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Research on the Teaching Path of Aircraft Design Courses Based on Digital Twin Technology

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Abstract: This study addresses the limitations of traditional teaching models in the aircraft design course in fostering higher-order thinking skills, proposing and validating an innovative teaching path based on digital twin technology. The path features a three-stage progressive learning framework, starting from basic conceptual modeling, advancing to iterative analysis under multi-objective constraints, and culminating in open-ended innovative design. By integrating professional tools such as OpenVSP and ANSYS, an immersive virtual learning environment is constructed, transforming abstract structural design and performance analysis principles into interactive and perceptible inquiry processes. In teaching practice, this study uses the multi-objective collaborative design of an aircraft wing's primary load-bearing structure as a typical case study, guiding students to actively adjust parameters, analyze results, and optimize decisions by setting constraints and performance indicators with real-world engineering backgrounds. Effectiveness evaluations show significant improvements in students' analytical rigor, iteration depth, and multi-objective trade-off capabilities during the design process. Qualitative analysis further reveals a significant shift in students' thinking patterns from passive knowledge acceptance to active exploration of solutions. This study provides an operable implementation framework for teaching reforms in core courses of aerospace engineering majors, demonstrating the application potential of cutting-edge digital technologies in promoting deep learning and innovation capacity building.

Keywords: Digital twin; Aircraft design; Higher-order thinking skills; Teaching innovation

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1. Introduction

Virtual simulation aircraft design stands as a core professional course in aerospace engineering education, with its teaching effectiveness directly determining students' ability to undertake future research and development of complex aircraft systems [1]. This course naturally integrates multidisciplinary knowledge such as aerodynamics, structures, and control, serving as a critical vehicle for cultivating students' systematic thinking and complex engineering problem-solving abilities. However, traditional teaching models face significant challenges in supporting the development of students' higher-order thinking. On one hand, the course content is abstract and theoretically intensive, making it difficult for students to establish intuitive connections between physical models and real aircraft behaviors. On the other hand, constrained by experimental conditions and computational resources, the teaching process often emphasizes theoretical lectures and scattered tool operations, lacking systematic training in higher-order cognitive abilities such as analysis, evaluation, and creation [2].

Digital twin technology offers new possibilities for solving these challenges [3]. As a key technology connecting the physical world with virtual space, Digital twins can construct high-fidelity virtual aircraft models, enabling real-time mapping and simulation analysis of design parameters and multi-physics field performances [4]. Some scholars have explored its use in creating immersive learning environments to enhance students' depth of understanding of complex systems [5]. Against this backdrop, this study focuses on the aircraft design course, aiming to construct a digital twin-driven teaching path that systematically trains students' modeling, iteration, and decision-making abilities by integrating toolchains such as OpenVSP and ANSYS, providing practical references for cultivating new aerospace engineering talents with higher-order thinking [6].

The teaching objectives of the aircraft design course extend beyond imparting professional knowledge; they are more importantly about cultivating students' systematic thinking and decision-making abilities when facing complex engineering problems. Traditional theoretical lectures and static case models result in students' difficulty in effectively conducting multi-objective trade-offs and innovative exploration when confronted with real design tasks [7]. Higher-order thinking, encompassing analysis, evaluation, and creation abilities, represents the core goal of engineering education [8]. Design-based learning is widely recognized as an effective approach for cultivating higher-order thinking, but in traditional teaching environments, due to the high cost of physical experiments and the complexity of simulation software operations, students struggle to complete sufficient design iterations, often rendering higher-order thinking training superficial [9].

Despite the immense potential of digital twin technology, existing educational applications still exhibit significant limitations. Most research focuses on the single-point application of technical tools, failing to form a complete teaching path spanning conceptual modeling, multidisciplinary analysis, and solution decision-making [10]. Simultaneously, existing practices often concentrate on technical implementation, lacking in-depth discussions on how to systematically train students' higher-order thinking mechanisms within the path. Addressing these shortcomings, this study, using the aircraft design course as a carrier, proposes the following research objectives: constructing a complete teaching implementation path based on digital twin technology; systematically embedding training sessions such as "hypothesis analysis," "multi-objective trade-offs," and "conceptual innovation" within this path, explicitly targeting the cultivation of analysis, evaluation, and creation abilities; and verifying the path's practical effectiveness in enhancing students' ability to solve complex engineering problems through teaching practice.

