

# ***Dual-Drive Teaching Reform of 'Robotics Mechanisms' Empowering High-Precision Heavy-Duty Machine Tools: Parallel Mechanisms and Compliant Positioning Mechanisms***

**Yinjun Zhao<sup>1</sup>, Long Chen<sup>1</sup>, Jieyu Wang<sup>2,\*</sup>**

<sup>1</sup>*School of Mechanical Engineering, University of Shanghai for Science and Technology, Shanghai, 200093, China*

<sup>2</sup>*School of Mechatronic Engineering and Automation, Shanghai Key Laboratory of Intelligent Manufacturing and Robotics, Shanghai University, Shanghai, 200444, China*

*\*Corresponding author*

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**Abstract:** In response to the urgent demand for top-tier innovative talents in the field of advanced manufacturing and the intrinsic shortcomings of the traditional "Robotics Mechanisms" course-such as the superficiality of engineering backgrounds and the rigidification of mechanism theories, this paper proposes a comprehensive, "rigid-flexible dual-drive" teaching reform framework. Empowering the development of high-precision, heavy-duty machine tools, the reform fundamentally reconstructs the course content by introducing heavy-duty parallel machine tools and compliant precision positioning platforms as core case studies. This approach effectively shatters the traditional cognitive constraints of the "rigid-body assumption." By deeply integrating algorithmic scripting, SolidWorks three-dimensional motion simulation, and ANSYS finite element analysis, the curriculum establishes a highly immersive "theory-practice-simulation" pedagogical ecosystem. Furthermore, driven by real-world industrial pain points sourced from front-line robotics and equipment enterprises, the reform incorporates project-based learning to bridge the gap between abstract mathematical derivation and complex engineering application. Practical implementation of this reform has yielded significant outcomes: it has successfully accumulated a high-order case library, revolutionized the classroom dynamic from passive absorption to active inquiry, and substantially elevated students' capabilities in designing and analyzing complex, macro-micro composite CNC equipment. Ultimately, this paradigm shift provides a robust, scalable model for cultivating high-quality, interdisciplinary engineering talents tailored for the modern machine tool industry.

## 1. Introduction

'Robotics Mechanisms' serves as a foundational and indispensable core course for undergraduate students majoring in mechanical engineering, robotics, and intelligent manufacturing. The theoretical framework imparted through this course constitutes the bedrock upon which students comprehend complex spatial mechanisms, perform kinematic and dynamic analyses, and ultimately engage in original mechanical equipment innovation [1]. In the contemporary industrial landscape, high-end Computer Numerical Control (CNC) machine tools are universally acknowledged as the "industrial mother machines." The capability to independently design and manufacture these sophisticated systems is a critical bottleneck determining a nation's transition from a mere manufacturing participant to a global manufacturing powerhouse [2].

Modern high-end machine tools are currently undergoing a profound technological metamorphosis. The industry is rapidly shifting from traditional single-axis, serial kinematic structures to multi-axis, multi-dimensional parallel and hybrid kinematic architectures [3]. Simultaneously, the manufacturing scale is transitioning from macroscopic, heavy-duty rough cutting to micro-nano-level ultra-precision machining [4]. This monumental industrial upgrade places unprecedented demands on the "modern mechanism" literacy of future engineering R&D personnel. Consequently, the "Robotics Mechanisms" course is endowed with a new historical mission: it must evolve beyond classical planar linkages to address the cutting-edge requirements of spatial, high-stiffness, and ultra-high-precision systems [4,3]. However, the existing teaching models and pedagogical contents have largely failed to keep pace with the rigorous standards dictated by the advanced manufacturing sector, necessitating a deep, systematic, and industry-aligned teaching reform [5,6].

## 2. Deep Analysis of Pain Points in the Traditional Teaching Model

When evaluated against the urgent imperative to cultivate top-tier, innovative engineering talents for the CNC machine tool sector, the routine pedagogical practices of the traditional "Robotics Mechanisms" course reveal two deep-seated structural pain points.

