

# Innovation in the Practical Teaching Mode of CNC Machining Based on the Cultivation of Engineering Ability

Banglang Chen\*

Hainan Vocational University of Science and Technology, Haikou, 571126, China

\*Corresponding author: 15076631686@163.com

**Abstract:** As the manufacturing industry undergoes transformation towards digitalization and intelligentization, it places higher demands on the systematic abilities of engineering talents. Traditional CNC machining teaching exhibits structural and contextual limitations in cultivating students' abilities to solve complex engineering problems. This research aims to construct an innovative model for practical CNC machining teaching oriented towards engineering ability cultivation. Firstly, by analyzing the core dimensions of engineering ability and the systematic characteristics of CNC machining teaching, a structured mapping mechanism between ability orientation and teaching content is established. Secondly, in view of the shortcomings of the traditional linear teaching model, a path for the transformation of teaching design is proposed, which is driven by technological evolution and aimed at the integration of abilities. Finally, a three-dimensional innovative model framework is systematically constructed, encompassing the design of multi-level ability objectives, a virtual-actual integrated teaching environment, and a continuously iterative evaluation mechanism. This model emphasizes the realization of knowledge integration and ability enhancement within authentic engineering contexts, providing a theoretical reference and practical paradigm for the systematic reform of higher engineering practice teaching.

**Keywords:** engineering ability; CNC machining; teaching mode innovation; virtual-actual integration; ability evaluation

## Introduction

The core challenge currently facing engineering education lies in how to transform discrete technical knowledge into students' systematic ability to solve complex engineering problems. Traditional CNC machining teaching often exhibits the characteristics of a separation between theoretical instruction and skills training, discrete knowledge modules, and a lack of engineering context. This makes it difficult to effectively support the development of modern engineering abilities, with their core focus on design thinking, system integration, and innovative decision-making. This limitation not only affects teaching effectiveness but also restricts the alignment between talent cultivation and the demands of industrial technological evolution. Therefore, exploring innovative paths for the practical teaching mode of CNC machining holds significant theoretical necessity and practical urgency. This research proceeds from the deconstruction of the connotation of engineering ability and the characteristic analysis of the teaching system. It aims to construct a teaching paradigm, capable of promoting the deep transformation of knowledge into ability and adapted to the context of intelligent manufacturing, by systematically reconstructing teaching objectives, the environment, and evaluation mechanisms, thereby providing a systematic solution for the quality improvement and connotative development of engineering practice teaching.

## 1. Theoretical Correlation between the Connotation of Engineering Ability and CNC Machining Teaching

### 1.1 Analysis of the Core Dimensions of Engineering Ability

The composition of engineering ability is an integrated system comprising multiple levels of cognitive and practical elements. Its core dimension is first manifested as systematic cognitive ability, which is grounded in mathematics, natural sciences, and engineering science. This ability requires

practitioners to employ abstract theories and models to analyze the inherent laws and constraints of complex technical systems. Beyond this foundational cognition, design-implementation capability constitutes the core link of engineering practice. It emphasizes the completion of the full-process technical integration and materialized creation, from conceptualization and scheme design to physical realization, under specific requirements and resource constraints. This dimension pertains not only to the generation of technical solutions but also involves the thought process of making trade-offs and decisions under multiple constraints such as cost, time, performance, and reliability.

Furthermore, the high complexity of modern engineering activities requires practitioners to possess significant collaborative and metacognitive abilities. This involves the collaborative competence to communicate effectively within multidisciplinary teams, coordinate resources, and manage project processes, as well as the reflective thinking to monitor, evaluate, and regulate one's own cognitive processes. Metacognitive ability enables engineers to discern the essence of problems, plan solution paths, evaluate the effectiveness of strategies, and make dynamic adjustments during execution. The aforementioned dimensions collectively constitute a dynamic, interactive, and hierarchical framework of abilities. It is not a collection of static knowledge but a transferable paradigm of thinking and action oriented towards solving problems under uncertainty. This framework provides a clear spectrum of competencies for the goal-setting of specialized teaching, requiring that instructional activities must transcend the mere transmission of knowledge and instead focus on cultivating this composite and reflective professional capability<sup>[1]</sup>.