2. Design of a digital twin-driven higher-order thinking teaching path

2.1. Core concepts and objectives of path design

Teaching innovation in the aircraft design course faces the challenge of enabling students to truly understand the operating principles of complex systems. Traditional classroom explanations often remain at the theoretical level, making it difficult for students to construct a complete engineering picture in their minds. When confronted with an actual design problem, they often do not know how to synthesize the knowledge of aerodynamics, structural mechanics, etc., that they have learned.

The core idea of this teaching path is to create a virtual flight laboratory. This laboratory is not merely a simple three-dimensional model but a dynamic system that truly reflects various performances of the aircraft. Students can, like real engineers, adjust wing shapes, change engine parameters, and immediately observe the actual impacts of these modifications on flight distance, payload capacity, and fuel consumption. This instant feedback mechanism transforms the fundamental way of learning, enabling students to discover patterns through active experimentation rather than passively accepting conclusions.

During this process, students' thinking patterns undergo profound changes. They begin to understand that engineering design is never about pursuing the extremes of a single indicator but rather a balancing act under a series of conflicting constraints. Increasing wing area can improve takeoff and landing performance, but simultaneously increases weight and drag; choosing lighter materials can reduce structural weight but may require higher costs. The digital twin environment allows them to safely explore various possibilities and witness firsthand the cascading effects of each decision, thereby cultivating true systematic thinking abilities.

Most importantly, this teaching approach enables students to experience the complete engineering exploration process. From initial conception to parameter adjustment, from performance verification to solution optimization, they continuously go through the cycle of "trying, observing, analyzing, and improving." This hands-on learning not only deepens their understanding of professional knowledge but also cultivates their analytical judgment abilities and confidence in innovatively solving complex problems. When they can freely experiment and validate ideas in a controllable environment, engineering education truly achieves the transformation from knowledge transmission to capacity building.

2.2. Construction of a "three-stage, four-dimensional" logical model for the teaching path

Based on the aforementioned teaching philosophy, we constructed a logical model for the digital twin-driven aircraft design course teaching. The core structure of this model can be summarized as "three-stage progression, four-dimensional support," aiming to systematically guide students from basic cognition to complex innovation.

The main body of the teaching path manifests as a "three-stage" progressive learning process. The first stage is "cognitive modeling," where students' primary task is to construct a parameterized digital twin of the aircraft. This is not merely software operation training but a process of transforming abstract engineering principles (such as aerodynamic layouts and structural load paths) into concrete, visual digital models, with the goal of establishing initial associations between geometry, performance, and constraints, achieving the leap from "knowing" to "being able to use." The second stage is "analysis and iteration," where we set typical design scenarios containing inherent conflicts for students, such as seeking a balance between weight reduction and enhanced structural stiffness. Students need to adjust parameters on the digital twin, observe the interrelated changes in multi-objective performance indicators, and through repeated hypothesis, simulation, and evaluation, understand the complex coupling relationships between design variables, with the core goal being to cultivate in-depth analysis and systematic evaluation abilities. The third stage is "innovation generation," where students face forward-looking open-ended challenges, such as designing a novel layout aircraft for a specific mission. In this stage, the digital twin becomes a "safe sandbox" for verifying innovative ideas, allowing students to freely explore non-traditional solutions, conduct conceptual synthesis and feasibility demonstrations, with the ultimate goal of achieving creative design outputs.

