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

Yunhan Mu*

Hainan Vocational University of Science and Technology, Haikou, 570100, China
**Corresponding author: qq444524605@hotmail.com*

Abstract: *The application of digital teaching tools in the teaching of mechanical engineering has been developing gradually, and now the research and development trends of these tools have attracted the attention of many scholars in the interdisciplinary field of educational technology and mechanical engineering. Good results have been achieved in many areas of research so far, such as mechanical design and production processes, electromechanical control and virtual simulation, 3D model platforms, learning analytics systems, etc., and hot spot research has also emerged in these fields. The four types of tools are Model and Analysis, Simulation and Application, Modelling, Analysis, etc. Most of the previous studies have used the system development and effect verification method, but they are lacking in sample representativeness, longitudinal tracking and measurement of mediating variables. The Design of Tool Interaction Based on Cognitive Load Theory, the Creation of Concept Visualisations with Geometry and Physics Engines, and the Construction of Teaching Feedback Models Based on Learning Behaviour Data are representative cases of the application of digital technology in teaching mechanics. In the future, the direction of development will be the integration of intelligent tools and adaptive learning environments, the construction of immersive scenarios based on extended reality technology, and the joint construction of cross-platform toolchains and mechanical knowledge graphs. A systematic review of the above content will offer some references for research and development in this area.*

Keywords: *Digital Teaching Tools, Mechanical Engineering Teaching, Cognitive Load Theory, Extended Reality, Knowledge Graph*

Introduction

Mechanical Engineering teaching has a large number of abstract concepts, spatial arrangement relationships and dynamic motion logic. The traditional way of teaching is to use two-dimensional drawings, physical models and static blackboard writing; thus, it is difficult to present all the internal force transmission paths, assembly constraints and temporal characteristics of machining processes in mechanisms comprehensively. Digital teaching tools can be used to show students the results of solving partial differential equations, the process of three-dimensional solid modelling and motion simulation animations, etc., to connect abstract representation with concrete cognition. There have been no organised studies on the application scenarios, basic support mechanisms and future development directions of many of the tools and various technical routes that have been developed so far in this field. At the same time, most of the previous studies have only confirmed the short-term effects and single-scenario experiments, and little attention has been paid to the teaching adaptability limits of all kinds of tools, the degree of utilisation of learning behaviour data, and cross-platform collaboration capabilities. Therefore, an organised summary of the research on the application of digital teaching tools in mechanical engineering teaching should be carried out, and its internal structure and development direction clarified, a theoretical basis provided for the design of teaching tools and integration with teaching, etc.

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

1.1 Disciplinary Distribution and Hot Topics of Application Research

Research on the application of digital teaching tools in mechanical engineering education has been carried out at all levels, and it is mainly concentrated in second-level courses such as mechanical design, manufacturing and automation, material forming and control engineering, and mechatronics engineering. Among them, the proportion of research in the direction of mechanical design is the highest; therefore, tools such as Computer-Aided Design (CAD) and Computer-Aided Engineering (CAE) will be introduced in the course teaching. The goal of the production process is to offer teaching aids for numerical control simulation and machining process simulation in the classroom. Research in the field of electromechanical control is relatively scarce, and most of what has been achieved so far is virtual simulation of PLCs and offline programming tools for robots. Most of the research on tools at the first level of discipline has been conducted in mechanical engineering, and only a small number of extensions have been made to the field of educational technology; thus, a two-way coupling structure driven by technology and teaching demands has been formed.

At present, the front of research is the virtual simulation tool, the interactive three-dimensional model platform and the online collaborative learning environment. In short, one can learn about the structure of machinery, analyse the motion of mechanisms and machining paths, and has gained some attention recently. At the same time, light teaching tools based on augmented reality (AR) and mixed reality (MR) are gradually gaining the attention of scholars, and their purpose is to solve the problem of representation gaps between traditional two-dimensional drawings and physical models. At the same time, integrated platforms for digital tools in learning analytics have also begun to be built to collect data on students' behaviour and mistakes and provide teaching feedback, etc. The above hot spots show that people are using many tools for teaching now, and these tools are becoming more and more integrated[1].

1.2 Analysis of Teaching Adaptability for Typical Tool Types

Generally speaking, the four kinds of digital teaching tools can be divided into the following four categories according to their functions: modelling tools, analysis tools, simulation tools and collaboration tools. Parametric Design Software, such as SolidWorks and Inventor, is a modeler; it is suitable for teaching because one can build a 3D model logically based on a 2D sketch and learn how to add space and engineering constraints. Finite-element programs are the analysis tools, such as ANSYS and Abaqus; these programs have been used to numerically present abstract ideas, such as mechanical strength and heat conduction, and to show the solution results of partial differential equations in the form of contour plots or deformation animations. Simulation Tools for Numerical Control Machining and Robot Motion Simulation Systems can show the process steps and movement logic of the work in real time to reduce the risk and cost of operating physical equipment.