### 2.1 Superficial Engineering Context and the Absence of Heavy-Duty Core Component Mapping

Historically, the teaching cases utilized in mechanism courses have been overly reliant on basic planar linkages (e.g., four-bar mechanisms) or lightweight serial robotic arms. The theoretical instruction is heavily skewed towards highly abstract mathematical matrix derivations—such as the Denavit-Hartenberg (D-H) parameters, Jacobian matrices, and screw theory—which often remain completely isolated from authentic, heavy-duty engineering scenarios. Because students lack direct, visual, and analytical connections with "heavy-duty parallel or hybrid machine tools" (such as 5-axis parallel machining centers), they struggle to profoundly comprehend why parallel mechanisms are mathematically and physically indispensable for enhancing machine tool processing stiffness, minimizing moving inertia, and optimizing high-dynamic response capabilities under immense cutting loads. This disconnect renders the mathematical tools dry and seemingly devoid of practical engineering value.

### 2.2 Rigidification of Mechanism Theory and the Missing Micro-Nano Manufacturing Frontier

The existing syllabus is constructed almost entirely upon the absolute "rigid-body assumption." It focuses on components that do not deform and joints that possess perfect, frictionless articulation.

Consequently, the curriculum entirely overlooks the "compliant, backlash-free positioning mechanisms" that are absolutely critical in the realm of ultra-precision CNC machine tools and semiconductor manufacturing equipment. This severely skewed "heavy-on-rigidity, light-on-compliance" knowledge structure leaves students at a severe disadvantage. When confronted with sub-micron or nanometer-level feed platforms, students are intellectually constrained by their rigid-body mindset. They lack the theoretical scaffolding required to execute cutting-edge mechanism innovations based on rigid-flexible coupling, material elastic deformation, and monolithic compliant joint design.

### **2.3 Design of the "Rigid-Flexible Dual-Drive, Macro-Micro Composite" Pedagogical Framework**

To systematically eradicate these pain points, this teaching reform pioneers the pedagogical concept of "Robotics Mechanisms' Empowering High-Precision Heavy-Duty Machine Tools." The core philosophy is built upon a "Dual-Drive" framework that seamlessly integrates "Parallel Actuation" (representing macroscopic scale, heavy payload, and high stiffness) with "Compliant Positioning" (representing microscopic scale, zero friction, and ultra-high precision).

This framework strips away the tedium of purely abstract mathematical derivations and instead translates state-of-the-art CNC execution components into "living textbooks" for classroom exploration. The overarching objective is to demolish the cognitive barriers between "traditional rigid theory," "rigid-flexible coupling," and "high-end equipment application." By establishing a macro-micro composite teaching model, the reform substantially elevates the engineering caliber and contemporary relevance of the curriculum, ensuring that the theoretical tools taught are directly applicable to the most advanced challenges in the machine tool industry.

## **3. Comprehensive Implementation of the Teaching Reform**

Adhering strictly to the pragmatic principles of "enhancing software-based resources and driving innovation through industrial cases," the implementation of this reform eschews massive hardware expenditures in favor of building a robust, intellectually stimulating digital and theoretical ecosystem. The specific implementation strategies are meticulously detailed below.

### **3.1. Development of a High-Order, "Rigid-Flexible Dual-Drive" Demonstration Case Library**

The traditional curriculum has been systematically deconstructed and reconstructed to feature two primary, industry-aligned case clusters based on the core components of modern CNC machine tools.

#### **(1) The Heavy-Duty Parallel Actuation Case Cluster (Macroscopic Feed Module)**

This module utilizes large-scale, complex surface machining equipment-specifically, the Stewart six-degree-of-freedom platform, the Tricept mechanism, and the Exechon hybrid-driven mechanism-as the foundational blueprints. During the chapters dedicated to "Kinematics and Singularity Analysis," instructors guide students to fuse complex spatial degree-of-freedom calculations directly with "machine tool cutter posture control." Instead of solving generic equations, students calculate the inverse kinematics required to position a milling tool accurately on a complex aerospace component. In the "Statics and Stiffness" chapters, the principle of virtual work is introduced to derive the load-bearing capacity of the machine tool. This pedagogical translation allows students to intuitively perceive and mathematically prove the high-stiffness advantages of parallel topological structures when subjected to severe, multi-directional cutting forces.