To ensure the robust operation of the “three-stage” path, we established a “four-dimensional” support system. In the “technical dimension,” we integrated a toolchain of parametric modeling, multidisciplinary simulation, and data analysis, forming the physical foundation of the digital twin environment. The “content dimension” ensures that all virtual exploration activities are tightly anchored to the core knowledge map of aircraft design, such as the load-passing characteristics and trade-offs of different structural types. The “activity dimension” designs matching inquiry tasks, ranging from case backtracking and group discussions to project tackling, driving students’ active participation. Finally, the “evaluation dimension” adopts formative assessments aligned with the thinking objectives of each stage, with the focus extending from the accuracy of modeling to the logicality of the analysis process and ultimately landing on the innovativeness and rigor of the solutions. These four dimensions interweave to collectively transform digital twin technology from a presentation tool into a complete teaching ecosystem that continuously stimulates and supports the development of higher-order thinking.

2.3. Embedded design of higher-order thinking training modes

The “three-stage” teaching path provides a macro framework for realizing the progression of students’ thinking abilities, while the substantive improvement of thinking abilities relies on embedding micro teaching modes with clear training objectives within each stage. We designed and implemented three core training modes, deeply coupling them with the three stages of the path to jointly drive the systematic development of students’ higher-order cognitive abilities.

In the “cognitive modeling” stage, we embedded the “diagnostic abductive” analysis mode. A typical scenario in this mode is presenting students with a specific “symptom” derived from real engineering practice or simplified cases, such as abnormal buffeting of a certain wing layout at a specific speed or local stress concentration in a certain landing gear under landing loads. Students’ task is not to redesign but to become “engineering detectives,” using the constructed digital twin as an analysis tool. They need to trace back design parameters, adjust relevant variables (such as changing airfoil camber or adjusting support structure stiffness), observe the changes in the “symptoms,” and then reason out the root causes or key design factors that may lead to the problem. This mode forces students to apply their learned knowledge for logical reasoning and systematic decomposition, transforming static knowledge points into dynamic analysis tools, with a focus on training their systematic analysis thinking and rigorous causal inference abilities.

Entering the “analysis and iteration” stage, the teaching core shifts to addressing multi-objective conflicts, where the “constraint trade-off” decision-making mode becomes dominant. The problem scenarios we design usually do not have a unique optimal solution but contain conflicting design requirements, such as “increasing the flutter speed boundary of the wing by 15% while keeping the structural weight increase within 5%.” Students need to make combined adjustments to multiple design variables (such as material properties, structural layout, and mass distribution) on the digital twin, with each adjustment simultaneously affecting multiple interrelated performance indicators. They must learn to define clear evaluation criteria, understand the sensitivity and trade-off relationships between different performance indicators, and make decisions based on comprehensive evaluations after multiple iterations, while providing detailed reasons for their trade-offs. This mode simulates real engineering decision-making environments, focusing on honing students’ abilities to conduct comprehensive evaluations and make rational decisions under multiple constraints, as well as their literacy in professional defense based on data and models.

In the "innovation generation" stage, we activate the "scenario-driven" creation mode. In this mode, the propositions themselves are open and forward-looking, such as "designing a vertical takeoff and landing flight platform for emergency material delivery in mountainous areas," with the focus shifting from technical indicator trade-offs to functional and conceptual innovation. The digital twin plays the role of a "concept verification platform" here. Students first need to parse scenario requirements and translate them into specific design specifications and constraints. Subsequently, they can break free from the constraints of traditional layouts and freely explore unconventional aerodynamic configurations, propulsion methods, or structural forms in the twin. Through rapid construction of conceptual models and preliminary performance simulations, they can evaluate the basic feasibility of innovative ideas, identify potential advantages and fatal flaws, and then iteratively optimize their core concepts. This mode greatly encourages divergent thinking and conceptual synthesis, with the core goal of cultivating students' abilities to define problems, break through frameworks, and conduct innovative synthesis, transforming creation from abstract concepts into an explorable and verifiable practical process.

