc., 1991), but these systems entail high financial costs—often ranging from thousands to tens of thousands of dollars—as well as operational complexity and spatial constraints, limiting their scalability and accessibility in educational contexts. Rapid Control Prototyping (RCP) has already been actively employed in fields such as mechatronics (Deppe et al., 2004; Isermann, 2008), automotive dynamics control (Lee et al., 2004), and precision motion control (Hercog and Jezernik, 2005; Bodo et al., 2024), where it has

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demonstrated high effectiveness in rapid controller design and iterative testing using real hardware systems. Although this methodology has clear potential for educational applications, the high entry barriers associated with conventional educational platforms have prevented its widespread adoption in academic settings. As a result, many students are limited to simulation-based learning or passive observation of instructor-led demonstrations, thereby missing the opportunity to experience real-time controller implementation and feedback-driven design processes firsthand.

To address these limitations, this paper proposes an integrated educational platform consisting of a compact rotary inverted pendulum system driven by a stepper motor and a Simulink-based Light Weight Rapid Control Prototyping (LW-RCP) environment (Lee et al., 2017). The hardware configuration includes a hollow-shaft stepper motor, an L6234 three-phase inverter circuit, a pendulum sensor, and an analog current sensor, all assembled using cost-effective 3D printing techniques. The stepper motor exhibits synchronous motor characteristics, making it suitable for experimental learning in various control techniques such as current regulation, vector control, and PWM-based speed control. The pendulum's sensor data is transmitted through a slip ring passing through the central axis of the motor. Owing to its compact and lightweight design, the system can be operated independently on a tabletop, enabling a one-device-per-student setup. This facilitates an accessible and scalable experimental environment, thereby offering a practical alternative to cost-intensive educational solutions.

In addition, on the software side, the Simulink-based LW-RCP environment allows users to design and execute control algorithms in real time using a block diagram approach without requiring complex programming. The system supports high-frequency control loops operating at approximately 2 kHz and integrates essential real-time functionalities such as PWM generation, current feedback, and velocity response measurement into modular blocks. This enables users to intuitively construct control loops, perform parameter tuning, and visualize system responses in real time. Furthermore, integration with Python allows the deployment of reinforcement learning-based controllers in sim-to-real experiments. As a result, the platform extends its instructional scope beyond traditional control theory to include cutting-edge AI-based control strategies. Ultimately, this integrated framework enables students to engage in the complete cycle of control system design, implementation, and evaluation, fostering deeper conceptual understanding and enhancing motivation through hands-on learning in control engineering.

This paper systematically describes the design principles and overall system architecture of the proposed control education platform and evaluates its educational effectiveness and practical learning outcomes through a set of representative experiments. Section 2 discusses the hardware structure of the rotary inverted pendulum system based on a stepper motor, including mechanical design elements and essential techniques for implementing current and vector control. Section 3 elaborates on the software aspects of the Simulink-based LW-RCP environment, such as control loop design, real-time data acquisition, and Python integration. Section 4 presents two major experimental applications conducted on the proposed platform:(1) energy-based swing-up followed by LQR stabilization using vector control, and (2) swing-up control of the rotary inverted pendulum using a reinforcement learning controller trained via a sim-to-real approach. These experiments demonstrate the platform's practicality and expandability in supporting both classical and modern control strategies. Finally, Section 5 summarizes the educational significance and current limitations of the platform, and discusses its potential applications and future directions in control engineering education.

2 DESIGN AND EDUCATIONAL FEATURES OF A ROTARY INVERTED PENDULUM SYSTEM USING A STEPPER MOTOR

To simultaneously achieve hardware simplicity and scalability for educational use, the proposed platform is built around a stepper motor-based rotary inverted pendulum system. Figure 1 illustrates a conceptual diagram of the system, designed to provide an intuitive understanding of its operating principle. The complete hardware setup consists of a 3D-printed frame, a hollow-shaft stepper motor, a three-phase inverter based on the L6234 driver, and a single-board microcontroller serving as the control interface. The platform is compact and lightweight enough for tabletop use, and all components can be easily sourced from standard electronics markets. Furthermore, the total cost remains within an affordable range of several tens of thousands of Korean won, making it feasible to implement one-device-per-student configurations for hands-on control education.

