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Teaching Content and Strategies of Robot Statics Calculation and Simulation Course Oriented towards New Engineering Education and AI Technologies

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Abstract: This paper explores the teaching reform of the "Robot Statics Calculation and Simulation" course under the new engineering education framework, proposing an integrated teaching model centered around elasticity mechanics theory and Abaqus finite element simulation platform with AI-assisted modeling tools. Through case studies involving three types of typical robotic systems (rigid industrial robots, continuum surgical robots, and micro/nano operation robots), it systematically builds a complete knowledge chain from theoretical modeling to numerical analysis and AI optimization. The course adopts a closed-loop teaching strategy of "modeling-simulation-validation-AI integration," enhancing students' understanding and application abilities in complex robot structure statics performance. Feedback from a completed class of 32 students shows significant improvement in their engineering modeling skills, software proficiency, and interdisciplinary problem-solving capabilities, providing an effective pathway for nurturing high-quality engineering talents suitable for intelligent manufacturing and advanced robotics fields.

1. Introduction

Driven by the new engineering education initiative[1], robot technology is rapidly evolving towards higher precision and adaptability, expanding its applications into cutting-edge areas such as biomedical engineering and micro/nano operations[2]. In high-end manufacturing, industrial robots must meet stringent statics performance requirements: for example, welding point deviations caused by insufficient rigidity in automotive welding robots have become critical factors affecting welding quality; structural deformations in heavy-duty handling robots directly impact load capacity and operational stability. Meanwhile, emerging configurations like continuum robots [3] and micro/nano operation robots are challenging traditional rigid body assumptions. For instance, flexible surgical robotic arms [4, 5] achieve precise operations in confined spaces through controlled elastic deformations, requiring mechanical models that consider both geometric and material nonlinearities; in semiconductor packaging or cell manipulation at the micro/nano scale, deformations of flexible hinges significantly affect positioning accuracy, demanding more refined statics analyses[6].

However, existing engineering education frameworks have not fully responded to these technological changes, particularly in addressing complex system statics analysis. Traditional courses focus on simple rigid body systems based on theoretical mechanics and materials science but lack systematic training in multi-body coupled elastic deformation and nonlinear contact problems. Research indicates that most students struggle to correlate component-level mechanical characteristics with system-level performance and cannot proficiently use numerical simulation tools for multi-scale validation. This capability gap leads to issues such as over-simplified models or improperly configured simulations during practical projects, directly impacting the validity of simulation results and product iteration efficiency.

To address these challenges, we have discussed the content of this new course—Robot Statics Calculation and Simulation, and it has been implemented in the Robotics Engineering program at Shanghai University of Technology. Specifically, this course reconstructs the teaching framework for robot statics under the core principles of "interdisciplinary integration and competency linkage" advocated by new engineering education. Theoretically, it breaks the boundaries of classical rigid body mechanics and material science by integrating elasticity mechanics modeling methods, covering unified statics analysis paradigms for traditional industrial robots, flexible continuum mechanisms, and micro/nano operation systems. Technologically, it fosters full-chain capabilities from parameterized component modeling to overall system performance optimization through deep integration of finite element simulation and multiphysics verification tools. The course design closely aligns with industry needs, focusing on structural stiffness optimization for heavy-duty industrial robots, constructing hyperelastic constitutive models for flexible robots, and introducing micro/nano scale contact mechanics simulations. Additionally, it introduces AI-assisted [7] model generation for efficient simulations. By bridging the loop from "theoretical modeling-numerical computation-experimental validation-AI assistance," this course aims to nurture composite talents capable of solving complex engineering problems in emerging fields such as intelligent manufacturing and biomedical engineering, facilitating the leapfrog development of robot technologies from "rigid execution" to "intelligent adaptation.

2. Course Content Oriented Toward Advanced Robotic System Applications and AI Technologies

2.1 Part I: Building Static Models of Robotic Systems Based on Elasticity Mechanics Modeling Concepts

This section uses fundamental elasticity mechanics theories to guide students in understanding and mastering how to establish static models applicable to different robotic systems. The course emphasizes stress-strain relationships, equilibrium equations, geometric equations, and constitutive equation derivations, illustrated through three representative robotic system cases:

(1) Elasticity Mechanics Modeling Concepts

The course begins by reviewing basic assumptions and governing equations of elasticity mechanics, including isotropic material small deformation theory, Hooke's Law, and boundary conditions. It highlights how to select appropriate coordinate systems, simplify structural models, and establish suitable mathematical models based on actual force conditions.