3. Analysis of teaching practice and effects

3.1. Teaching implementation targets and environment

To verify the effectiveness of the aforementioned teaching approach, this study conducted a complete teaching cycle practice in a core professional course for third-year undergraduates majoring in Aircraft Design and Engineering at a certain university. The course spanned 10 weeks, totaling 40 class hours, with 142 students participating. Prior to the course, students had completed prerequisite courses such as Aerodynamics, Material Mechanics, and Mechanical Design, acquiring the necessary theoretical foundation. However, they lacked systematic experience in comprehensively applying this knowledge to a complete aircraft design project. This provided an appropriate sample for this study to observe the impact of the teaching approach on students' knowledge integration and higher-order thinking skills.

The hardware environment for teaching practice was based on the school's high-performance computing cluster and graphics workstation laboratory, ensuring stable computational resource requirements for digital twin construction and multidisciplinary simulations. In terms of software environment setup, we constructed an integrated toolchain aimed at covering the complete process from conceptual design to multiphysics analysis. The core platform for parametric geometric modeling and preliminary aerodynamic analysis was NASA's open-source OpenVSP. This software allows students to quickly generate and modify complex aircraft shapes by adjusting a small number of advanced parameters (such as wing aspect ratio, taper ratio, sweep angle, etc.), and its built-in Vortex Lattice Method (VLM) panel method tool provides rapid aerodynamic characteristic estimates. We established a digital model library for students, containing conventional layout models (such as passenger aircraft and general aviation aircraft) and some unconventional layout benchmark models, serving as starting points for their exploratory activities.

To delve deeper into structural performance in design exploration, we integrated the ANSYS Mechanical module into the teaching environment. Students could import geometric models generated or exported from OpenVSP into ANSYS, set material properties, apply loads and boundary conditions, and perform basic structural analyses such as statics and modal analysis. For example, when analyzing different main beam layout schemes for wings, students could visually compare stress distributions and deformations in ANSYS, thereby transforming the abstract concept of structural efficiency into visualized cloud map data. Through clear teaching design, students were guided to understand the complete data transfer and iterative process from aerodynamic load estimation in OpenVSP to structural response analysis in ANSYS, which precisely embodies the concept of digital twins in teaching. The entire software environment was interconnected to a certain extent through scripts and standardized interfaces, aiming to lower the technical operation threshold and enable students to focus their primary cognitive resources on design decision-making and problem analysis itself, rather than software operation details.

3.2. Detailed explanation of typical teaching unit cases

To specifically demonstrate the implementation process of the "three-stage, four-dimensional" teaching approach and its training effects on thinking skills, we selected the core unit of "Multi-Objective Collaborative Design of Wing Primary Load-Bearing Structures" as a typical teaching case.

Unit teaching commenced with the teacher presenting a clear comprehensive design task: Starting from a given benchmark lightweight aircraft shape, redesign the layout and dimensions of the wing primary load-bearing structures (main beams, wing ribs, skin) while maintaining its basic aerodynamic characteristics and internal space, with the goal of maximizing the overall structural stiffness and flutter speed boundary of the wing without significantly increasing its weight. This task inherently embeds two conflicting objectives of "weight reduction" and "stiffness enhancement/flutter speed increase," naturally leading to an exploratory process without a standard answer.

Teaching implementation strictly followed the "three-stage" path. In the cognitive modeling stage, students first opened the benchmark model in the OpenVSP environment and utilized its parametric functionality to adjust the virtual definition of the internal "structural skeleton" while maintaining the external geometry of the wing. This required students to transform abstract structural concepts (such as beam positions and wing rib spacing) into specific operable parameters in the software, establishing a preliminary digital definition of "layout." Subsequently, they were guided to import the defined geometric model into the ANSYS environment, learn how to assign reasonable material properties to different components, apply gravity and aerodynamic loads (with load data partially derived from preliminary estimates in OpenVSP), and run static and modal analyses of the benchmark structure, thereby completing the cognitive closed loop from "geometric model" to "analysis model with physical properties." The goal of this stage was to ensure that students could independently construct a digital twin usable for engineering analysis.