The rotary inverted pendulum typically requires

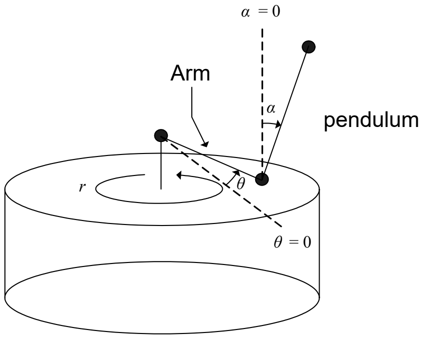

Figure 1: Conceptual diagram of the rotary inverted pendulum system.

one motor for arm rotation and two encoders to measure the angular positions of both the arm and the pendulum rod. Additionally, a slip ring is commonly required to enable unlimited rotation. However, applying such a configuration to a compact platform often leads to increased mechanical complexity and higher component costs. To address this issue, this study proposes a hardware structure centered around a hollow-shaft stepper motor. This type of motor offers high design flexibility for rotary experimental setups such as inverted pendulums, allowing the pendulum rod to be directly mounted through the motor's central shaft. A slip ring can be integrated within the shaft to securely transmit sensor signals that capture the pendulum's angular motion. This design effectively minimizes potential hardware failures during experiments, such as cable twisting, signal loss due to poor contact, and sensor noise. Furthermore, it simplifies maintenance. Figure 2 illustrates the structural concept of the rotary inverted pendulum reflecting this design approach.

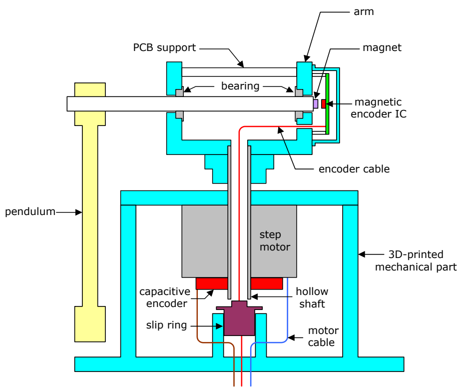

Figure 2: Conceptual structural diagram of the proposed rotary inverted pendulum.

The actual appearance of the fabricated rotary inverted pendulum is presented in Fig.3, where the overall structure and design features for miniaturization of the proposed system can be intuitively observed. The pendulum unit is approximately 17cm in height and 7 cm in width, and the base has been designed with a wider footprint to ensure stability against reaction torques.

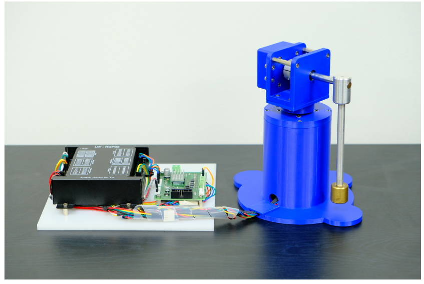

Figure 3: A rotary inverted pendulum constructed in the laboratory.

The stepper motor is typically operated in an open-loop configuration; however, in this system, precise control of the phase currents enables the experimental implementation of various closed-loop strategies such as vector control, current control, and PWM-based speed control. This is based on the theoretical interpretation of the stepper motor as a synchronous motor, thereby providing a pedagogical environment in which students can experiment with and compare different control techniques on a physical system.

One of the most valuable educational features of the stepper motor is its ability to visualize the relationship between control inputs and physical responses in an intuitive manner. The one-to-one correspondence between pulse count and angular displacement, as well as the linear relationship between current commands and torque generation, enables a foundational understanding of system response. Through position and speed control experiments, students can directly observe the effects of control algorithms in real-time, facilitating a shift from theoretical modeling to practical system understanding. This structural and functional simplicity lowers the entry barrier for beginners while offering a scalable experimental platform for advanced learners to explore complex control strategies.