(2) Rigid Industrial Robots - Stiffness Optimization in High-Precision Machining Scenarios

Using a six-degree-of-freedom industrial robotic arm as an example, the course discusses sources of static errors due to joint clearance and link flexibility during high-speed movements. Students build elastic beam models for each robotic arm component, solve static deformations using finite difference methods, and compare results with experimental data to evaluate model accuracy.

(3) Continuum Surgical Robots - Predicting Accurate Deformations in Confined Spaces

Focusing on flexible surgical robotic arms made up of multiple hyperelastic silicone segments, the course explains how to establish Mooney-Rivlin constitutive equations and predict bending and stretching behaviors under external loads using a combination of analytical and finite element methods.

(4) Micro/Nano Operation Robots - Micro-Scale Static Modeling of Flexible Mechanisms

For flexible hinges in microelectromechanical systems (MEMS), the course covers micro-deformation modeling techniques, considering surface effects and size effects, and constructs modified elasticity models suitable for nanoscale displacement control. Students use COMSOL Multiphysics and Abaqus for combined simulations to validate model applicability in nanometer-level position control.

2.2 Part II: Finite Element Methods and Software Usage

This section aims to help students master the foundational operations and advanced features of the Abaqus finite element simulation platform, covering the entire workflow from geometry modeling, mesh generation, material definition, analysis step definition, boundary condition setting, to post-processing analysis. Specific teaching content includes:

(1) Part-Level Simulations

Using individual robotic arm links as examples, guide students through 3D modeling, material property definitions (e.g., aluminum alloys, carbon fiber composites), mesh generation (structured/unstructured), load application, and constraint condition settings.

(2) Component-Level Simulations

Extending to multi-body connected structures, such as contact modeling between joints and links, learn friction coefficient settings, contact pressure distribution analysis, etc.

(3) System-Level Simulations

Based on complete robot models, simulate overall stiffness performance under typical operating conditions, analyze coupling effects between components, and assess dynamic response characteristics through modal analysis.

Throughout the simulation teaching process, emphasize the integration of theory and practice, encouraging students to design simulation schemes independently after completing standard exercises, thereby enhancing their engineering problem modeling and debugging capabilities.

2.3 Part III: AI-Assisted Modeling Techniques Integrated with CAE Software

With advancements in generative AI technologies, especially large language models (LLMs) in code generation and logical reasoning, the course introduces these technologies into the finite element modeling phase. Students can prompt AI models to automatically generate Abaqus INP file scripts compliant with Abaqus syntax norms, achieving automated parametric modeling. For example, in batch processing multiple sets of different material parameters for simulation tasks, students only need to provide basic structural information and load conditions, and AI generates corresponding Python scripts for iterative simulations. This module not only improves modeling and simulation efficiency but also stimulates student interest in AI-enhanced engineering design, laying a foundation for future intelligent CAE tool applications.

3. Teaching Strategies: Modeling Theory + Engineering Cases + Practice + Validation

The course adopts a four-dimensional teaching strategy of "modeling-simulation-validation-AI integration," creating a closed-loop teaching process. To effectively achieve the teaching objectives of the "Robot Statics Calculation and Simulation" course, we have designed a systematic teaching strategy. This strategy is divided into two main parts: Modeling Theory and Case-Driven Learning and Simulation Practice Learning. Each part is reasonably planned according to the course outline, with a total of 64 class hours. Specifically, 32 class hours are allocated for teaching the modeling ideas of elasticity mechanics and the theoretical concepts of finite element methods, while the remaining 32 class hours are used for software operation as well as AI-CAE based simulation. Implementation details are as follows:

3.1 Theoretical Lectures and Foundation Reinforcement (32 Class Hours)

(1) Basic Elasticity Mechanics:

In the early stages of the course, classroom lectures and multimedia presentations systematically introduce fundamental concepts of elasticity mechanics, equilibrium equations, geometric equations, and physical equations (such as Hooke's Law). We emphasize the application of these basic principles in solving complex robotic structures.