### ***1.2 Analysis of the Systemic Characteristics of CNC Machining Teaching***

As a typical carrier of technical education, the CNC machining teaching system is intrinsically characterized by technological integration and process closure. Its teaching content naturally integrates multidisciplinary knowledge, including mechanical principles, materials science, computer programming, automatic control, and measurement technology. The teaching process strictly follows the complete manufacturing chain, from part drawing analysis, process planning, and machining program compilation, to machine tool operation and finished product quality inspection. This characteristic dictates that teaching cannot impart discrete knowledge points in isolation; instead, it must construct a cognitive and practical environment capable of reflecting authentic technological integration and process logic. This system is, in essence, a miniature and controlled prototype of an engineering system. Its pedagogical value lies in enabling students to experience the complete transformation chain from abstract design requirements to a physical product.

Another key characteristic of this system is its high interactivity and real-time feedback capability. The learning process occurs within an interactive interface constituted by the "human-software-hardware" triad. Learners' decisions directly drive physical equipment through CNC codes, and the machining results immediately provide physical verification of the correctness of prior process decisions and programs. This tightly coupled "decision-execution-feedback" loop endows the teaching process itself with an objective, formative evaluation mechanism based on tangible outputs. Each machining attempt produces an irreversible physical outcome, thereby providing a concrete basis for analysis and reflection. This immediate, objective, and embodied feedback mechanism creates a unique context for cultivating engineering judgment and a sense of responsibility—a core pedagogical trait that many purely theoretical or offline simulation-based teaching methods cannot replicate.

### ***1.3 The Mapping Mechanism between Ability Orientation and Teaching Content***

The key to achieving the goal of ability cultivation lies in establishing a structured mapping mechanism from abstract ability dimensions to specific teaching content elements. This mechanism first requires the deconstruction and reconstruction of the CNC machining knowledge system. Guided by the "cognition-design-implementation-collaboration" ability framework, it transforms the traditional content modules centered on equipment and operation into task sequences oriented by a chain of engineering problems. For instance, the learning of "programming commands" is placed within the design context of "realizing a process plan for specific geometric features and precision requirements," thereby naturally embedding design thinking and systematic trade-off abilities into knowledge transmission. The mapping process essentially translates ability goals into a series of meticulously designed teaching activities that carry specific cognitive challenges, rendering ability development concrete as observable and executable learning behaviors<sup>[2]</sup>.

The deeper logic of this mapping lies in constructing an iterative cycle of knowledge application

and a progressive increase in cognitive load. The design of teaching content should enable learners to repeatedly experience the complete process of "requirements analysis - scheme formation - program implementation - result verification - reflection and optimization," and gradually introduce more complex constraints (such as efficiency, cost, and multi-process coordination) within this cycle. In this way, the learning of technical knowledge and the cultivation of engineering ability are no longer two parallel lines. Instead, within the same process of solving progressively complex tasks, the internalization, integration, and transformative ability-development of knowledge are achieved. This spiral, ascending learning path motivates learners to transform from passive recipients of knowledge into active problem-solvers. Ultimately, it fosters a stable mental schema and action pattern that is transferable to broader engineering domains, achieving a fundamental shift from "know-how" to "competence."