Furthermore, the system is also well-suited for experiments in system modeling and parameter estimation. Electrical parameters of the motor (e.g., resistance and inductance) and mechanical parameters (e.g., inertia and friction coefficients) can be empirically identified from experimental data. This supports white-box modeling approaches that foster deeper physical understanding of control systems and meet the goals of practice-oriented education. Unlike black-box approaches, this integration of experiment and modeling reinforces students' insight into the physical structure of the system.

In summary, the proposed platform provides a compact, simplified, and cost-effective hardware architecture that fulfills key practical requirements in control engineering education without reliance on expensive laboratory equipment. It enables learners to engage directly with core concepts such as actuator control, system identification, and feedback design, thus creating a unified educational framework that bridges theory, practice, design, and application.

3 REAL-TIME CONTROLLER IMPLEMENTATION USING LW-RCP

Traditional methods of real-time controller development require implementing control algorithms in C on a microcontroller and manually configuring hardware components such as PWM, ADC, timers, and interrupts. This workflow demands advanced programming skills and often distracts learners from the core principles of control design, redirecting their focus toward low-level debugging and peripheral handling. In educational settings where the objective is to link theoretical knowledge to practical systems, such complexity can become a barrier to effective learning. To address these issues, this study introduces a Simulink-based Light Weight Rapid Control Prototyping (LW-RCP) environment, integrated with a rotary inverted pendulum system. The environment enables intuitive and iterative hands-on real-time control experiments without requiring low-level coding. LW-RCP, developed in-house, allows users to construct control systems graphically using block diagrams while seamlessly interfacing with the hardware.

This environment has been successfully applied in various experimental control tasks, including the control of a rotary double inverted pendulum using direct collocation, and sim-to-real reinforcement learning experiments on a linear double pendulum system (Lee et al., 2025; Ju et al., 2025).

The control loop constructed in Simulink communicates in real-time with the LW-RCP hardware via USB, supporting a high-frequency control rate of up to 2 kHz. Since the stepper motor used in the rotary inverted pendulum can be interpreted as a synchronous motor, each phase current can be precisely regulated to implement advanced control strategies such as vector control, current control, and PWM-based speed control. This enables students to go beyond simple position control and intuitively learn current-based vector control architectures widely adopted in industrial systems. Figure 5 illustrates an example configuration of core blocks provided in the LW-RCP environment. Students can easily construct position and velocity feedback loops using blocks such as ENC, PWM, and FREQ, and conduct experiments by assigning reference inputs via analog channels while observing system responses in real time. Additionally, Figure 6 presents the integrated hardware setup, where the LW-RCP control board and motor driver circuit are mounted together on a single platform.

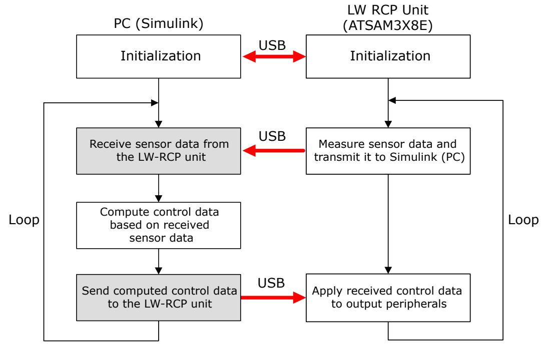

Figure 4: Real-time execution and hardware interaction process in LW-RCP.

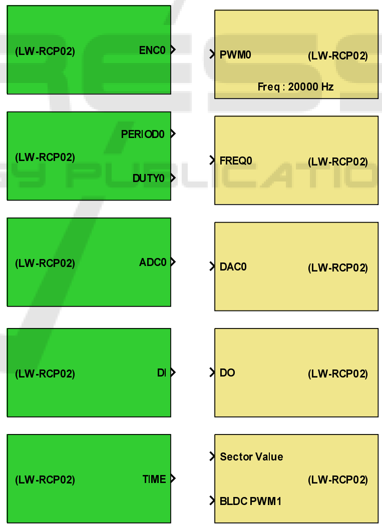

Figure 5: Simulink blocks for I/O and real-time control in LW-RCP.