Collaboration tools are project management tools that are built on the cloud platform, and the shared Design Space has shown that it can support good multi-terminal collaboration and modification of three-dimensional models and design documents, as well as simulation of distributed design processes in real engineering situations. The teaching adaptability of all kinds of tools is not the same. Modeling tools have a high initial cognitive load and are suitable for simplified task sets; analysis tools require prior theoretical explanation, otherwise students will only learn how to set parameters and fail to grasp the physical meaning; simulation tools are very good at teaching machining processes but do not have the high precision needed for fine tasks such as assembly tolerance analysis; collaboration tools are suitable for group design projects but may be distracting in situations that need to train individual skills. Based on the type of tool and teaching objectives, it can be determined how suitable the tool is for use.

1.3 Methodological Features and Shortcomings of Existing Studies

The two main kinds of research in the present studies are system construction and effect analysis. Most research on the development of systems has focused on the Design architecture, functional modules and interaction logic of a particular digital teaching tool; it gives more weight to the reproducibility of technical implementation and often presents the tool in the form of a prototype system or a plug-in. Most of the studies on the impact of verification have employed a quasi-experimental method, established experimental and control groups, and evaluated the teaching utility of tools based on various quantitative indicators, such as pre- and post-test scores, operation time, error rates, etc. Some studies have gathered the subjective experience of users in the form of questionnaires and interviews, but few have combined research methods to investigate the process data in detail (e.g., operation logs, eye-tracking trajectories). In short, the main way is quantitative analysis, and most of the qualitative studies are secondary.

There are some methodological flaws. First, the research subjects are only from one school or one class; thus, there is a lack of external validity, and we have not systematically studied how suitable these tools are for different levels of education and various students with different prior knowledge. Second, most of the research is concentrated on the short-term effects of teaching (a single experiment or one semester), and relatively speaking, there are few long-term studies on the retention and application of knowledge after tool intervention. Thirdly, as the purpose of the index in the evaluation tool is to assess students' academic performance, it does not cover many related factors such as cognitive load, interest in learning and metacognition. Fourth, many studies have found that some tools are effective, but the circumstances in which they fail have not been studied; therefore, the conclusions drawn may be too general. Therefore, we need to extend the toolset of methods and improve the design of cross-context comparison and longitudinal tracking in the following studies[2].

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

2.1 Tool Interaction Design Based on Cognitive Load Theory

Cognitive Load Theory can be employed to design the Interaction Interface and Task Flow of digital teaching tools. Students in the class of mechanical engineering need to learn many things at the same time, such as shapes and sizes, material properties, motion links, etc.; thus, they are likely to be overloaded with intrinsic cognitive load. Model the tasks, gradually show the information and omit the unnecessary parts to reduce the cognitive load with digital tools. For example, the tool of the 3D modeler can arrange the space of the feature tree, property panel and graphics area so that the most frequently used operation path is in the user's field of view and the effort for visual search is reduced. At the same time, according to the current stage of user operation, the dynamic prompt system will hide irrelevant options to keep the interface neat and simple.

Scaffolding and error prevention can also be employed to organise the use of tools. Common errors in mechanical drawings, such as incorrect view projection or conflicting assembly constraints, can be found in real time by syntax checking and logical verification in the tool, and warnings or automatic correction suggestions will be given before the user makes a mistake. The Design will be relatively simple, so the students do not need to use too much of their working memory to remember the steps of operation while learning about it. The tool has many types of input, such as mouse dragging, parameter entry, gesture control, etc., so it can be more convenient for students with different cognitive styles to learn according to their own needs and strengths.

2.2 Technical Realization Paths for Mechanical Concept Visualization

The display of mechanical concepts is the result of cooperation between geometric modelling engines and physics engines. A Geometry Modelling Engine is employed to construct a 3D solid model according to the shape of the component, how it is connected with other parts, and the structure of the assembly; often, Boundary Representation (B-rep) and Constructive Solid Geometry (CSG) methods are used for this purpose to achieve high accuracy and good computational efficiency. A physics engine can simulate the motion of rigid bodies, collisions, force deformation, etc., and obtain explicit maps of abstract concepts such as degrees of freedom, constraint reaction forces and stress concentration. For example, in the instructions for gear meshing, a colour contour map of the movement of the tooth surface contact line and transmission error can be shown in real time to make the implicit dynamic process of meshing explicit and visual.

