

Research Status and Trends of the Application of Digital Teaching Tools in Mechanical Engineering Teaching

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Abstract: *The application of digital teaching tools in mechanical engineering teaching is becoming increasingly widespread, and the research status and evolutionary trends of these tools have become a focus of attention in the interdisciplinary field of educational technology and mechanical engineering. Current research exhibits multidisciplinary distribution characteristics, concentrating on directions such as mechanical design, manufacturing processes, and electromechanical control, with hotspots covering virtual simulation, three-dimensional modeling platforms, and learning analytics systems. Typical tools are classified into four categories—modeling, analysis, simulation, and collaboration—each with differentiated teaching adaptability. Existing studies mainly adopt the paradigm of system development and effect verification, but they have limitations in sample representativeness, longitudinal tracking, and measurement of mediating variables. The core mechanisms of digital tools supporting mechanical teaching consist of tool interaction design guided by cognitive load theory, concept visualization driven by geometry and physics engines, and teaching feedback models supported by learning behavior data. Future evolutionary trends manifest as the integration of intelligent tools with adaptive learning environments, the reconstruction of immersive scenarios driven by extended reality technologies, and the collaborative construction of cross-platform toolchains and mechanical knowledge graphs. A systematic review of the above content can provide a reference framework for research and development in this field.*

Keywords: *digital teaching tools; mechanical engineering teaching; cognitive load theory; extended reality; knowledge graph*

Introduction

Mechanical engineering teaching involves a large number of abstract concepts, spatial configuration relationships, and dynamic motion logic. Traditional teaching methods mainly rely on two-dimensional drawings, physical models, and static blackboard writing, which makes it difficult to fully present the internal force transmission paths, assembly constraints, and temporal characteristics of machining processes in mechanisms. The introduction of digital teaching tools can present the solution results of partial differential equations, three-dimensional solid modeling processes, and motion simulation animations in an interactive manner, thereby bridging the gap between abstract representation and concrete cognition. However, current research in this field is relatively fragmented, with diverse tool types and different technical paths, and there is a lack of systematic review of the application landscape, core supporting mechanisms, and future evolutionary trends. Meanwhile, existing research is methodologically limited mostly to short-term effect verification and single-scenario experiments, showing insufficient attention to the teaching adaptability boundaries of different tools, the depth of learning behavior data utilization, and cross-platform collaborative capabilities. Therefore, it is necessary to conduct a structured summary of the research on the application of digital teaching tools in mechanical engineering teaching, clarify its internal mechanisms and evolution directions, and provide a theoretical basis for subsequent tool design, teaching integration, and evaluation system construction.

1. Research Landscape of the Application of Digital Teaching Tools in Mechanical Engineering Teaching

1.1 Disciplinary Distribution and Hot Topics of Application Research

The application research of digital teaching tools in mechanical engineering teaching presents a multidisciplinary distribution characteristic, which is mainly concentrated in such second-level disciplines as mechanical design, manufacturing and automation, material forming and control engineering, and mechatronic engineering. Among these disciplines, the research in the direction of mechanical design accounts for the highest proportion, which involves the embedding analysis of tools such as computer-aided design (CAD) and computer-aided engineering (CAE) in course teaching. The direction of manufacturing processes focuses on the classroom application of tools such as numerical control simulation and machining process simulation. The research in the direction of electromechanical control is relatively limited, which mostly revolves around virtual simulation of programmable logic controllers (PLC) and robot offline programming tools. From the perspective of disciplinary affiliation, the application research of tools often relies on the first-level discipline of mechanical engineering, with a small amount of extension into the field of educational technology, thus forming a two-way coupling structure driven by technology and teaching demands.

The hot topics of current research revolve around virtual simulation tools, interactive three-dimensional modeling platforms, and online collaborative learning environments. Virtual simulation technology is used for mechanical structure cognition, mechanism motion analysis, and machining path verification, and it has become a high-frequency keyword. Meanwhile, lightweight teaching tools based on augmented reality (AR) and mixed reality (MR) are gradually attracting attention, aiming to address the representational gap between traditional two-dimensional drawings and physical models. In addition, integrated platforms of digital tools for learning analytics have also begun to emerge, which provide a data foundation for teaching feedback by recording students' operation trajectories and error patterns. These hotspots reflect an evolutionary trend from single-tool application to deep integration between tools and teaching content^[1].

