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Research on the Teaching Reform of Automatic Control Theory Course Based on Robotic Systems

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ABSTRACT

This paper examines the integration of robotic systems into the teaching of Automatic Control Theory, highlighting the impact of hands-on learning. It discusses the course implementation from three key aspects: curriculum design and optimization, the creation of robot control system projects, and the development of robotic platforms. The curriculum is tailored to the Electronic Information Engineering program at Hebei North University, incorporating a robot project library and knowledge base to support student projects. Three robotic platforms, a bionic hexapod, an underactuated robotic arm, and an automatic track-following car have also been developed. Incorporating these systems has significantly enhanced student motivation and improved learning outcomes.

KEYWORDS

Automatic Control Theory; robotics; teaching reform; project-based learning

1 Introduction

The Automatic Control Theory course is a foundational and critical component for engineering majors, characterized by its dual emphasis on theoretical understanding and practical application. It holds a central position within the curriculum of related disciplines, serving as a cornerstone for developing essential engineering competencies. Over the years, numerous scholars have made significant contributions to the reform and innovation of this course, proposing various teaching methodologies and frameworks. Professor Wang Wanliang[1] from Zhejiang University of Technology conducted an in-depth analysis of key issues in the course ' s pedagogy, offering valuable insights into the organization of teaching content and the construction of textbooks. Xu Yingqin[2] from Jiangnan University introduced a novel three-dimensional teaching system, designed to optimize the curriculum of Automatic Control Theory for different engineering specializations. Yu Jie[3] from Shanghai University of Electric Power integrated multiple teaching methods to achieve substantial improvements in student learning outcomes. While these theories and methods provide important guidance for the teaching of Automatic Control Theory, their direct application to the Electronic Information Engineering program at Hebei North University presents challenges due to differences in academic context and discipline focus.

In response to the need for enhancing the practical relevance of the curriculum and aligning to build a high-level applied university, the author has integrated robotic systems into the teaching of Automatic Control Theory. Drawing from extensive teaching experience and the specific needs of the Electronic Information Engineering program, this approach leverages cutting-edge technology to foster greater student engagement and strengthen their engineering practice skills. The incorporation of robotic systems has not only increased student interest but also improved the overall teaching effectiveness of the course, contributing to the applied transformation of the discipline and supporting the university's educational goals. The robot control system represents a quintessential application of automatic control theory, embodying an integration of multiple disciplines, including mechanics, electronics, and computer science. Its interdisciplinary nature makes it an ideal tool for demonstrating the real-world application of theoretical concepts. Incorporating robotic systems into the teaching of Automatic Control Theory enables a comprehensive, hands-on approach to engineering practice, spanning key stages from system modeling and performance analysis to the design and implementation of control systems. This approach not only enriches the theoretical understanding of students but also bridges the gap between theory and practical application, fostering a deeper connection with the subject matter.

The following section outlines the curriculum reform in three key areas: the design and optimization of the curriculum content, the development of robot control system projects, and the construction of robotic platforms. Each of these aspects contributes to enhancing the overall educational experience by integrating practical engineering challenges into the learning process, thereby reinforcing the relevance and applicability of the theoretical principles of automatic control.

2 Curriculum Content Design and Optimization

The Automatic Control Theory course for the Electronic Information Engineering program at Hebei North University consists of 60 class hours, with 48 hours dedicated to theoretical instruction and 12 hours for experimental teaching. It is offered in the fifth semester and primarily focuses on classical control theory. The foundational courses that precede it include higher mathematics, college physics, electrical engineering fundamentals, electronic technology fundamentals, and signal and systems theory. These courses provide the necessary theoretical background and analytical methods, which form the basis for students to further study modern control theory, computer control systems, and related subjects.

The course content can be categorized into three main areas: "System Mathematical Modeling," "System Performance Analysis," and "System Design and Calibration." These components are interconnected, with mathematical modeling and system analysis forming the essential groundwork for effective system design and calibration. The course covers a broad range of topics, incorporating numerous mathematical formulas and derivations. However, the lack of practical case studies has made it challenging for students to connect theory with real-world applications, leading to a dry and difficult learning experience.