## **2. Limitations of the Traditional Teaching Mode and Pathways for Innovation**

### ***2.1 Examining the Effectiveness of the Existing Teaching Structure***

The existing teaching structure for CNC machining typically presents itself as a linear sequence model of "theoretical instruction - skills training." The theoretical teaching phase focuses on the modularized transmission of knowledge concerning CNC principles, code syntax, and process parameters, while the experimental or practical training phase often concentrates on familiarizing students with machine tool operating procedures and the repetitive machining of fixed workpieces. This structure separates knowledge acquisition from application in both time and space. Consequently, students' understanding of CNC technology remains at the level of functional cognition, making it difficult for them to gain a deep-seated grasp of the integrity of the manufacturing system, the chain of process decision-making, and the trade-offs among solutions under multiple constraints. Its more profound limitation lies in its presupposition of a standardized path for skill acquisition, which fails to adequately accommodate the inherent uncertainty and exploratory nature of engineering design.

Upon further examination, the core predicament of this structure lies in the fragmentation of knowledge modules and the absence of an authentic engineering context. The teaching process is broken down into mutually independent parts — for instance, programming, operation, and measurement are arranged in different courses or teaching units. This arrangement severs the highly coupled, iterative internal relationships among various elements inherent in real engineering tasks. After completing one part, students' cognitive process is forcibly interrupted, leaving them without the opportunity to bring their learning outcomes into the subsequent part for verification, feedback, and optimization. Consequently, critical engineering abilities such as systems thinking, problem definition, and comprehensive problem-solving struggle to be effectively nurtured and developed within these fragmented and de-contextualized teaching activities, ultimately resulting in poor transferability of learning outcomes<sup>[3]</sup>.

### ***2.2 The Drive of Technological Evolution on the Teaching Paradigm***

New-generation information technologies, represented by digital twins, virtual simulation, the industrial internet, and intelligent programming techniques, are profoundly reshaping the technological paradigm of the manufacturing field. These technologies not only alter the processes of product design and production but also place new demands on the competency structure of technical personnel who support industrial development. The intelligent manufacturing environment requires practitioners not only to master traditional machining skills but also to possess competencies in cross-domain model construction, data-driven decision-making, and the interaction between virtual and physical systems. This constitutes the fundamental driving force for the evolution of the teaching paradigm. The equipment-operation-centered ability cultivation under the traditional model can no longer meet the expectations of future manufacturing systems for talents in the realms of digital modeling, process optimization, and autonomous decision-making.

Technological evolution provides both the direct tools and the methodological foundation for breakthroughs in the teaching paradigm. High-fidelity virtual simulation and digital twin technologies can construct a safe, low-cost, and highly flexible digital manufacturing environment. This allows students to conduct complex process planning verification, collision detection, program debugging, and performance prediction without occupying physical equipment and materials. This offers the possibility of breaking through the limitations of physical resources, time, and space, and realizing a rapid iterative

cycle of "design-simulation-optimization." Technology-driven teaching is no longer confined to the operational replication of physical equipment but shifts towards the systematic cultivation of abilities in digital modeling, analysis, prediction, and optimization of all elements within the manufacturing process. This fundamentally redirects the focus of teaching from skills training towards the development of engineering thinking and an innovative mindset.

### ***2.3 The Pedagogical Design Shift towards Ability Integration***

To overcome the limitations of the traditional model and respond to technological drivers, the core shift in pedagogical design lies in constructing a new framework oriented towards ability integration. This shift means that the logical starting point of teaching design is no longer the breadth of knowledge coverage, but rather the organic integration and encapsulation of required theoretical knowledge, technical skills, tools and methods, as well as non-technical competencies such as collaboration and communication, using typical, progressive engineering tasks or projects as the vehicle. The objective output of teaching shifts from "knowing what" and "being able to operate what" to "what level of complex engineering problems can be comprehensively solved by integrating knowledge and resources," emphasizing the emergent and holistic nature of ability<sup>[4]</sup>.