1.2 Analysis of Teaching Adaptability of Typical Tool Types

Typical digital teaching tools can be divided into four types according to their functional dimensions: modeling tools, analysis tools, simulation tools, and collaboration tools. Modeling tools are represented by parametric design software such as SolidWorks and Inventor, and their teaching adaptability is reflected in supporting the logical construction process from two-dimensional sketches to three-dimensional entities, which helps students establish the mapping relationship between spatial configuration and engineering constraints. Analysis tools include finite element software such as ANSYS and Abaqus, which are adapted to the numerical visualization of abstract concepts such as mechanical strength and heat conduction, presenting the solution results of partial differential equations in the form of contour plots or deformation animations. Simulation tools, such as numerical control machining simulation systems and robot motion simulation platforms, focus on the dynamic reproduction of process procedures and motion logic, thereby reducing the risk and cost of operating physical equipment.

Collaboration tools refer to project management tools based on cloud platforms and shared design spaces, and their adaptability is reflected in supporting multi-terminal collaborative modification of three-dimensional models and design documents, thereby simulating the distributed design process in real engineering environments. Different types of tools have differences in teaching adaptability: modeling tools have higher requirements for initial cognitive load and need to be used with simplified task sets; analysis tools require prerequisite theoretical explanations; otherwise, students may easily focus on parameter settings while neglecting physical meanings; simulation tools have high adaptability in machining process teaching but have limited accuracy in fine tasks such as assembly tolerance analysis; collaboration tools are well adapted in team design projects but may distract attention in individual skill training scenarios. The degree of match between tool types and teaching objectives determines the upper limit of their application effectiveness.

1.3 Methodological Characteristics and Limitations of Existing Research

Existing research mainly adopts two paradigms in terms of methodology: system development and effect verification. System development research typically describes the design architecture, functional

modules, and interaction logic of a specific digital teaching tool, focusing on the reproducibility of technical implementation, and it often presents the tool in the form of a prototype system or plug-in. Effect verification research mostly employs quasi-experimental designs, sets up experimental groups and control groups, and evaluates the teaching utility of tools through quantitative indicators such as pretest and posttest scores, operation time, and error rates. Some studies introduce questionnaires or interviews to obtain users' subjective experiences, but few adopt mixed research methods to deeply mine process data (e.g., operation logs, eye-tracking trajectories). Overall, quantitative analysis occupies a dominant position, while qualitative research mostly appears in a supporting role.

There are several methodological limitations. First, the research samples are mostly limited to a single institution or class, which restricts the external validity, and there is a lack of systematic comparison of the applicability of the tools under different educational levels and students' prior knowledge conditions. Second, most studies focus on short-term teaching effects (a single experiment or one semester), and there is a relative scarcity of longitudinal research on long-term knowledge retention and transfer ability after tool intervention. Third, tool evaluation indicators mostly focus on academic performance improvement, while the measurement of mediating variables such as cognitive load, learning engagement, and metacognitive ability is relatively weak. Fourth, existing studies tend to verify the effectiveness of specific tools but rarely explore the boundary conditions under which tools fail, leading to the risk of overgeneralization of conclusions. These limitations suggest that subsequent research needs to expand the methodological toolbox and enhance cross-context comparison and longitudinal tracking designs^[2].

2. Core Mechanisms of Digital Teaching Tools Supporting Mechanical Engineering Teaching

2.1 Tool Interaction Design Based on Cognitive Load Theory

Cognitive load theory provides a theoretical framework for the interaction interface and task flow design of digital teaching tools. In mechanical engineering teaching scenarios, students need to simultaneously process multi-dimensional information such as geometric configurations, dimensional constraints, material properties, and motion relationships, which can easily lead to an overload of intrinsic cognitive load. Digital tools can reduce extraneous cognitive load through strategies such as modular task decomposition, progressive information presentation, and redundant information filtering. For example, three-dimensional modeling tools optimize the spatial layout of the feature tree, property panel, and graphics area, keeping common operation paths within the user's visual center and reducing visual search costs. Meanwhile, the dynamic prompting system automatically hides non-relevant options based on the user's current operation steps, thereby avoiding excessive information density on the interface.

Another key mechanism in tool interaction design is scaffolded prompting and error prevention. For common errors in mechanical drawing such as view projection mistakes or assembly constraint conflicts, the tool can set real-time syntax checking and logical verification, and it can issue warnings or provide automatic correction suggestions before the user submits an erroneous operation. This design transfers part of the cognitive burden to the tool side, thereby allowing learners to focus their limited working memory resources on principle understanding rather than operation correction. In addition, the tool supports multimodal input (mouse dragging, parameter input, gesture control), which can accommodate the operation preferences of students with different cognitive styles and further optimize the efficiency of cognitive resource allocation.