Introduction to Numerical Methods: Detailed introduction to the basic concepts of the finite element method and its advantages in solving complex problems, including discretization principles, element type selection, and boundary condition settings. We help students understand the conversion process from continuous to discrete problems through example analysis.

(2) Engineering Case-Driven Learning

Case Selection and Design: Each teaching module includes practical engineering cases, such as rigid industrial robots, continuum surgical robots, and micro/nano operation robots. These cases cover various types of robotic systems and involve diverse application scenarios for statics analysis.

(3) Case Analysis and Discussion

Teachers guide students to start from real-world problems, gradually building theoretical and simulation models. We encourage group discussions and classroom interactions, allowing students to propose their insights and learn how to reasonably simplify complex problems to extract core elements for modeling.

3.2 Practical Operations and Skill Enhancement (24 Class Hours)

(1) Laboratory Practices

Students participate in weekly lab sessions where they, under teacher guidance, use Abaqus software to complete part-level, component-level, and system-level simulations. Specific contents include:

Part-Level Simulations: Using individual robotic arm links as examples, guide students through 3D modeling, material property definitions, mesh generation, load application, and constraint condition settings.

Component-Level Simulations: Extending to multi-body connected structures, such as contact modeling between joints and links, learning friction coefficient settings, contact pressure distribution analysis, etc.

(2) System-Level Simulations

Students simulate the overall stiffness performance of complete robot models under typical operating conditions, analyze coupling effects between components, and assess dynamic response characteristics through modal analysis under teacher guidance.

(3) Project-Based Learning

At the end of each semester, instructors assign comprehensive projects that require students to work in groups to complete a full robotic statics analysis task. Students must submit simulation reports and visualization results and present their findings and undergo peer review and feedback in class.

3.3 AI-Assisted Modeling and Innovation Exploration (8 Class Hours)

(1) Integration of AI Tools

With advances in generative AI technologies, particularly large language models (LLMs), the course integrates these technologies into the finite element modeling phase. Students can prompt AI models to automatically generate Abaqus INP file scripts, enabling automated parametric modeling.

(2) Innovative Project Design

Introduce AI-assisted modeling projects in later parts of the course, where students design AI generation templates and apply them to actual simulation tasks, enhancing their engineering innovation capabilities. For example, in batch processing multiple sets of different material parameters for simulation tasks, students only need to provide basic structural information and load conditions, and AI generates corresponding Python scripts for iterative simulations.

3.4 Validation and Feedback Mechanisms

(1) Stage Assessments:

Multiple stage assessments throughout the course, such as quizzes and homework checks, to monitor students' learning progress and comprehension. Teachers offer individualized guidance and academic support tailored to the specific difficulties identified in students' learning progress.

(2) Simulation Result Verification:

Students need to verify simulation results against experimental data or literature references to ensure model accuracy and reliability. Teachers promote the application of multiple validation approaches, including theoretical analysis and experimental verification, to foster a rigorous and disciplined scientific mind-set among students.

(3) Continuous Improvement:

Instructors regularly collect student feedback to adjust teaching content and methods, thereby continuously optimizing the curriculum. For example, at the end of the course, they organize student surveys to gather opinions on course structure, teaching approaches, and other relevant aspects.

3.5 Interdisciplinary Integration and Competency Linkage

(1) Interdisciplinary Fusion:

Instructors integrate knowledge points from mechanical engineering, computer science, and other related disciplines to design comprehensive course content, thereby fostering students' ability to synthesize interdisciplinary knowledge in addressing complex engineering problems. For example, when explaining the statics analysis of flexible robots, introduce related knowledge from materials science and control theory.

(2) Teamwork and Communication Skills Development:

Through project-based learning and group discussions, enhance students' teamwork spirit and communication skills. We encourage cross-disciplinary collaboration to jointly solve complex engineering problems, laying a solid foundation for future career development.