To address this gap, the course has been restructured to integrate robotic control system case studies into the curriculum. This approach not only optimizes the theoretical content but also strengthens the practical and applied aspects of the course. By incorporating real-world examples, the revised curriculum has successfully sparked student interest and enhanced their understanding of theoretical concepts. This integration has led to improved teaching outcomes, fostering both deeper engagement and a stronger grasp of the subject matter. The updated course structure is summarized in Table 1.

Table 1 The main contents of the course

Course Content	Introduction	General concept Systematic classification Basic requirements of the system
	System mathematical modeling	Differential calculus equation method Transfer function method Block diagram model
	System performance analysis	Time domain analysis Root-locus method Frequency domain analysis
	System design and Calibration	Root locus tandem correction Frequency method tandem correction Partly feedback compensation Composite control corrections

Integrating the robot control system throughout the entire course teaching process creates a seamless connection between disparate theoretical concepts, facilitating a cohesive learning experience. This integration enables students to understand how various knowledge points—spanning system modeling, performance analysis, and control system design—interrelate and build upon one another. By applying these concepts to the real-world context of robotic systems, students gain a more comprehensive understanding of their practical application. The iterative processes of system analysis, calibration, and design are not only illustrated but also exemplified through the robot control system, thereby reinforcing the theoretical principles taught in the course. The workflow involved in analyzing, calibrating, and designing the robot system is visually represented in Figure 1, providing a clear and structured overview of these key stages.

To further illustrate the aforementioned process, Figure 2 presents a 2-DOF (Degrees of Freedom) planar manipulator arm, a widely used system in planar grasping applications. The manipulator features driving motors positioned at points O and A, which control the motion of the arm. A mathematical relationship is established between the rotation angles of these motors and the position of point B, the endpoint of the manipulator arm. This relationship, which forms the basis for controlling the arm's movement, is expressed in Equation (1), providing a precise link between the motor angles and the spatial coordinates of the manipulator's end-effector.

$$\begin{cases} x = l_{OA}\cos\theta_1 + l_{AB}\cos(\theta_1+\theta_2) \\ y = l_{OA}\sin\theta_1 + l_{AB}\sin(\theta_1+\theta_2) \end{cases} \tag{1}$$

Where $\theta_i (i=1,2)$ represents the angle of each joint of the manipulator arm, with the counterclockwise direction designated as positive. Consequently, controlling the position of point B—the end effector of the manipulator—ultimately involves regulating the rotational angles of the motors at each joint. This process aligns with the fundamental concepts of speed and position control systems, as outlined in standard textbooks. By introducing and analyzing this practical case, students are provided with a concrete example that bridges the gap between theoretical knowledge and real-world application. This approach not only reinforces the principles of motor control and kinematics but also deepens students' understanding of the textbook material, enabling them to apply theoretical concepts in a tangible context.

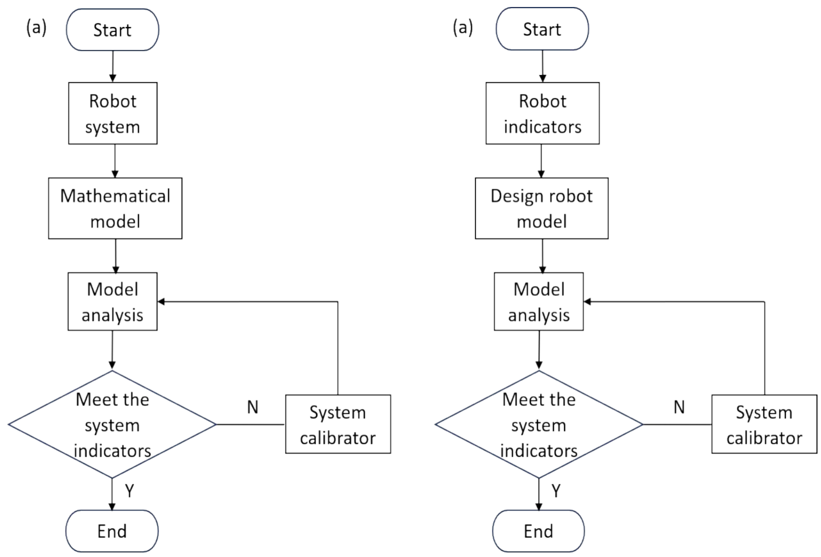

Figure 1 Robot system analysis, calibration, and design (a) System analysis and calibration; (b) System design and analysis

