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Original article

REINVENTING CLASSIC COURSES: A PARADIGM RECONSTRUCTION STUDY OF AI-EMPOWERED SIGNAL PROCESSING CURRICULUM

REINVENTANDO LOS CURSOS CLÁSICOS: UN ESTUDIO DE RECONSTRUCCIÓN DE PARADIGMAS DEL CURRÍCULO DE PROCESAMIENTO DE SEÑALES POTENCIADO POR IA

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Abstract

With the rapid advancement of Artificial Intelligence (AI) technology, traditional signal processing education faces challenges such as outdated knowledge structures misaligned with industrial advancements, single teaching models and insufficient cultivation of innovation ability, and an imbalance between theory and practice, and lack of real-world application scenarios. This study adopts constructivist learning theory and backward curriculum design, proposing an "AI-empowered Four-Dimensional Reconstruction Framework". Building on the national first-class course construction experience at Beijing Institute of Technology, this framework drives the transformation of Digital Signal Processing (DSP) curriculum from "mathematics-oriented" to "engineering problem-driven", from "knowledge transmission" to "meta-cognitive ability cultivation", from "tool application" to "intelligent

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method innovation", and from "single assessment" to "multimodal competency evaluation." It establishes a systematic course architecture, covering "demand analysis, content construction, teaching implementation, and dynamic evaluation". By restructuring knowledge systems, innovating experimental methods, and reforming assessment mechanisms, a new teaching ecosystem is created, deeply integrating fundamental theories, intelligent technologies, and cutting-edge applications. Teaching practice demonstrates that the reconstructed course significantly enhances students' innovation capabilities and complex problem-solving skills, providing a replicable model for upgrading traditional core courses in the new engineering context.

Keywords: signal processing; curriculum paradigm; artificial intelligence (AI); competency-oriented; teaching reform.

Resumen

Artificial (IA), la educación tradicional en procesamiento de señales se enfrenta a desafíos como estructuras de conocimiento obsoletas que no se ajustan a los avances industriales, modelos de enseñanza únicos y un desarrollo insuficiente de la capacidad de innovación, un desequilibrio entre la teoría y la práctica, y la falta de escenarios de aplicación en el mundo real. Este estudio adopta la teoría del aprendizaje constructivista y un diseño curricular retrospectivo, proponiendo un "Marco de Reconstrucción Cuatridimensional potenciado por IA". Basándose en la experiencia nacional de excelencia en la creación de cursos del Instituto de Tecnología de Pekín, este marco impulsa la transformación del currículo de Procesamiento Digital de Señales (DSP) de "orientado a las matemáticas" a "orientado a problemas de ingeniería", de "transmisión de conocimiento" a "desarrollo de habilidades metacognitivas", de "aplicación de herramientas" a "innovación de métodos inteligentes", y de "evaluación única" a "evaluación de competencias multimodal". Establece una arquitectura sistemática de cursos que abarca el análisis de la demanda, la construcción de contenidos, la implementación de la enseñanza y la evaluación dinámica. Mediante la reestructuración de los sistemas de conocimiento, la innovación en métodos experimentales y la reforma de los mecanismos de evaluación, se crea un nuevo ecosistema docente que integra profundamente teorías fundamentales, tecnologías inteligentes y aplicaciones de vanguardia. La práctica docente demuestra que el curso reconstruido mejora significativamente la capacidad de innovación y la resolución de problemas complejos de los estudiantes, proporcionando un modelo replicable para modernizar los cursos básicos tradicionales en el nuevo contexto de la ingeniería.

Palabras clave: procesamiento de señales; paradigma curricular; inteligencia artificial (IA); orientado a competencias; reforma docente.

