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AI-Empowered "Three-Stage Human-Machine Collaboration" Teaching Reform in Microwave Techniques and Antennas

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Abstract: To address the long-standing pedagogical challenges in Microwave Techniques and Antennas, such as abstract electromagnetic concepts, cumbersome mathematical derivations, and difficulties in cultivating students' engineering intuition, this paper proposes and implements an AI-empowered teaching model based on a "three-stage human-machine collaboration" framework. Without overburdening teachers, this model effectively enhances students' physical intuition in electromagnetics and their ability to solve complex engineering problems, providing a replicable pathway for microwave-course reform in the AI era.

Keywords: AI-empowered teaching; Microwave Techniques and Antennas; Human-machine collaboration; Project-based learning

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1. Introduction

Microwave Techniques and Antennas is a core compulsory course for communications engineering majors, serving as a critical bridge for students to transition from "circuit thinking" to "field-and-wave thinking." However, the course has faced significant pedagogical difficulties for a long time. First, the knowledge modules are highly progressive and tightly interconnected; a gap in any link can obstruct subsequent learning. Second, the course content is highly abstract, and many concepts lack intuitive counterparts, so students often complain that they "cannot see, cannot touch, and can only memorize mechanically." Third, the course involves extensive mathematical derivations and complex-number operations, so it's easy for students to get bogged down in tedious calculations and lose sight of the underlying physical principles [1–2].

Meanwhile, generative AI technologies are profoundly reshaping higher education. AI demonstrates powerful capabilities in knowledge retrieval, code generation, and data visualization, but it also has inherent limitations such as AI hallucinations and lack of physical constraints. Therefore, the core question for this course reform is not "whether AI can enter the classroom?" but "how and to what extent AI should enter, and what roles teachers and students should play" [3].

The "three-stage human-machine collaboration" model proposed in this paper is a systematic response to this question. It is built on the following core philosophy: AI handles computation and retrieval, teachers handle diagnosis and guidance, and students handle decision-making and hands-on operations. These three parties form a complementary closed loop across the pre-class, in-class, and post-class stages, neither idolizing nor rejecting AI, but precisely delineating the optimal boundary of human-machine division of labor.

2. Analysis of pedagogical pain points

Through teaching observations and examination data analysis of our communications engineering students, the three difficulties mentioned above manifest in the traditional teaching mode as the following three layers of disconnection [2, 4].

First disconnection: information asymmetry at the cognitive starting point. The knowledge system of microwave technology is tightly progressive, but teachers lack precise awareness of students' mastery of prerequisite knowledge. Teaching at a uniform pace causes some students to fall behind progressively due to missing prerequisites. Moreover, without a systematic compilation of historically difficult points, teachers often rely on experience each semester, and it's difficult to implement targeted interventions.

Second disconnection: lack of visualization and interactivity for abstract concepts. When teaching core content such as waveguide field distributions and radiation pattern formation, traditional static PPT diagrams fail to present the dynamic evolution of physical quantities, and classroom interaction means are limited. Even if students can recite formulas, they cannot build the causal intuition chain of "parameter change → field distribution change → macroscopic performance change," and they don't have an interactive channel for immediate questioning and verification.

Third disconnection: superficial post-class thinking and the risk of AI-assisted cheating. Traditional homework mainly consists of derivations and calculations that students can complete by plugging into formulas, without training in deeper questions such as "Why is this done? What is the physical root?" At the same time, the proliferation of generative AI makes "derivation-type homework" easily replaceable by AI, seriously challenging the validity of traditional assessment methods.

3. Design of the "three-stage human-machine collaboration" teaching model

To address the above three disconnections, and following the reform rationale of "using AI to offload low-order cognitive burdens and re-focusing class time and energy on higher-order thinking cultivation," the authors propose the "three-stage human-machine collaboration" teaching model.

3.1. Pre-class stage: early warning of learning status based on historical exam data and knowledge-graph-guided preview

The primary objective of this stage is to enable teachers to grasp the distribution of course difficulties before the semester begins, and to allow students to identify potential risk points in advance. The authors elaborate on it from three aspects.

(1) Data foundation. The authors compile the final examination scores of the Microwave Techniques and

Antennas course over the past two years, recording each question's corresponding chapter, knowledge point, and each student's score, to obtain fine-grained performance data. The authors choose the course's own historical data because the syllabus and assessed knowledge points remain relatively stable across offerings; persistently low scores on the same knowledge point across cohorts effectively reveal "inherent, cohort-invariant" teaching difficulties.

(2) Processing and modeling. Data are mined from two dimensions. Longitudinal dimension: The authors compute the average loss rate for each knowledge point across cohorts, ranking them to identify "high-risk error-prone points." Horizontal dimension: The authors apply the Apriori algorithm to uncover "cognitive dependency chains" between knowledge points. For example, if a student fails to master point A, they are highly likely to also fail point B.

(3) Teaching application. The modeling results are applied in two directions. For teachers: the longitudinal ranking of high-risk points guides intensified practice; the horizontal dependency chains help teachers clarify the teaching sequence, cutting off the chain reaction of "prerequisite gaps leading to subsequent collapse" at its root. For students: teachers release the knowledge graph annotated with risk levels in advance, so students can identify key areas for focused preview [5].

3.2. In-class stage: AI-scheduled pre-simulation instant retrieval system and interactive teaching mini-programs

To address the pain point of "invisible field distributions," we build a classroom interactive system comprising "AI semantic retrieval + parameterized pre-simulation library + teaching demo mini-programs," enhancing the immediacy and interactivity of in-class demonstrations.