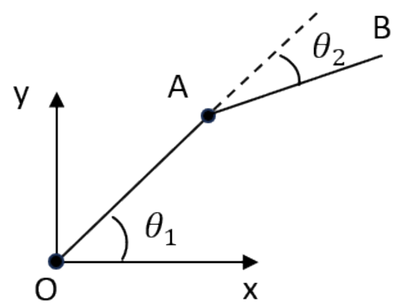

Figure 2 Schematic Diagram of a 2-DOF (Degrees of Freedom) Planar Robotic Mechanism

3 Project Design of Robot Control System

This section integrates robotic systems into the teaching process by leveraging established control models from key textbooks on automatic control theory and aligning them with practical robot models. By bridging theoretical concepts with real-world applications, the approach enhances students' understanding of control systems and their practical implementation. The robot projects developed for this curriculum, which serve as illustrative case studies for the application of control theory, are presented in Table 2. These projects not only reinforce theoretical learning but also provide hands-on experience, demonstrating the applicability of control models in various robotic systems.

Table 2 Content of Robot Control System Projects

Controlling Cases in Textbooks	Corresponding robot system
Inverted Pendulum	Two-wheeled self-balancing scooter
	Bipedal robot
Speed control of DC motors	Wheeled mobile robot
Speed and position control system	2-DOF (Degrees of Freedom) Planar Robotic Arm Underactuated Manipulator Drive Mechanism
Spring-mass-damper	The walking legs of a legged robot

The inverted pendulum[4] model is a fundamental example in automatic control theory, often used to demonstrate concepts of stability and control. This model can be derived by inverting a simple pendulum, a widely recognized system from everyday life. To maintain the inverted pendulum in a stable equilibrium, as depicted in Figure 3, the cart must move horizontally at a specific speed to counteract the destabilizing forces acting on the pendulum. Through an analysis of the forces involved, a mathematical relationship between the pendulum's rotational angle and the cart's horizontal displacement can be established. By dynamically adjusting the speed of the cart, the inverted pendulum can be kept in balance, showcasing key principles of feedback control.

This principle has significant real-world applications, such as in two-wheeled self-balancing vehicles and bipedal robots, where similar control strategies are employed to maintain stability during motion. These applications exemplify how the inverted pendulum model serves as a foundational concept in the design and control of dynamic robotic systems, offering practical insights into balancing and stabilization techniques commonly used in modern robotics.

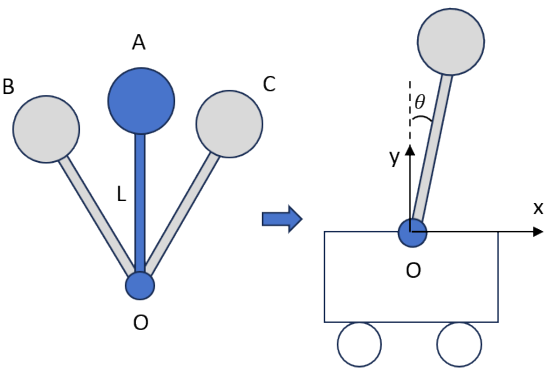

Figure 3 Inverted Pendulum Model

The speed control model of a direct current (DC) motor[4] is a classic model frequently introduced in the curriculum, illustrating the relationship between armature voltage and the rotational speed of the motor shaft. This model is typically formulated as a second-order linear differential equation. However, when the inductance of the armature winding is neglected, the system simplifies to a first-order linear differential equation, making it more accessible for analysis. The control of wheeled mobile robots, which rely on the adjustment of motor speed for movement and steering, can be directly linked to this model. As such, wheeled mobile robots, such as automatic track-following vehicles, automatic obstacle-avoiding vehicles, and maze-searching robots, serve as ideal application scenarios for demonstrating the principles of motor speed control in practical settings.

The speed-position control system[4] is another key concept in the curriculum, which requires the controlled object to reach a given position at a specified speed. A typical example used in teaching is the disk drive control system, where the position of the magnetic head is precisely controlled to read and write data in designated areas. In robotic applications, this principle is seen in the position control of robotic arm end-effectors and the speed and position control of actuation devices in underactuated robotic manipulators. These applications provide concrete examples of how speed-position control systems operate in real-world robotic systems.