Introduction

Digital Signal Processing (DSP) serves as ~~is~~ a core course in electronic and information majors, with long-standing teaching objectives centered on the cultivation of basic theories and practical engineering skills in areas like spectrum analysis and filter design.[1,2] This course, characterized by its blend of theory and practice, forms a cornerstone in the professional talent training system, connecting mathematical foundations, system theory and cutting-edge technology fields such as modern communications, radar, biomedical imaging, and AI-driven perception. The quality of DSP course development and the success of its reforms directly impact students' abilities to master the essential skills of information acquisition, transmission, and processing, thereby affecting their innovation potential and competitiveness in emerging national strategic fields such as intelligent manufacturing, smart medical care, and aerospace information.[3,4]

However, the rapid development and widespread penetration of Artificial Intelligence (AI) technology is triggering a profound transformation of the education sector.[5,6] Consequently, the traditional teaching model of DSP courses faces severe challenges and urgently requires a paradigm shift to accommodate the new demands placed on high-quality engineering and technical talents in the AI age. The fundamental challenges in current DSP teaching are becoming increasingly prominent, mainly in the following three aspects:

1. Outdated knowledge structures misaligned with industrial advancements: Although the core theoretical system of DSP courses (such as Fourier transform and filter design) are highly well-established, the update cycle for textbook content (averaging 5-7 years) lags far behind the rapid iteration of cutting-edge signal processing technologies (such as compressed sensing and deep learning, which evolve approximately every 18 months). Modern methods like these are often taught as independent courses, rather than being effectively integrated into the knowledge context and teaching practice of the core DSP course. This results in a significant gap between teaching content and the practical demands of fast-evolving fields like 5G communications and biomedical engineering.
2. Single teaching models and insufficient cultivation of innovation ability: Traditional teaching relies heavily on formula derivation and theoretical teaching, which struggle to foster students' innovative thinking and critical thinking. At the same time, the standardized assessment and evaluation system cannot accommodate the increasingly diverse learning needs and potential of students. The absence of personalized learning paths restricts the development first-class innovators.
3. Imbalance between theory and practice, and lack of real-world application scenarios: Course structures often allocate excessive time to theoretical lectures (commonly over 70%), leaving insufficient space for cultivating practical innovation capabilities. The existing experimental designs tend to "focus more on verification-type experiments rather than comprehensive design". This disconnect from real and complex engineering application scenarios in areas like smart sensors and 5G communications, makes it difficult for students to effectively transform theoretical knowledge into core problem-solving skills for real-world engineering challenges.

The breakthrough progress of AI technology and its innovative application in education present an unprecedented opportunity to resolve the deep-seated challenges in DSP courses and drive their transformation and upgrading.[7-10] This study aims to explore how AI can be leveraged to systematically and fundamentally reconstruct the DSP course, so as to effectively solve key bottlenecks in traditional teaching models, such as "outdated knowledge, disconnect from practice, and lack of innovation". The ultimate goal is to comprehensively improve teaching quality and learning effectiveness. Based on the experiences gained from the development of the national first-class undergraduate course "Signal Processing Theory and Technology" at Beijing Institute of Technology, and aligning with the Ministry of Education’s strategic initiative “Artificial Intelligence + Higher Education”, this paper proposes the “AI-Empowered Four-Dimensional Reconstruction Framework” as the core pathway for curriculum transformation.

This framework aims to fundamentally promote three key shifts in DSP courses: from mathematics-oriented to problem-oriented, from tool application to methodological innovation, and from knowledge transfer to cognitive construction. Through the exploration and practice of this framework, the study hopes to provide innovative educational solutions for cultivating new generation of signal processing professionals equipped to tackle the complex engineering challenges of the AI era.

Problem Context Reconstruction: From Mathematics-Oriented to Engineering Problem-Oriented

Transform traditional theoretical teaching methods by using real-world engineering problems as the starting point. By placing students in practical application scenarios, this approach stimulates their enthusiasm and motivation to solve signal processing challenges in complex situations. In this way, students will not only better understand and master mathematical theories but also cultivate their problem-solving skills, thus laying a solid foundation for their future careers.