2.2 Technical Implementation Paths for Mechanical Concept Visualization

The visualization of mechanical concepts relies on the collaborative work of geometric modeling engines and physics engines. The geometric modeling engine is responsible for converting part shapes, mating relationships, and assembly hierarchies into three-dimensional solid representations, and it commonly uses boundary representation (B-Rep) and constructive solid geometry (CSG) to achieve a balance between accuracy and computational efficiency. The physics engine simulates rigid body motion, collision detection, and force deformation, thereby enabling abstract concepts such as degrees of freedom, constraint reaction forces, and stress concentration to obtain concrete mapping. For example, in gear meshing instruction, the tool can display in real time the colored contour maps of tooth surface contact line movement and transmission error, transforming the implicit meshing dynamics process into an explicit visual sequence.

Extended reality technologies further enrich the visualization paths. Augmented reality tools overlay virtual mechanical models onto real parts or drawings, enabling multi-angle sectioning, exploded views, and internal structure perspective, thereby solving the problem of internal assembly relationships that traditional models cannot display. Mixed reality environments allow users to grab a virtual crank-slider mechanism with gestures and drag its motion, while simultaneously displaying the displacement-time curve of key points. The core of these technical paths lies in unifying the static structure and dynamic behavior of mechanical systems within the same visualization framework, thus preventing students from performing multiple conversions from two dimensions to three dimensions and from static to dynamic states in their minds, and reducing the cognitive threshold of spatial reasoning^[3].

2.3 Teaching Feedback Model Driven by Learning Behavior Data

Digital teaching tools can record fine-grained behavioral data during students' operation processes, including mouse click sequences, parameter modification frequencies, time spent on modeling steps, and error retry counts. These data constitute the raw material of learning behavior trajectories. Based on sequential pattern mining or hidden Markov models, typical behavior patterns can be identified. For example, frequent switching between the reference plane and the sketch plane during shaft part modeling may indicate an insufficient understanding of the reference system. By comparing these patterns with expert operation sequences, cognitive breaks in students can be located, and then targeted feedback prompts can be generated, such as suggesting a review of "rules for selecting reference planes" or demonstrating standard operation procedures.

Another type of feedback model uses classification algorithms to make real-time judgments about learning states. For example, in finite element analysis tools, there is a statistical correlation between students' operational behaviors (such as the choice of mesh density and the order of applying boundary conditions) and the convergence of the final analysis results. By training decision tree or support vector machine models, the tool can predict possible convergence errors before students submit the solution and provide specific modification suggestions. The feedback forms include text prompts, color-highlighted error areas, or automatic playback of correct operation segments. This model does not rely on manual annotation or post-hoc evaluation; it is entirely based on the intrinsic patterns of behavioral data, thus achieving a shift from outcome-oriented feedback to process-oriented feedback and enhancing the immediacy and precision of teaching interventions.

3. Evolutionary Trends of Digital Teaching Tools in Mechanical Engineering Teaching

3.1 Integration of Intelligent Tools and Adaptive Learning Environments

Intelligent tools gradually acquire the ability to identify and predict learners' operation intentions by embedding machine learning algorithms and knowledge representation models. In mechanical drawing or computer-aided design tasks, a tool can analyze the sketch contours, dimensioning sequences, and modification trajectories drawn by a student, infer the deviation direction between the student's design thinking and standard engineering expression, and proactively provide correction strategies. This intelligent assistance is no longer limited to passively responding to commands; instead, it can predict the next operation and generate candidate solutions, such as automatically recommending tolerance grades or surface roughness values during shaft-hole fit modeling. Meanwhile, an adaptive learning environment dynamically adjusts task difficulty and prompt frequency according to the student's operational proficiency and error types, thereby forming an individualized learning path planning^[4].

The core support of an adaptive learning environment lies in the construction and updating of a learner model. This model integrates a cognitive diagnosis model and sequential behavioral features, and it maps the behavioral data of students in three-dimensional modeling, motion simulation, or finite element analysis into a knowledge mastery vector. When the system detects that a student makes repeated errors in applying a certain type of constraint (such as parallelism, coaxiality, or tangency), it will automatically push relevant micro-videos or interactive exercises and reduce the frequency of that constraint type in subsequent tasks; then, after the mastery level improves, the system gradually restores the difficulty. The two-way data flow between tools and the environment enables the teaching support system to abstract general strategies from group learning patterns and also to fine-tune parameters according to individual differences, thus forming a dynamically convergent teaching adaptation mechanism.