The spring-mass-damper model[4], widely used to describe the vibrational characteristics of various mechanical systems, has broad engineering applications, including in automobile suspension systems, seismic design of buildings, and vibration dampening in tampers. In robotics, this model finds particular relevance in the design of cushioning foot mechanisms for legged robots, as shown in Figure 4. These mechanisms help reduce the rigid impacts during robot motion, improving stability and mitigating shock during locomotion.

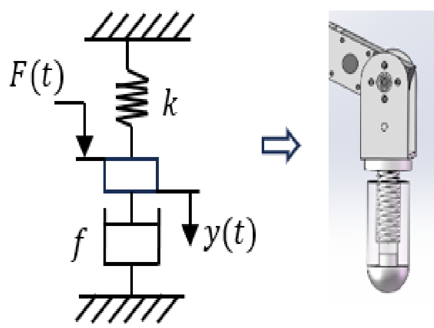

Figure 4 Application of the Spring-Mass-Damper Model in Robotics

Integrating actual robotic systems throughout the course teaching process significantly enhances students' comprehension of the interconnections between various theoretical concepts within the curriculum. By providing tangible, real-world applications, students can better appreciate the practical implications of abstract control theories, thus fostering a deeper understanding of the subject matter. A critical component of this approach is the systematic accumulation of robotic-related projects, which should be continuously integrated into the teaching process. These projects must be carefully classified, organized in increasing order of difficulty, and equipped with well-defined performance metrics to guide students' learning and assessment.

In addition, each robotic project should be supported by a comprehensive knowledge base, which includes essential resources such as the underlying principles of automatic control, detailed robotic models, control algorithms, and source code. This knowledge repository serves as an invaluable tool for students, offering them the opportunity to independently explore and deepen their understanding of robotic systems. The establishment of such a project library is not a one-time task, but rather a long-term, iterative process that evolves with the teaching content and technological advancements. Continuous refinement and expansion of the project library ensure that it remains relevant and useful, providing a dynamic learning environment for students and supporting their development of both theoretical and practical expertise in robotic control systems.

4 Robot platform construction

In the context of our course, we explore three primary sources of robotic platforms that significantly enrich the learning experience. First, we utilize innovative designs developed by instructors, which are grounded in cutting-edge scientific research. These platforms reflect the latest advancements in robotics and automatic control theory, providing a robust foundation for hands-on learning. Second, we foster student-driven innovation, where learners, under the expert guidance of instructors, design and construct their own robots, often for participation in dynamic competitions. This process nurtures creativity, problem-solving, and teamwork skills while encouraging deeper engagement with course material. Finally, we incorporate commercially purchased experimental platforms, which offer a reliable and standardized basis for exploring core robotic principles in a controlled environment.

Among the notable robotic creations is the six-legged mantis-inspired robot, shown in Figure 5(a). This sophisticated platform features five degrees of freedom per leg, endowing it with remarkable flexibility and the ability to execute a diverse range of locomotion gaits. The control of such an advanced robotic system necessitates a deep understanding of automatic control principles. Key areas of focus in the course include speed control, ensuring the robot can adjust its movement velocity dynamically; position control, enabling precise leg placement; and stability analysis, which ensures balance during dynamic and multi-modal movements.

Additionally, we engage with system design to develop the architecture that governs the robot's operations and systematic calibration to fine-tune its performance and ensure reliability. This hands-on involvement with the robotic platform serves not only to reinforce theoretical knowledge but also to provide invaluable practical experience in robotic design and control. By actively participating in the development, testing, and refinement of such platforms, students gain comprehensive insights into both the theoretical and applied aspects of robotics, strengthening their skills and deepening their understanding of control systems.