#### **(2) The Compliant Precision Positioning Platform Case Cluster (Microscopic Compensation**

Module)

Targeting extreme-precision equipment such as lithography machines and ultra-precision lathes, this module introduces the concept of compliant mechanisms-specifically utilizing flexure hinges and leaf springs-into the undergraduate curriculum for the very first time. The instructional approach employs the cutting-edge "Pseudo-Rigid-Body Model (PRBM)" and the "Compliance Matrix Method." Instructors guide students in constructing equivalent mapping models of compliant parallel worktables. By treating a thin flexible hinge as a rigid link connected by a torsional spring, students can apply the fundamental rigid-body kinematic tools (like the previously learned Jacobian matrix) to smoothly transition into the analysis of complex compliant mechanism deformation and parasitic motion. This elegant theoretical bridge broadens their knowledge base without overwhelming them with advanced continuum mechanics, perfectly linking classical robotics with modern micro-positioning.

### **3.2 Construction of a Low-Cost, High-Yield "Digital Virtual Simulation" Ecosystem**

To overcome the objective limitations of expensive precision machine tool hardware and the impossibility of conducting large-scale, hands-on physical experiments for every student, the project focuses intensely on building a comprehensive, highly visual digital simulation resource package. During classroom practical sessions and project work, students are required to use a single laptop in front of them to run complex simulations, ensuring an uncluttered, focused digital workbench.

#### **(1) Algorithm-Level Computational Assistance**

Modern kinematics involves tedious numerical iterations that can obscure the underlying physical principles. To counter this, the reform introduces the development of interactive MATLAB computational scripts (Live Scripts) tailored for the forward/inverse kinematics and workspace searching of CNC machine tools. These scripts relieve students from the drudgery of manual numerical iteration, allowing them to focus on algorithm design, singularity avoidance, and the optimization of mechanism parameters.

#### **(2) 3D Assembly and Kinematic Simulation via SolidWorks**

Moving beyond 2D diagrams, the curriculum relies heavily on SolidWorks to develop 3D solid models and kinematic simulations of heavy-duty parallel machine tools. Students learn to assemble complex joints (such as spherical and universal joints) and define mechanical mates to simulate the true motion of the Tricept or Stewart platforms. This stage is critical for performing interference checks-ensuring that the parallel struts do not collide during extreme articulation-and for the dynamic visualization of the machine tool's machining trajectory. Witnessing the virtual machine move precisely according to their calculated inverse kinematic trajectories provides a profound sense of engineering validation.

#### **(3) Finite Element Analysis (FEA) via ANSYS**

To visualize the invisible micro-deformations of compliant mechanisms, the curriculum integrates ANSYS finite element analysis. A comprehensive library of deformation and stress contour models for compliant worktables has been established. Students apply boundary conditions and micro-forces to visualize the micrometer-level elastic deformation laws and identify areas of critical stress concentration within the flexure hinges. This establishes a novel, three-dimensional teaching ecosystem that organically fuses "Theoretical Calculation, 3D Solid Modeling, and Digital FEA Simulation."

### **3.3 Implementation of Project-Based Learning (PBL) Driven by Real Industrial Pain Points**

Shattering the traditional closed-door teaching paradigm, the reform deeply integrates industry

resources, leveraging established collaborative relationships with leading robotics enterprises. This facilitates a highly practical "school-enterprise collaborative, pain-point-driven" pedagogical approach.

The curriculum directly imports the authentic engineering challenges and "lessons learned" encountered by frontline engineers during the research and development of multi-degree-of-freedom precision motion platforms. Real-world problems-such as the fatigue fracture risks of compliant platforms under large strokes, or the highly constrained dexterous workspace of heavy-duty parallel machine tools-are distilled into classroom discussion topics and final capstone project prompts. Students, working in collaborative teams, select a specific micro-component of a machine tool for architectural synthesis and design optimization. They must complete the entire innovation closed-loop, from theoretical mathematical calculation and 3D model construction to comprehensive engineering evaluation and simulation, genuinely executing "real projects for real problems."

#### **4. Reform Effectiveness and Practical Outcomes**

Following rigorous implementation, this pedagogical reform has transcended theoretical planning to deliver profound, measurable, and highly substantive educational outcomes. The reform has effectively empowered the discipline and elevated the holistic quality of student training across four distinct dimensions.