The real-time control experiments enabled by LW-RCP significantly broaden the scope of control theory application and offer structured opportunities for comparative learning of diverse control strategies. First, through vector control experiments with stepper motors, students can learn how torque is generated from current references to drive the pendulum arm precisely. TThis fosters an intuitive understanding of how current, speed, and position are linked within the feedback loop. Second, swing-up and stabiliza-

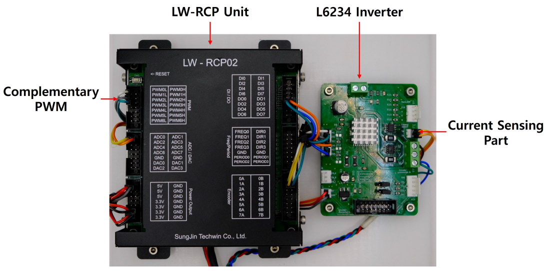

Figure 6: Control board integrating LW-RCP and motor driver.

tion control experiments allow learners to implement and compare nonlinear energy-based controllers and linear LQR-based stabilizers, as well as reinforcement learning (RL) control policies. Simulink's S-Function and Stateflow tools enable students to construct condition-based switching logics with block-based modeling. Third, the platform supports model-based control design. Electrical parameters (e.g., resistance, inductance) and mechanical parameters (e.g., inertia, friction) of the motor can be estimated from real experimental data and incorporated into dynamic models for designing state-space controllers. This approach goes beyond black-box modeling to cultivate white-box modeling and control synthesis skills. Finally, Python integration allows sim-to-real experimentation, where RL policies trained in simulation can be transferred to physical systems. This provides hands-on exposure to both classical and modern AI-based control strategies and allows students to evaluate the feasibility and limitations of neural-network-based control in real-time environments.

Ultimately, LW-RCP functions not merely as an experimental tool but as a practical medium for control engineering education. When combined with the proposed rotary inverted pendulum system, it enables repetitive, individual experimentation and fosters autonomous learning of the entire feedback process: controller design, implementation, verification, tuning, and response analysis. This hands-on setup bridges the gap between theory and practice by addressing real-time system behavior and hardware responsiveness—key elements often overlooked in simulation-centric curricula.

4 VECTOR-CONTROL-BASED EXPERIMENTS WITH A ROTARY INVERTED PENDULUM

This section presents three representative control experiments conducted using the proposed experimental platform to validate the connection between control theory and real-world implementation and to demonstrate its effectiveness in practice-based education. All experiments were implemented in real-time using the Simulink-based LW-RCP environment. The hardware platform consisted of a stepper motor-based rotary inverted pendulum system, an L6234 inverter, current sensors, and an analog input interface. The experiments focused on the following two strategies:(1) energy-based swing-up using vector control for speed regulation, and (2) sim-to-real application of a reinforcement learning-based controller.

In the first experiment, a vector-control-based speed controller was implemented for the stepper motor driving the arm of the rotary inverted pendulum, and this controller was used to realize an energy-based swing-up control strategy. The stepper motor was modeled as a synchronous motor, and the current references generated in the d-q coordinate frame were transformed via a Park transformation and modulated using space vector pulse width modulation (SVPWM) before being transmitted to the L6234 motor driver. Closed-loop control was achieved through real-time current feedback (Yang et al., 2003). The entire control algorithm was implemented in Simulink using block diagrams, with a control cycle set to 2 kHz. Figure 7 illustrates the Simulink implementation of the speed controller, and Figure 8 shows the SVPWM modulation and signal output structure. The swing-up control strategy was based on the energy-shaping method proposed by Åström and Furuta (Åström and Furuta, 2000), which gradually increases the pendulum's kinetic energy until it reaches a critical threshold. The controller estimates the current energy of the pendulum using its position and velocity, then adjusts the control input to compensate for the energy gap relative to the reference value. Figure 9 presents the structure of this energy-based control algorithm and visualizes the measured pendulum angle and velocity response. The experiment showed that the pendulum, starting from a downward-hanging position, accumulated energy through successive motor actions, reached the required energy level, and successfully transitioned to the upright position. Afterward, the control was switched to a Linear Quadratic Regulator (LQR) based on a linearized state-space model, and the pendulum maintained its upright equilibrium reliably. This experiment allows students to experience the integrated process of applying both nonlinear energy-based and linear state-space-based control strategies to a real-time system, thereby bridging the gap between theoretical understanding and practical implementation.