(i) Construction of Dynamic Question Database Empowered by AI

1. Integrate cases from significant national engineering projects like Beidou navigation, 5G communications, and medical imaging. Utilize AI technology and knowledge graphs to build a “problem-knowledge point” mapping. Generate engineering problem chains related to theoretical modules (such as filter design) based on keywords in the field of interest (like ECG noise reduction). This approach achieves accurate matching between problems and knowledge, enhancing students’ independent research capabilities. Dynamically update the database content to ensure the timeliness and cutting-edge nature of the problems, continuously stimulating learning interest.
2. Provide case exercises by simulating engineering scenarios: dynamically generate open-ended tasks that include noise interference and hardware constraints (such as “design a signal compression algorithm for a Mars rover”). These tasks replace traditional exercises that tend to be mathematically deduced. Display intelligent analysis and difficulty grading of problems. Students can choose appropriate problems to challenge based on their own ability level, and the system can also dynamically adjust the difficulty of problems according to their learning progress. This ensures that the learning path is personalized and efficient.

(ii) Five-Dimensional Problem Design Method

This study adopts the “problem-oriented teaching method” and designs a chain of questions that encompass hierarchical, focused, open, in-depth, and enjoying qualities:

1. Hierarchy: Progress from basic issues (e.g. the role of FFT in 5G signal demodulation) → comprehensive issues (multi-source signal fusion processing) → innovative issues (AI-driven real-time signal enhancement system design).

2. Focus: Design specific questions around core knowledge points (e.g., filtering algorithms).
3. Openness: Encourage diverse solutions (e.g. different filter selections).
4. In-depth: Explore the theoretical depth behind the problem (e.g. filter performance optimization).
5. Enjoyment: Incorporate real-life examples (e.g. music signal processing) to enhance learning interest.

(iii) Integration of Ideological and Political Education into Problem Contexts

Incorporate ideological and political cases, such as “Model Scientists of the Times Tackle Signal Processing Challenge”, using examples like “China’s Sky Eye FAST Radio Signal Processing”, to guide students in reflecting on the connection between technological breakthroughs and national strategies. Through these cases, students not only feel the mission of serving the country through science and technology but also hone their professional skills in practical operations. This approach kindles their patriotic sentiments and scientific research enthusiasm, achieving an organic integration of knowledge transmission and value guidance.

Cognitive Process Reconstruction: Shifting from Knowledge Transmission to Metacognitive Ability Development

Utilize AI-assisted cognitive scaffolding to cultivate students’ ability to independently construct knowledge systems and engineering thinking.

(i) Personalized Learning Path Driven by Knowledge Graph

1. Construct a knowledge graph in the field of signal processing, covering core concepts and cutting-edge technologies. Based on students’ cognitive status (e.g. pre-class test results), push learning resources (such as micro-course videos, detailed explanations of knowledge points, engineering cases, and interactive simulation experiments). Dynamically generate personalized learning paths to ensure students efficiently absorb knowledge as needed. Provide real-time feedback on learning outcomes, with the system accurately identifying knowledge gaps based on students’ answers and offering targeted intensive training. Encourage students to explore independently, using the knowledge graph to navigate and delve into related knowledge points, forming a systematic cognitive structure.

2. Implement the constructivist “four-step method”: Situation creation (virtual radar signal processing scenario) → independent exploration (MATLAB/Simulink simulation experiment) → collaborative construction (group optimization algorithm) → metacognitive reflection (AI-generated learning reports, highlighting cognitive gaps). Transform static engineering cases into interactive, intelligent problem chains, aligning with the “real problems, real exploration” orientation. Through this self-directed learning model, students not only consolidate basic knowledge but also cultivate critical thinking and innovation capabilities in exploration, gradually developing a global perspective for solving complex engineering problems. Meanwhile, the system records the learning trajectory, which is convenient for teachers to provide precise guidance and achieve mutual benefit in teaching. Dynamically adjust learning strategies to ensure students’ continuous progress.

(ii) AI-Empowered Cognitive Scaffolding Tools

1. Virtual Course Assistant: Provides real-time answers to theoretical derivation questions (e.g., "the physical meaning of the convolution theorem") and offers relevant examples (audio de-reverberation application).