(1) Resource construction. Before class, teachers use MATLAB and HFSS to perform parameterized simulations of core physical cases, generating multiple sets of comparative results, each tagged with a set of "key parameter labels." Lightweight teaching demo mini-programs for instant interactive demonstrations are generated using DeepSeek. All these resources are stored in a local database.

(2) Classroom application. When a visual demonstration is needed during class, a lightweight AI interface accepts a query instruction and automatically retrieves the closest matching pre-simulation result or demo program. If the result does not fully match the question, the teacher can guide students to reason using similar cases, or modify and debug the program on the spot.

(3) Educational value. These approaches transform the traditional passive "teacher shows, students watch" classroom into an active inquiry loop of "students ask → AI retrieves and demonstrates → teacher interprets → students reason." Here, AI acts as a "generator" of mini-programs and a "dispatcher" of the pre-simulation library, freeing teachers' cognitive resources from "writing demo tools" and "memorizing and searching for cases," so they can focus on "interpretation and guide to reason [6]."

3.3. Post-class stage: Human-machine collaborative project-driven assignments

The project-based homework design in the post-class stage represents the most distinctive innovation of this model. The design principles are: AI handles knowledge explanation and strategy suggestions, while students personally complete the modeling, iteration, and critical judgment that AI cannot replace. The core logic of assessment is: completely abandon the traditional mode of "checking whether calculation steps are correct"; any content that AI can generate receives no credit; only "physical evidence" reflecting students' physical thinking and hands-on operations is graded. This fundamentally eliminates the risk of "AI ghostwriting" [7].

Using “Impedance matching design of a 2.45 GHz microstrip antenna” as the project vehicle, the workflow tasks and evaluation dimensions are shown in **Table 1.**

Table 1. Workflow tasks and evaluation dimensions

Task Description	**In an RF front end, the input impedance of a microstrip antenna must match the 50 Ω feed line; otherwise, the radiation pattern will distort and gain will drop. Please design a rectangular microstrip patch antenna with a center frequency of 2.45 GHz, input impedance of 50 Ω, and E-plane main-lobe gain ≥ 6 dBi. Substrate: FR4.**		
Workflow	Specific Tasks	Design Rationale	Evaluation Dimensions
1. Teacher releases knowledge anchors	(1) Modified formula for resonant length of microstrip antenna; (2) Physical principle of impedance matching by shifting of the feed point; (3) Effect of patch width on main-lobe width of the radiation pattern.	Define learning boundaries to prevent students from being overwhelmed by AI information	/
2. AI-assisted knowledge construction	Students inquire AI to explain the physical mechanisms and calculation formulas of the above three anchors.	Information filtering and concept extraction	Effectiveness of questions; appropriateness of information filtering.
3. Students complete core tasks that AI cannot replace	(1) Build a 3D antenna model in HFSS/CST; (2) Vary the feed point position in some manner (AI may suggest options), perform at least 5 full-wave simulations, and record the S_{11} curve for each run; (3) Organize iteration data and annotate the physical reason for the next adjustment.	Hands-on practice; build engineering intuition through perception, recording, and reflection.	Completeness of model and data; logical consistency of annotations.
4. AI-assisted strategy consultation, student independent decision-making	When simulation results are unsatisfactory, students ask AI. (e.g., “If frequency is too low, should I adjust length or width first? Which adjustment has less impact on the pattern?”). Based on AI’s reference suggestions, students make their own final decisions and justify them in their reports.	Establish the role perception that AI is a consultant, not a commander.	Quality of questions; depth of analysis of AI suggestions; consistency between final decisions and simulation results.

4. Reflections and conclusion

4.1. Reflections

During the implementation of the above teaching model, several noteworthy issues emerged that merit deep reflection; these reflections point both to optimization directions and to deeper propositions of AI-empowered engineering education.

First, there is a tension between historical data and current student profiles. The pre-class early-warning model reveals “statistical regularities,” but teaching faces “this cohort of students.” Over-reliance on historical data may obscure the particularities of the current cohort. An improvement direction is to combine historical warnings with an early-semester quick pretest, establishing a dual-track mechanism of “historical patterns + real-time diagnosis.”

Second, AI assistance may induce cognitive dependence. AI lowers the threshold for knowledge acquisition, but some students begin to show a tendency of “being at a loss without AI.” Their first response to simulation errors is to consult AI rather than to analyze independently. In subsequent iterations, we plan to set “AI-free periods” deliberately in certain tasks, forcing students to perform independent physical reasoning.

Third, the upgrading of the teacher’s role demands institutional support. The focus of teachers’ work shifts from “grading and explaining” to “designing anchors, building library resources, and interpreting AI outputs," requiring not only deep domain expertise but also judgment in AI tools. Relying on individual teachers leads to slow learning; universities need to establish development mechanisms for teaching competencies for the AI era. Without systematic support, the model's replicability will be limited.

4.2. Conclusion

The integration of AI technology into higher education classrooms is an irreversible trend, but "how to integrate" is far more important than "whether to integrate." This paper proposed a "three-stage human-machine collaboration" model for the Microwave Techniques and Antennas course, which adheres to the philosophy that "the power of AI should not lead to the degradation of students' hands-on abilities; rather, it should serve as a tool to liberate students from low-order computations and redirect them toward higher-order engineering thinking." The core role of the teacher evolves from the sole knowledge transmitter to a designer of cognitive pathways and a guide of human-machine collaboration. This approach is not only applicable to microwave courses in the AI era but also offers reference value for other engineering courses that are highly abstract and demand strong practical skills.

Disclosure statement

The authors declare no conflict of interest.

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