4. Teaching Effectiveness

This course has been implemented for a class of undergraduate sophomore students majoring in robotics engineering at University of Shanghai for Science and Technology, with a total of 32 students. Over the course of 16 weeks of systematic teaching, significant improvements were observed across several key areas:

(1) Theoretical Modeling Ability

Final exam results indicated that over 85% of students could independently complete complex robotic structure statics modeling. This represents a significant improvement compared to previous students, who didn't participate this class, demonstrating substantial growth in their theoretical understanding and ability to apply these concepts.

(2) Software Proficiency

All students became proficient in using Abaqus for part-level and component-level simulations. Specifically:

Part-Level Simulations: All students successfully completed tasks involving three-dimensional modeling, material property definition, mesh division, load application, and constraint condition setting.

Component-Level Simulations: Approximately 70% of students were capable of performing system-level modeling and multi-condition analyses, showcasing advanced proficiency in handling more complex simulation tasks.

(3) Engineering Problem-Solving Capability

The final course project required students to work in teams to complete a comprehensive robotic statics analysis topic. Results indicated that students generally applied theoretical knowledge and simulation tools effectively to solve practical problems. Specific achievements included:

Comprehensive Analysis: Students demonstrated the ability to integrate various aspects of finite element analysis, from initial model creation to detailed analysis and interpretation of results.

Team Collaboration: Enhanced teamwork and communication skills were evident as students collaborated on projects, sharing insights and working together to achieve common goals.

(4) Initial Application of AI Tools

Due to differences in comprehensive programming abilities, over half of the students successfully used AI tools to generate simulation scripts and optimized script logic under teacher guidance, achieving a certain degree of automated modeling. This exposure to AI-assisted modeling not only improved their technical skills but also fostered innovation and efficiency in their approach to problem-solving. In future teaching improvements, teaching time can be appropriately tilted in this section to cater to the learning quality of the vast majority of students.

5. Conclusions

This paper systematically elaborates on the teaching content design and implementation strategies of the "Robot Statics Calculation and Simulation" course, tailored for undergraduate students majoring in robotics engineering. Aligned with the development trend of new engineering education, this course integrates core knowledge from multiple disciplines—such as elasticity mechanics, finite element analysis, computational simulation, and AI-assisted modeling—to cultivate students' comprehensive capabilities in mechanical modeling, simulation practice, and intelligent application.

The teaching practice demonstrates that this interdisciplinary and application-oriented approach effectively enhances students' abilities across several dimensions:

Theoretical Modeling Ability: Students showed significant improvement in understanding and applying the fundamental principles of statics and continuum mechanics to real-world robotic systems.

Software Proficiency: All students achieved a solid command of Abaqus for part-level and component-level simulations, with over 70% capable of handling system-level models and complex boundary conditions.

Engineering Problem-Solving Capability: Through case-driven learning and project-based tasks, students were able to independently formulate problems, build appropriate models, perform simulations, and interpret results—mirroring real engineering workflows.

Innovative Application of AI Tools: More than half of the students successfully applied AI tools to automate parts of the modeling process, demonstrating early adaptability to emerging technologies and setting a foundation for future digital and intelligent engineering practices.

Moreover, the assessment methods—including regular assignments, classroom exercises, and a comprehensive final project—ensured continuous learning engagement and provided accurate feedback for both students and instructors. A post-course survey further confirmed high student satisfaction, with over 90% indicating that the course was well-paced, practically oriented, and highly relevant to their future careers.

These outcomes not only validate the effectiveness of the proposed teaching strategies but also highlight the importance of integrating theory, simulation, and intelligence in modern engineering education. The success of this course offers valuable insights into curriculum design and instructional methods for similar technical courses, particularly those involving computational modeling, simulation, and AI-enhanced engineering practices.

Looking forward, this framework can be further extended to other advanced robotics-related courses, such as dynamic simulation, control system modeling, or multi-physics coupling analysis. Additionally, incorporating more interactive teaching tools—such as virtual labs, collaborative platforms, and flipped classrooms—can further enhance learning efficiency and student engagement.

In conclusion, the "Robot Statics Calculation and Simulation" course represents a successful model of how new engineering education can bridge traditional theoretical instruction with practical simulation and intelligent tools, preparing students to meet the evolving demands of the robotics and automation industries.

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