New Forms of Presentation for Extended Reality Technology. Augmented Reality tools can be used to place virtual mechanical models on real parts or drawings, and all kinds of angles and exploded views of the internal structure can be shown to solve the problem of presenting assembly relationships with traditional models. A mixed-reality environment can be created to place a virtual crank-slider mechanism in one's hand, and by dragging it, all the displacement-time curves of the points will be shown at the same time. The first reason for using the above technical means is to show both the fixed structure and the motion characteristics of a mechanical system in a single figure; thus, students do not need to separate the two-dimensional and three-dimensional forms in their minds and are relieved of the difficulty of spatial reasoning[3].

2.3 Teaching Feedback Model Based on Learning Behaviour Data

Digital teaching tools can collect detailed behaviour data of students during the operation of a model, such as the sequence of mouse clicks, frequency of parameter changes, time spent at a certain step and number of error retries. The above data will be used to construct the learning behaviour path. Sequential Pattern Mining or Hidden Markov Models can be used to find the typical behaviour pattern. For example, if you switch between the reference plane and the sketch plane often in the modelling of a shaft part, it may be that you have not grasped the reference system. According to the above pattern and the expert's operation sequence, we can find cognitive breaks in the students and generate corresponding feedback prompts, such as recommending a review of the "rules for selecting reference planes" or displaying the standard operating procedure.

The other is to divide the students according to how much they have been taught. For example, in the finite element analysis tool, it can be seen that students' operation behaviour (such as selecting a mesh density and the order of applying boundary conditions) is related to the convergence of the final analysis results. Train a Decision Tree or a Support Vector Machine model to predict the expected convergence error of a student's work before submission and offer some corrective advice. Feedback forms can have text prompts, colour-highlighted error areas, or automatically play back the correct operation part. The model does not need to be annotated or evaluated manually after the fact; it is based on patterns in behaviour data, so it can provide process-oriented feedback instead of outcome-oriented feedback and improve the timeliness and accuracy of teaching intervention.

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

3.1 Integration of Intelligent Tools and Adaptive Learning Environments

Gradually, intelligent tools have been able to find information on and predict learners' behaviour by means of machine learning algorithms and knowledge representation models. Mechanical drawing or computer-aided design tools can analyse the shape of a sketch, the order of dimensions, and any changes made by a student; they can find a discrepancy in their design ideas and standard engineering language, and then offer correction guidance in advance. Now that I am an intelligent assistant, I will no longer wait for you to give me instructions; instead, I will proactively consider what needs to be done next and put forward some suggestions, such as automatically recommending tolerance grades and surface roughness values for shaft-hole fit modelling. At the same time, based on the current abilities and errors of the students, the problems and hints in an adaptive learning environment will be dynamically adjusted to create personalised learning plans[4].

The first step in building an adaptive learning environment is to build a learner model and continuously improve it. The two are models for cognitive diagnosis and sequential behaviour, and they map the behavioural data of students in 3D modelling, motion simulation or finite element analysis to a knowledge mastery vector. If the system finds that a student has made the same mistake in applying a certain kind of constraint (e.g., parallelism, coaxiality, tangency) several times, it will automatically show relevant micro-videos or interactive exercises for correction, reduce the number of such constraints in the next set of problems, and then, after the student has learned this knowledge, gradually increase the difficulty. The two-way data flow from the tool to the environment can be used to obtain general strategies based on the group learning pattern in the teaching support system, and by adjusting parameters according to individual differences, a dynamic convergence teaching adaptation mechanism can be established.

3.2 Construction of Immersive Teaching Scenarios Based on Extended Reality Technology

Extended Reality Technology refers to Virtual Reality, Augmented Reality, Mixed Reality, etc., and all of them have the attribute of breaking the representation barrier between 2D screens and 3D physical objects. Virtual Reality can create an all-sensory and very rich learning environment for mechanical assembly, and with the help of a head-mounted display and controller, one can perform virtual disassembly and assembly of reducers, fixtures, hydraulic valve groups, etc. At any time, the system can obtain the position, grip strength and part alignment accuracy of the hand; then, it will compare this kinematic data with the standard assembly sequence to find any order errors or interference areas. Compared with the old method of 3D animation demonstration, an immersive environment can provide haptic feedback and a sense of space to help people learn about assembly language and spatial relationships by doing rather than just looking.