Achieving this shift requires a systematic reconstruction of teaching design, the core of which lies in the creation of comprehensive learning task sequences that possess appropriate complexity, openness, and authenticity. These sequences should simulate the ambiguity, multi-objectivity, and iterativity inherent in real engineering problems, guiding students through a complete closed loop encompassing requirements analysis, scheme design, program implementation, virtual verification, physical processing, quality assessment, and iterative optimization. Within this framework, traditional disciplinary boundaries are organically integrated. Knowledge elements such as mathematical calculation, material mechanics, computer programming, and precision control become natural requirements and intrinsic tools for completing tasks, rather than isolated learning objectives. Consequently, the entire teaching process evolves into a cognitive construction journey where students, under guidance, engage in autonomous inquiry, collaborative decision-making, and reflective practice. Thus, within the context of solving authentic technical problems, multi-dimensional engineering abilities are simultaneously stimulated, deeply integrated, and consolidated.

## **3. Systematic Construction of an Innovative Teaching Model for CNC Machining**

### ***3.1 Structured Design of Multi-Level Ability Objectives***

The effectiveness of an innovative teaching model first depends on whether its objective system can precisely correspond to and guide the phased development of engineering ability. The structured design of multi-level ability objectives aims to construct a progressive competency spectrum, spanning from foundational cognition to comprehensive innovation. Its underlying objectives focus on the instrumental mastery of CNC system principles, process fundamentals, and programming syntax; the intermediate-level objectives emphasize the application of these tools to accomplish the process planning and realization of specific components within simulated or simplified contexts, fostering preliminary system integration and problem-solving skills; the highest-level objectives target the capacity for innovative solution design, multi-objective trade-offs, and full-process management within open, multi-constraint complex engineering tasks. These objectives across different levels are not merely juxtaposed but rather constitute progressively supportive cognitive scaffolding, where lower-level automated skills serve as the foundation upon which higher-level creative thinking can be unleashed.

This structured design breaks the limitations of traditional single-skill objectives, requiring each teaching module or project task to clarify its positioning within the entire competency spectrum and its supporting and transitional role between adjacent ability levels. The design process necessitates deconstructing abstract descriptions of abilities such as "analysis," "design," and "optimization" into observable and assessable specific teaching behaviors and output indicators. For example, the "optimization ability" might manifest at the foundational level as adjusting a single machining parameter to improve surface quality; at the advanced level, it is embodied in modeling and collaboratively optimizing multiple objectives, including material, efficiency, cost, and equipment load. Through this refined and progressively structured mapping of objectives, the teaching process transforms into a purposeful and sequential accumulation, integration, and internalization of ability

components, ensuring that learners' competency development follows a clear path with attainable goals<sup>[5]</sup>.

### ***3.2 Integration of Virtual and Physical Teaching Environments and Resource Allocation***

Supporting the realization of the aforementioned ability objectives requires an integrated teaching environment that breaks physical boundaries and expands cognitive dimensions. The essence of the virtual-actual integration environment lies in constructing a mixed-reality learning space where a digital twin is deeply interconnected with the physical machining system, enabling bidirectional data flow. The virtual environment, relying on high-precision simulation software and digital process platforms, undertakes functions such as process feasibility verification, risk-free program debugging, machining process prediction, and rapid iteration of multiple solutions, thereby expanding the exploratory boundaries and error tolerance of learning. The physical environment provides authentic experiences of material interaction, force, and heat, along with physical validation of the final product, consolidating cognition and cultivating on-site response capabilities to uncertainties. These two environments are connected through a unified digital thread, forming an augmented cognitive cycle where "virtual prediction guides physical operations, and physical results feed back to refine the virtual model."

The logic of resource allocation must adapt to this environment, shifting from an "equipment-centric" approach to a "data and task-flow-centric" one. Hardware resources (such as CNC machine tools and measuring instruments) and software resources (such as CAD/CAM, PLM, and simulation cloud platforms) are flexibly scheduled and combined according to the needs of the teaching task flow, forming a technological ecosystem that supports a rapid cycle of "virtual experimentation - physical validation." The key lies in establishing a unified data management and interaction interface, ensuring the full-process digital connection and traceability from 3D models and process sheets to CNC codes and machining feedback data. This allows for the complete recording and analysis of students' learning trajectories, decision-making data, and operational feedback, providing a data foundation for personalized learning support and process-oriented evaluation. Consequently, resource allocation evolves from merely ensuring basic operations to an enabling architecture that underpins deep learning. Its core value is to provide a seamless, data-rich experience flow, maximizing the efficiency and depth of competency construction.