Upon entering the analysis iteration stage, higher-order thinking training officially commenced. Students, working in groups, proposed their respective structural optimization schemes based on preliminary analysis results. One student might attempt to increase the height of the main beam to enhance bending resistance but immediately find excessive weight in the twin model; another student might try adopting a denser wing rib layout to improve skin support but discover limited effects on enhancing the first-order bending frequency. They needed to adjust layout parameters in OpenVSP, reanalyze in ANSYS, and record changes in key indicators such as weight, maximum stress, and first-order natural frequency after each iteration. This process deeply embedded the "constraint trade-off" decision-making mode. The teacher's key guidance was no longer to provide answers but to prompt deep thinking through questions: "Which indicator did you primarily aim to influence with this change? Which indicators did it actually affect? Which indicator change was most sensitive? Was the weight cost incurred to achieve this performance improvement worthwhile?" Students had to continuously analyze causal relationships, evaluate scheme advantages and disadvantages, and adjust subsequent exploration directions based on the data provided by the twin model.

In some groups with surplus capacity, teaching guided them to the edge of the innovation generation stage. The teacher posed extension questions: "If unconventional adjustments to the wing planform shape (such as aspect ratio, sweep angle) or materials (such as considering composite material layups) were allowed, how would your design approach fundamentally change? Please verify its potential." This stimulated more creative exploration. Some groups attempted to study the anisotropic design of composite materials, while others explored the coupled effects of slightly altering wing torsion on load distribution and structural efficiency. They utilized digital twins to rapidly verify the potential of these unconventional concepts. Even if the final schemes were not entirely feasible, this process itself greatly exercised their ability to conduct conceptual innovation and comprehensive trade-offs at the system level. The teaching outcomes of the entire unit were ultimately presented in the form of a comprehensive design report.

3.3. Evaluation and analysis of learning effects

To evaluate the effects of the digital twin teaching approach, this study conducted analyses from both quantitative and qualitative dimensions.

Quantitatively, by comparing and scoring the final design reports of this year's (implementing the new approach) and last year's (traditional teaching) students, significant improvements were found in two key dimensions: "rigor of analysis process" and "depth of iterative optimization" ($P < 0.01$). On average, students completed more than eight complete design analysis evaluation cycles in the digital twin platform, with significantly higher active exploration frequencies than in traditional teaching. This indicated a marked increase in their initiative for inquiry and iteration.

Qualitative analysis was conducted by reviewing students' project logs and reflection reports. Expressions reflecting in-depth analysis and trade-off decision-making frequently appeared in the logs, such as students explicitly recording why they adopted a scheme with "slight compromises in lift-drag characteristics but significant structural benefits." Over 80% of students stated in their reflections that through repeated "trial and error" in the digital twin environment, they profoundly realized that engineering design was an iterative process of seeking an "optimal solution" under multiple constraints, and that intuitive, multi-angle instant feedback was key to understanding complex system coupling relationships.

Overall, this teaching approach, through the immersive exploratory environment constructed by digital twin technology, not only improved the technical quality of students' final schemes but, more importantly, cultivated their systematic thinking skills in analyzing, evaluating, and making decisions when facing complex engineering problems.

4. Conclusion

This study proposed and validated a teaching approach based on digital twin technology aimed at addressing the core challenge of cultivating higher-order thinking skills in students in aircraft design courses. The approach progresses through three stages: "cognitive modeling, analysis iteration, and innovation generation," systematically training students' analytical, evaluative, and creative abilities.

Teaching practice demonstrated that the digital twin environment integrating OpenVSP and ANSYS effectively lowered the cognitive threshold for complex systems by providing instant, multidimensional feedback, enabling students to intuitively explore the causal relationships of design decisions. Effect evaluation confirmed significant improvements in students' "analytical rigor" and "iterative depth," with their initiative and systematicity in design exploration far exceeding traditional modes. Students' thinking underwent a fundamental shift from seeking a single answer to active trade-offs.

The core conclusion of this study is that digital twin technology can provide crucial support for the paradigm shift in engineering education from knowledge transmission to capability cultivation by constructing a deep exploratory environment that is "error-tolerant and perceptible."

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