##### **4.1 Resource Accumulation: Establishment of a Premier "Rigid-Flexible Dual-Drive" Case Library**

The most immediate outcome of the reform has been the creation of a tangible, high-value asset base that completely breaks the mold of outdated textbooks disconnected from high-end equipment. The instructional team has successfully produced a suite of advanced, industry-demonstration lesson plans centered on "heavy-duty parallel machine tools" and "compliant micro-motion worktables." Accompanying this is a fully matched, digital auxiliary teaching package. This package includes upgraded multimedia courseware, detailed practical training manuals, and the corresponding MATLAB algorithm scripts, SolidWorks 3D motion simulation models, and ANSYS FEA models. Crucially, this resource repository not only serves the "Robotics Mechanisms" course directly but is designed with high modularity. It seamlessly interfaces with other related professional courses within the faculty, enabling the highly efficient reuse and continuous iterative improvement of premium soft teaching resources.

##### **4.2 Classroom Ecosystem Transformation: Realizing Authentic Industry-Education Integration**

The reform has successfully reversed the historically dry and passive classroom dynamic characterized by wall-to-wall mathematical formula derivation. The introduction of intuitive SolidWorks 3D interference demonstrations and ANSYS mechanism deformation contour maps has drastically lowered the cognitive threshold for students. Visualizing complex spatial geometry and micro-strain distribution has sparked a profound intrinsic motivation among students to explore complex CNC mechanisms.

Furthermore, by directly docking with genuine industrial pain points-such as mitigating parasitic motion interference in compliant platforms or optimizing singular configurations in parallel kinematics-the classroom has transformed into a dynamic R&D incubator. This "theory-led, simulation-verified, and engineering-optimized" inquiry-based classroom ecosystem ensures that

industrial demands continually nourish and refine the pedagogical process.

### **4.3 Leap in Student Capabilities: Fortifying Complex Engineering Problem-Solving Skills**

The most vital metric of success lies in the intellectual and practical elevation of the student body. The dual-drive approach has successfully helped students bridge isolated islands of knowledge, enabling them to construct a comprehensive, modern mechanism worldview that spans from "macroscopic rigidity" to "microscopic compliance," and from "traditional serial" to "complex parallel" architectures.

Through the rigorously revamped after-school practical assignments and project-based learning modules, students have achieved a high degree of proficiency in utilizing 3D modeling and finite element tools to solve authentic mechanism problems. Evaluative data and capstone performance indicate that students who complete this reformed curriculum exhibit a significantly enhanced capacity for innovative design and software-based analytical reasoning. When tasked with the development of high-end CNC machine tool components or the structural design of cutting-edge robots, these students demonstrate a distinct competitive advantage, laying an incredibly solid foundation for their senior graduation designs and their participation in high-level academic and mechanical design competitions.

### **4.4 Professional Empowerment: Precisely Nourishing the Innovative Talent Cultivation System**

At the macro-disciplinary level, the successful implementation of this project has catalyzed a paradigm shift for the "Robotics Mechanisms" course. It has transitioned from a purely theoretical, foundational science class into a vital bridge course that inextricably links "fundamental mechanics" with "advanced manufacturing equipment." By precisely aligning the curriculum's learning outcomes with the national strategic demand for advanced R&D personnel in the "Industrial Mother Machine" sector, the course's intrinsic value and industry relevance have been dramatically amplified. Consequently, the reform directly empowers the broader faculty by consistently supplying a pipeline of high-quality, interdisciplinary, and innovative engineering talents who possess both profound theoretical mechanism foundations and the pragmatic, battle-tested spirit required by the modern CNC machine tool industry.

## **5. Conclusions**

The "rigid-flexible dual-drive" teaching reform of the "Robotics Mechanisms" course, specifically tailored to empower high-precision, heavy-duty machine tools, represents a critical evolutionary step in engineering education. By systematically integrating parallel mechanisms and compliant positioning platforms into the core curriculum, the reform effectively resolves the chronic disconnect between traditional pedagogical content and the rapid, sophisticated advancements of the modern manufacturing sector. The establishment of a robust digital teaching resource library-anchored by SolidWorks and ANSYS-combined with a deeply integrated, industry-driven classroom ecosystem, provides a highly scalable and effective model for cultivating top-tier engineering talent. Ultimately, this educational paradigm shift provides unwavering foundational support for the development of outstanding engineering teams, ensuring they are intellectually and practically equipped to drive future innovations in the global high-end equipment manufacturing arena.

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