### ***3.3 Continuous Iterative Teaching Evaluation and Optimization Mechanism***

An innovative teaching model with vitality must embed a set of evaluation and optimization mechanisms capable of driving its self-improvement. The core characteristic of this mechanism is the shift from summative, single-dimensional evaluation to process-oriented, multi-source assessment of ability development. Evaluation data is no longer derived solely from the final workpiece or test paper but is extensively collected from students' simulation iteration records within the virtual environment, their process decision-making logic, operational sequences and exception handling during physical processing, communication logs in project collaboration, and reflective reports throughout the entire process. This multi-modal data collectively depicts the dynamic trajectory and thought patterns of students' competency construction, providing empirical evidence for understanding the micro-processes of learning occurrence.

Based on this data foundation, the optimization mechanism forms a closed loop of "evaluation - diagnosis - intervention - redesign." By analyzing the performance data of individual students and groups at various points on the competency spectrum, specific bottlenecks in the teaching process regarding goal attainment, task suitability, or support effectiveness can be diagnosed. Optimization interventions thus become highly targeted, potentially manifesting as adjustments to the difficulty gradient of a virtual simulation task, the supplementation of micro-lecture resources for a specific knowledge module, or the redesign of guidance strategies for team projects. This mechanism renders the teaching model itself an adaptive system capable of responding to learning feedback and continuously evolving. It emphasizes the dynamic and generative nature of teaching design, ensuring that its cultivation effectiveness continuously improves in step with technological evolution, disciplinary development, and changes in student cohort characteristics. This achieves long-term sustainability and contemporary relevance in engineering ability cultivation, transforming the teaching model itself into an evolvable professional practice.

## Conclusion

This research, through theoretical analysis, problem diagnosis, and systematic construction, has proposed an innovative practical teaching model for CNC machining centered on the cultivation of engineering ability. This model takes the structured design of multi-level ability objectives as its guide, is supported by a deeply integrated virtual-actual teaching environment, and uses continuous iterative evaluation based on multi-source data as its optimization engine, forming a tripartite teaching system of objectives-environment-mechanism. It overcomes the limitations of linearization and fragmentation inherent in traditional teaching, promoting the organic unity of knowledge learning and ability construction within an engineering context. Future research can be deepened in the following directions: first, exploring the methods for deep integration of digital twin technology within the closed teaching loop and the mechanisms of its learning effects; second, developing a more adaptive recommendation system for personalized ability development paths based on learning analytics; third, validating the transferability and scalability of this model across a broader range of engineering training course clusters. The innovation of teaching models is a dynamically evolving process, requiring continuous responsiveness to technological changes and the development of educational philosophies, in order to achieve a sustained improvement in the quality of engineering talent cultivation.

## References

- [1] Xiao, H. J. "Analysis of Practical Teaching in CNC Machining Courses." *Integrated Circuit Applications* 42.09(2025): 230-231.
- [2] Du, J. S. "Practical Research on the 'Theory-Practice Integration' Teaching Model in Secondary Vocational CNC Machining Majors." *Auto Time* .02(2025): 85-87.
- [3] Li, T. Y., and Zhao, F. "Reform and Practice of CNC Machining Practical Teaching under the Background of Intelligent Manufacturing." *Die & Mould Manufacture* 24.09(2024): 50-52.
- [4] Sun, G. J. "Curriculum Reform and Practice of CNC Machining Technology Based on Engineering Practice." *Die & Mould Manufacture* 24.03(2024): 103-105.
- [5] Lin, D. Y. "Research on the Construction of CNC Machining Practical Training Courses Based on Engineering Ability Cultivation." *Scientific Consultation (Science & Technology • Management)* .19(2021): 105-106.