The second experiment involves a sim-to-real

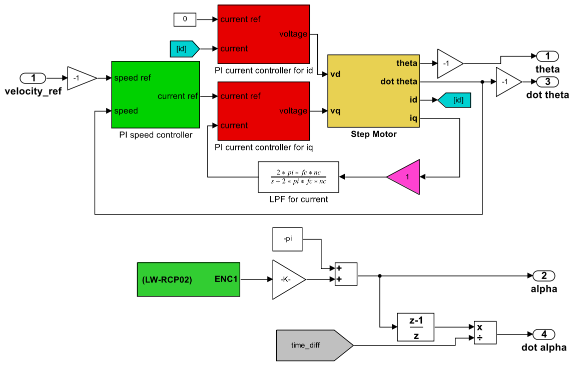

Figure 7: Simulink model of vector-control-based speed controller for swing-up energy control.

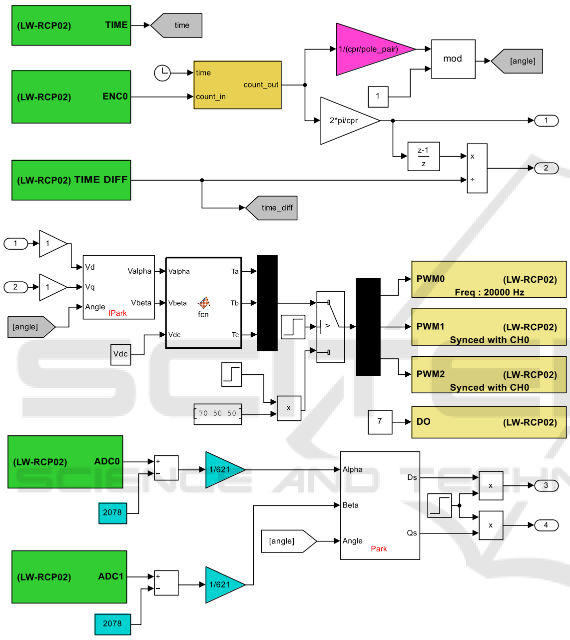

Figure 8: SVPWM generation block diagram converting dq-axis current commands.

transfer of a reinforcement learning (RL) policy trained in a Python environment to a real-world control platform. An agent trained using the Truncated Quantile Critics (TQC) algorithm (Kuznetsov et al., 2020) in a Python-based simulation was exported and deployed on the physical system. Real-time control commands were transmitted to the LW-RCP hardware via MATLAB Simulink, enabling the learned policy to operate the platform. The system receives torque and pendulum angle measurements as input and applies the RL model's output as PWM signals to the hardware. To minimize the sim-to-real transfer gap, physical factors such as friction and sensor noise were incorporated into the simulation model. Experimental results confirmed that the trained policy successfully executed both swing-up and balance control on the

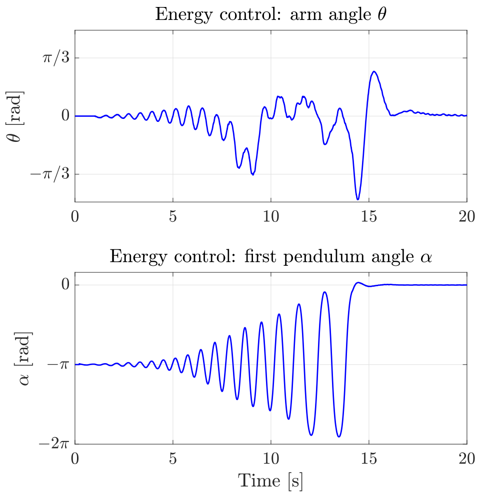

Figure 9: Experimental results of energy-based swing-up control.

real system. Specifically, the controller gradually increased the pendulum's energy and then stabilized it at the upright position by damping oscillations near the equilibrium. The control behavior is visualized in Figure 10, offering learners a direct and quantitative understanding of the gap between theoretical RL-based control and its real-world deployment.