2. Thinking Visualization Tools: Convert abstract concepts (frequency domain analysis) into dynamic spectrum diagrams, supporting interactive adjustment of parameters. With these tools, students can intuitively understand complex theories, enhancing learning efficiency. Based on student feedback, dynamically optimize teaching strategies to maximize personalized learning effect. Utilize AI-generated mind maps to help students organize knowledge structures and deepen their understanding. Combined with real-time interactive discussion areas, these tools promote idea exchange among teachers and students, stimulating innovative insights. Through multi-dimensional learning support, students not only master the core skills of signal processing but also cultivate the habit of lifelong learning, laying a solid foundation for future career development.

(iii) CDIO Engineering Thinking Training

Combining constructivist theory, design a full-cycle project of Conceive-Design-Implement-Operate (CDIO): In the conceptual stage, students propose innovative solutions based on knowledge graphs; in the design stage, they use simulation tools to optimize algorithms; and in the operation stage, they build experimental platforms to verify theories; in the operation stage, they analyze data, write reports, and present their findings.

Through full-process practice, students will seamlessly connect theoretical knowledge with engineering applications, significantly enhancing their ability to solve practical problems. For example, in Design of an intelligent diagnosis system for ECG signals, students start with ECG signal collection, design filtering algorithms to reduce noise, use machine learning models for feature extraction and classification, and finally realize intelligent diagnosis of ECG signals.

Reconstruction of Teaching Ecosystem ecology: From Tool Application to Intelligent Method Innovation

Create a three-way collaborative teaching ecosystem of "Teachers/Students/AI" and promote the intelligent transformation of teaching methods.

(i) Hybrid Smart Teaching Model

- Pre-class: AI pushes personalized preview materials (e.g. animation analysis of sampling theorem).
- In-class: Generate exercises on commonly misunderstood concepts (e.g. identify error spectrum) to trigger classroom debates and facilitate peer teaching.
- Post-class: Virtual digital teacher provides guidance on project debugging (e.g. feedback on FIR filter design errors).

(ii) Generative AI-Driven Three-Teacher Teaching Ecosystem

Updating the cases based on the LLM: Automatically introduces the latest research findings (e.g. “Application of Transformer in Radar Signal Recognition”) and simultaneously generates supporting experimental codes and data; Dynamically adjusts teaching cases to ensure content keeps pace with the times and accurately identifies knowledge gaps.

“Three-Teacher Classroom” Model: Digital teachers lead the explanation of principles and provide 24-hour project guidance, on-campus teachers are responsible for personalized Q&A discussions, and off-campus teachers explain industrial applications and engineering implementations. The “Three-Teacher” forms complementary advantages, achieving two-way optimization and iterative internalization of teaching and learning. Through this model, students gain comprehensive knowledge coverage and deepen their understanding through real-time interactions, improving their practical abilities.

(iii) Interdisciplinary Project-Based Learning (PBL)

Design integrated “AI+Signal Processing” projects, such as “Intelligent Traffic Signal Optimization System”. Students need to combine signal processing with AI algorithms to analyze traffic flow data and design dynamic signal control strategies, ultimately improving traffic efficiency. Through interdisciplinary collaboration, students develop into well-rounded professionals, improving their comprehensive ability to solve complex problems.

There is also intelligent traffic sound source positioning (need to integrate array signal processing and deep learning). Students need to build microphone arrays, collect traffic noise data, and use deep learning models to locate sound sources. Combine array signal processing technology to optimize positioning accuracy, and finally achieve real-time traffic sound source identification and tracking, improving the level of intelligent traffic management.

Industrial equipment fault diagnosis (vibration signal analysis + anomaly detection algorithm). Students need to collect equipment vibration signals, use time-frequency analysis technology to extract features, and combine anomaly detection algorithms to identify fault patterns. This process enables intelligent monitoring and early warning of equipment status, ensuring production safety.

Reconstruction of Evaluation System: From Single Assessment to Multimodal Capability Evaluation

Establish a multi-dimensional intelligent evaluation system covering knowledge, abilities and innovation competencies.

(i) Integrated Evaluation of Multimodal Data

Process-Oriented Evaluation: AI analyzes classroom activity data (such as discussion participation and question quality); programming experiment log analysis (code efficiency, number of debugging times).