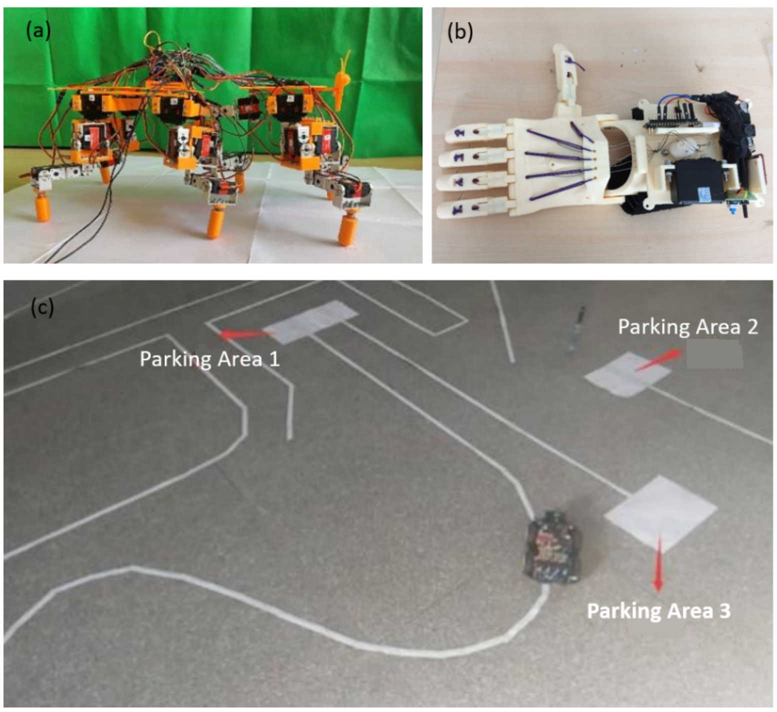

Figure 5 Educational robot platform (a) Mantis-Inspired Robot; (b) Underactuated Robotic Hand; (c) Autonomous track-following robot

Figure 5(b) presents an underactuated robot developed by students for a student competition[5]. This robot utilizes electromyographic (EMG) sensors to capture muscle surface signals, which are then used to control the motor rotation, enabling precise finger-gripping actions. The project primarily focuses on the application of position control techniques and the process of system calibration. By working with this robot, students gain hands-on experience in applying control theory to real-world scenarios, specifically in the context of human-robot interaction.

Figure 5(c) illustrates an automatic tracking car designed by students. This vehicle is intended for use in smart logistics, smart parking lots, and other autonomous navigation applications. It is capable of following a pre-designed path and autonomously identifying parking spaces. This project integrates a comprehensive set of control principles, allowing students to apply their knowledge of path tracking, obstacle avoidance, and autonomous decision-making. The cart's ability to navigate complex environments underscores the practical utility of control systems in modern robotics.

The continuous improvement of the robot teaching platform is essential to ensure that students stay at the forefront of technological advancements. It is crucial to align the course content with the latest developments in robotic technology, providing students with exposure to cutting-edge innovations in control systems and robotic applications. This integration of emerging technologies not only enhances the learning experience but also equips students with the skills and knowledge necessary to contribute to the future of automation and robotics.

5 Conclusion

This paper aims to streamline and optimize the teaching content of the Principles of Automatic Control course within the Electronic Information Engineering program at Hebei North University. By integrating robot control systems into the curriculum, we have established a robot project library and knowledge base, as well as developed a teaching-oriented robot platform, leading to significant improvements in the educational experience. The key enhancements can be summarized as follows:

(1) Increased Student Engagement. The course has become more interactive and stimulating, moving beyond traditional theoretical instruction. The introduction of practical robot systems has significantly heightened student interest, transforming the learning environment from passive reception to active participation.

(2) Improved Practical Skills and Teamwork. The process of building and operating the robot platforms requires students to work collaboratively in teams. This hands-on approach fosters the development of practical skills in hardware assembly, controller selection, mathematical modeling, and software programming. Moreover, students gain valuable teamwork experience, contributing to their overall skill set.

(3) Enhanced Theoretical Understanding. By incorporating real-world robot control systems into the teaching process, students gain a deeper understanding of the course material. This integration bridges the gap between theoretical knowledge and its practical application, allowing students to directly apply the principles of automatic control to complex, tangible systems.

The integration of actual robot systems into the Automatic Control Theory course represents a proactive step in realizing the university's broader goal of becoming a high-level applied institution and advancing the application-oriented transformation of its disciplines. This approach not only enriches the educational experience but also serves as a valuable model for similar courses at other institutions. The methodology outlined here has universal significance, offering a replicable framework for enhancing engineering education through the application of modern robotics.

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