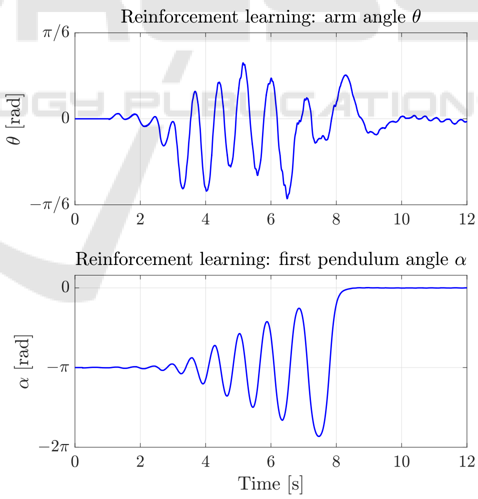

Figure 10: Execution of swing-up and stabilization tasks using a TQC-trained reinforcement learning.

Through the above experiments, it was verified that the proposed platform provides an environment capable of implementing and comparing a wide range of control strategies in real time—from classical vector control-based speed control and mathematically designed optimal control to data-driven reinforcement learning approaches. This integration of control theory with physical systems allows learners to validate the effectiveness of each strategy through experimentation and develop practical intuition for controller design. In particular, by experiencing the performance differences and implementation constraints of each control method firsthand, the platform demonstrates its potential to realize an experiment-centered educational environment that goes beyond traditional simulation-based learning.

5 CONCLUSION

This paper proposed a hands-on educational platform for control engineering that integrates a stepper-motor-based rotary inverted pendulum system with a Simulink-based Light Weight Rapid Control Prototyping (LW-RCP) environment. The proposed platform was validated through experiments that demonstrated both its design principles and educational effectiveness. By incorporating a hollow-shaft stepper motor, a low-cost L6234 motor driver, and a 3D-printed frame, the platform offers an affordable, compact, and scalable hardware solution. All components are easily obtainable from commercial markets, and the system is designed to support one-device-per-student deployment for large-scale classroom use.

On the hardware side, interpreting the stepper motor as a synchronous motor allows students to engage in advanced control practices such as current and vector control, extending their learning beyond basic position control toward current-based strategies used in industrial systems. Coupled with the Simulink-based LW-RCP environment, students can visually implement real-time controllers without writing code, perform parameter tuning, and analyze system responses in a fully autonomous manner. Moreover, Python integration enables sim-to-real transfer of reinforcement learning (RL) policies, offering intuitive and hands-on experiences with modern AI-based control techniques.

Experimental demonstrations included vector-control-based swing-up, LQR-based stabilization, and RL-based policy control, highlighting the platform's versatility in supporting diverse control strategies. These experiments allowed learners to compare different approaches under realistic constraints and to gain a deeper understanding of real-time control implementation. The integration of both classical and modern methods creates a meaningful bridge between theoretical concepts and practical execution.

Most importantly, the platform's educational significance lies in enabling students to experience the full process of controller design, system implementation, real-time experimentation, and data-driven analysis. This end-to-end learning cycle not only reinforces motivation but also helps translate abstract theory into real-world applications. It serves as an effective path toward fostering practical control engineering skills and can be regarded as a valuable example of hands-on engineering education.

Future work may extend the platform into remote laboratories and modular kits applicable to various physical systems. Control engineering education is expected to evolve into a more intuitive and personalized direction with such platforms, contributing significantly to the realization of a learner-centered educational paradigm that integrates theory, practice, design, and implementation.

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