Result-Oriented Evaluation: The automatic scoring system evaluates project results (such as algorithm performance and system stability);
Innovation Evaluation: AI identifies unique ideas and potential value in students' designs, providing a comprehensive assessment of overall competency. Combines students' self and peer evaluation to form a comprehensive evaluation report, offering precise insights for personalized teaching. Creates a "signal processing capability radar chart", covering dimensions such as theoretical understanding, algorithm innovation, engineering implementation, collaborative communication, and ethical awareness. Ensures the evaluation system is comprehensive, objective and fair. Through multi-dimensional evaluation, students are encouraged to develop comprehensively and cultivate innovative thinking and practical skills.

(ii) AI-Empowered Dynamic Feedback Mechanism

- Intelligent evaluation engine: Large models automatically analyze and evaluate the depth of course reports (e.g. comparing the gap between "filter design reports" and professional literature).
- Adaptive learning intervention: Based on evaluation results, pushes intensive training (e.g. directional reception of radar signals for those weak in frequency domain analysis).

(iii) Collaborative Evaluation by Multiple Entities

Four-dimensional evaluation network: Incorporates teacher evaluation, AI system evaluation, student peer/self-evaluation, and enterprise expert evaluation. Benchmarks against the capability map to form a multi-dimensional, dynamic evaluation system, ensuring that the evaluation results are multi-dimensional, three-dimensional and dynamic. Through data-driven precise feedback, guides students to improve themselves, promotes the positive interaction between teaching and learning, and comprehensively improves the quality of education.

The AI system monitors learning progress in real-time, dynamically adjusting teaching strategies to ensure personalized learning effects. Teachers use multi-dimensional evaluation data to precisely identify students' weaknesses and provide targeted guidance. Enterprise experts participate in the review of practical projects to improve students' practical skills and achieve seamless connection between education and industry. The diversified evaluation system inspires students' internal motivation and cultivates high-quality talents that can adapt to future challenges.

Achievement certification: Recommend outstanding student projects to competitions like the "Beidou Cup" and "Challenge Cup", or incubate them to meet industry needs, achieving deep integration of academic achievements and industrial applications. This enhances students' practical experience and innovation capabilities.

The Table 1 shows correspondence between framework and three key transformation.

Reconstruction Dimension	Core Problem Addressed	Supported Transformation Path
Reconstruction of Problem Context	Abstract mathematics teaching separated from engineering practice	Mathematics-oriented → Problem-oriented
Reconstruction of Cognitive Process	Passive knowledge reception, lack of systematic thinking	Knowledge transmission → Cognitive construction
Reconstruction of Teaching Ecosystem	Fragmented tool applications, lack of methodological innovation	Tool application → Methodological innovation
Reconstruction of Evaluation System	Single assessment, inadequate reflection of comprehensive ability	Closed-loop optimization across all three transformations

Table 1. Correspondence between framework and three key transformation
Source: own elaboration

Conclusions

This framework has been piloted in the courses of Beijing Institute of Technology, with a 40% increase in student project participation rate and a 25% rise in awards for innovation competitions. It has guided undergraduates to carry out national and Beijing-level innovation projects, supported teaching innovation combined with course competitions, and participated in international and national competitions across multiple disciplines and fields and achieved fruitful results. The average employment rate of students exceeds 95%, with over 70% pursuing further education. Many students have grown into leading talents in key industries and national scientific and technological talents.

The excellent undergraduate program implemented by the team has cultivated a group of new forces with academic ambitions. The teaching team has been recognized as an excellent undergraduate education team of Beijing universities, with members selected as national excellent teachers, and the team’s achievements have been reported multiple times on CCTV’s News Broadcast. In the future, the team will continue to deepen the new integration design of “AI+Course” to provide a paradigm reference for the digital transformation of engineering education in signal processing courses.

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Conflict of interests:

The authors declare that they have no conflicts of interest.

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- Yi Xin: Research, Writing- original draft, Writing - review & editing.
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- Kaiqi Liu: Formal Analysis. Writing - review & editing.