3.2 Reconstruction of Immersive Teaching Scenarios Driven by Extended Reality Technology

Extended reality technology includes virtual reality, augmented reality, and mixed reality, and its commonality lies in breaking the representational barrier between two-dimensional screens and three-dimensional physical objects. In mechanical assembly teaching scenarios, virtual reality tools can construct a fully enclosed immersive environment, in which students interact through head-mounted displays and controllers to complete virtual disassembly and assembly of reducers, fixtures, or hydraulic valve groups. The system records hand positions, grip forces, and part alignment accuracy in real time, and it compares these kinematic data with standard assembly sequences to identify order errors or interference areas. Compared with traditional three-dimensional animation demonstrations, the immersive environment provides haptic feedback and spatial presence, thereby transforming the understanding of assembly logic and spatial relationships from passive viewing into active operation.

Mixed reality technology further anchors virtual models onto workpieces or equipment in real physical space. Taking the teaching of numerical control machine tool operation as an example, while a student sees the actual machine panel through see-through glasses, the virtual overlay dynamically displays the spindle motion trajectory, tool compensation parameters, and coolant flow direction. This integration of virtual and real scenes reconstructs the traditional separation of “explanation-observation-operation,” thereby allowing principle cognition and hands-on operation to be completed within the same spatiotemporal coordinates. Furthermore, a multi-user collaborative mixed reality environment allows multiple students to gather around the same physical bench, with each student seeing targeted virtual annotations through his or her own terminal (e.g., one observes stress distribution while another observes the temperature field), thus achieving layered information sharing without mutual interference and expanding the information carrying capacity of teaching scenarios^[5].

3.3 Collaborative Construction of Cross-Platform Tool Chains and Mechanical Knowledge Graphs

Current digital teaching tools are presenting a trend of evolving from single-function software to cross-platform tool chains. A tool chain typically covers a design modeling module, a simulation analysis module, a process planning module, and a virtual debugging module. Each of these modules achieves unidirectional or bidirectional transmission of model parameters and simulation results through standardized data exchange formats (such as STEP, IGES, and JT) or application programming interfaces. In mechanical engineering teaching, this type of tool chain enables students to complete the entire task process from part modeling to machining simulation within an integrated framework, thereby avoiding data loss or format conversion errors caused by switching between different software. Meanwhile, a cloud-based collaborative platform allows students to access the same project file on different terminals (personal computers, tablets, virtual reality devices), thus achieving continuity of design iteration and version traceability.

The construction of a mechanical knowledge graph injects semantic association capabilities into cross-platform tool chains. A knowledge graph takes entities (such as gears, bearings, and bolts) and relationships (such as meshing, supporting, and fastening) as its basic units, and it structurally encodes mechanical design handbooks, national standards, and typical mechanism motion laws. When a student draws a gear in a modeling tool, the tool chain can automatically retrieve from the knowledge graph the module series, recommended number of teeth, and failure mode descriptions for that gear, and it can link to the meshing stiffness calculation equation in the simulation module. Different platforms share the service interface of the knowledge graph, thereby achieving collaborative representation and reasoning for the same mechanical concept. This collaborative construction mechanism enables the tool chain to no longer be an isolated collection of software but to form an ecosystem centered around the mechanical knowledge ontology, where every operation node in the teaching process can obtain semantic support from the knowledge graph and cross-tool context transfer.

Conclusion

The application research of digital teaching tools in mechanical engineering teaching has formed a relatively clear disciplinary distribution and tool type system. Among these tools, modeling tools, analysis tools, simulation tools, and collaboration tools each have their own applicable scenarios, but their effectiveness is subject to multiple constraints such as cognitive load, task complexity, and the degree of match with teaching objectives. Cognitive load theory provides load-reduction strategies for

tool interaction design; the visualization paths of geometry and physics engines achieve the mapping of mechanical concepts from abstraction to concreteness; and the feedback model driven by behavioral data shifts teaching intervention from outcome evaluation to process diagnosis. In terms of evolutionary trends, intelligent tools are deeply integrating with adaptive learning environments, dynamically adjusting task difficulty and prompt strategies according to learner behavior. Extended reality technology reconstructs immersive teaching scenarios through virtual reality and mixed reality, breaking the representational barrier between two-dimensional screens and three-dimensional physical objects. The collaborative construction of cross-platform tool chains and mechanical knowledge graphs provides semantic association and data interoperability capabilities across design, simulation, and machining processes.

Future research needs to further focus on the following directions: the cross-context generalization ability of learner models in intelligent tools, the long-term knowledge transfer effects in extended reality environments, and the maintenance mechanism of multi-platform semantic consistency driven by knowledge graphs. In addition, the identification of boundary conditions for tool failure and the development of adaptive adjustment strategies are also key issues for improving the application depth of digital teaching tools in mechanical engineering teaching.

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