Now, people are using mixed reality technology to show virtual models of real workpieces and equipment. A typical case is the teaching operation of numerical control machine tools; students can see the actual machine panel through see-through glasses, and at the same time, a virtual overlay will be displayed dynamically to show the path of spindle motion, tool offset parameters and direction of coolant flow. The old division of "explanation-observation-operation" in the virtual and real worlds has been broken; now, we can learn the rules and apply them in the same place and at the same time. A multi-user collaborative mixed reality environment can be created, and several students will be sitting at the same physical desk but can view different virtual annotations on their own terminals at the same time (e.g., one person can see the distribution of stress, and another can see a temperature field); thus, layered information can be shared without conflict, and the capacity for information dissemination in teaching will be improved[5].

3.3 Collaborative Construction of Cross-Platform Toolchains and Mechanical Knowledge Graphs

Most of the digital teaching tools now are not single-purpose programmes but have developed into multi-platform tool chains. The first two tools in a toolchain are Design Modeler and Simulation and Analysis; the other two are Process Planning Unit and Virtual Debugger. All the above modules can send the model parameters and simulation results in the same direction or in both directions via the standard data exchange format STEP, IGES and JT, or application programming interfaces. Tool chains in the teaching of mechanical engineering can be used to carry out all the steps of a task, from part modelling to machining simulation, in a single system and avoid data loss or format conversion errors caused by switching between different software. At the same time, the cloud-based collaborative platform will have the same project file on all terminals (personal computers, tablets, virtual reality devices), and you can continue to make design modifications and manage versions.

A Mechanical Knowledge Graph will be used to give semantics to the cross-platform toolchain. A knowledge graph takes entities (such as gears, bearings and bolts) and their relationships (such as meshing, supporting and fastening) as the basic units, and it can organise mechanical design handbooks, national standards and typical mechanism motion laws. When a student draws a gear in a modelling tool, the tool chain can automatically retrieve the module series, recommended number of teeth and failure mode descriptions for that gear from the knowledge graph, and it can also be connected to the meshing stiffness calculation equation in the simulation module. All the platforms have the same interface for the knowledge graph, so they can be used together to represent and reason about the same mechanical concept. Collaborative Construction Mode is no longer just a set of software; now, based on the mechanical knowledge ontology, an ecosystem has been built, and every operation node in the teaching process can obtain semantic support and cross-tool context transfer from the knowledge graph.

Conclusion

Research on the application of digital teaching tools in mechanical engineering has formed a general division of labour and a system for all kinds of tools. Although all kinds of model construction tools, analysis tools, simulation tools and collaboration tools are available, they are used to different extents and are limited by various factors such as cognitive load, task complexity and how well they fit the teaching goals. According to Cognitive Load Theory, reduce the amount of load caused by tool operation in the Design; show the visualisation path of geometry and the physics engine step by step to present mechanical concepts, and change the feedback model based on behaviour data from outcome assessment to process diagnosis for teaching intervention. As intelligent tools have changed over time, so too have the content and form of teaching in response to the needs of students. Virtual Reality (VR) and Mixed Reality (MR) can give students an illusion of reality and solve the problems of traditional 2D screens and real objects. Based on the cross-platform toolchain and the mechanical knowledge graph, joint construction will be used to establish semantic association and data interoperability among the Design, Simulation and Machining stages.

In the future, the following directions will be further studied in research: the cross-context generalization ability of learner models in intelligent tools, the long-term knowledge transfer effect in extended reality environments, and the maintenance mechanism of multi-platform semantic consistency driven by knowledge graphs. In addition, the boundary conditions of tool failure and the development of adaptive adjustment strategies are also problems that need to be solved in the application of digital teaching tools for mechanical engineering.

References

[1] Wu, J. J. "Exploration and Practice of the Curriculum System Reform of Mechanical Engineering under the Intelligent Manufacturing Environment." China Strategic Emerging Industry, no. 6 (2026): 145-147.

[2] Shi, S. W. "Exploration on the Reform of Talent Training Mode for Mechanical Manufacturing Majors in Higher Vocational Colleges under the Background of Digital Transformation of Manufacturing Industry." Southern Agricultural Machinery, vol. 56, no. 23 (2025): 182-185.

[3] Niu, M. M., and Guo, Y. "Research on the Construction of Digital Teaching Ecology for Mechanical Professional Groups in Higher Vocational Colleges in the Age of Artificial Intelligence." Wisdom, no. 29 (2025): 9-12.

[4] Wei, M. B. "Construction of the Practice Teaching System of Industry-Education Integration for Secondary Vocational Mechanical Majors under the Background of Intelligent Manufacturing." China Machinery, no. 18 (2025): 149-152.

[5] Gu, X. Y., and Chen, Z. Q. "Research on the Path of Integrating Innovation and Entrepreneurship Education into Mechanical Professional Courses: Taking the Digital Design of Mechanical Products Course as an Example." Shanxi Youth, no. 6 (2025): 28-30.