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Embodied Integration Design of Engineering Case and Ideological and Political Education for Mechanical System Dynamics Curriculum

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Abstract: ***To address the theory-practice gap in the teaching of Mechanical System Dynamics and the insufficient integration of engineering literacy with value cultivation, this study explores a teaching design framework that integrates engineering cases, ideological and political education, and embodied cognition in the context of industry-education integration. Taking the engineering development of marine gear reducers as the leading force, the course content is reconstructed into three modules, three stages, five key components, and nine engineering cases. A teaching case system of multi-level progressive practice by learning through application is proposed. Ideological and political education is embedded at three levels, namely, engineering-philosophy worldview, scientific and innovative spirit, and craftsmanship spirit, thereby establishing an engineering-science-oriented framework for ideological and political education. Furthermore, by combining digital twins with simulation deduction, a dual-loop embodied cognition framework is developed through knowledge acquisition-context construction–practical application–reflective iteration. This framework extends a novel virtual-physical interactive environment for engineering education, and ideological and political education. Consequently, it fosters students' coordinated development of theoretical knowledge, engineering competence, and value formation.***

Keywords: Mechanical system dynamics, Engineering case, Ideological and political integration, Embodied cognition, Industry-education integration.

1. Introduction

Since the 21st century, the connotation of advanced productive forces has undergone profound transformation, shifting from traditional factor-driven development to systemic innovation characterized by digital, intelligent, and green development, with new infrastructure and high-quality talent becoming key supports [1]. New-quality education is closely aligned with national new industrialization strategies such as intelligent manufacturing and the industrial internet, thereby bridging the gaps between the educational knowledge chain and emerging technologies, between ability development and complex engineering problems, and between the resource chain and industry-education integration [2]. With the deep integration of generative artificial intelligence into equipment manufacturing, engineering education must establish a multi-level, authentic, and digital-intelligent practical teaching system to enhance students' capacity to address complex engineering challenges and to innovate through intelligent technologies [3]. In response to the disconnection between theory and practice and insufficient interdisciplinary integration in frontier course instruction for engineering graduate students, Li et al. [4] developed a diversified practical teaching system integrating visual simulation, scenario-based design, and case-based practice. Hu et al. [5] analyzed the relationship between engineering and mechanics from a philosophical perspective and elucidated the fundamental logic and content of engineering mechanics methodology. Yang et al. [6] explored a "waist-drum-shaped" knowledge structure that places equal emphasis on mechanics fundamentals and practical applications, along with the dynamic characteristics of its interactions, thereby establishing a paradigm-fusion-oriented educational objective and curriculum system for mechanics majors. Luo et al. [7] broke through the "four-tier barriers" across courses, majors, colleges, and universities, proposing an interdisciplinary innovative talent cultivation model driven by the collaborative development of an aircraft. Lu et al. [8] concurrently advanced and thoroughly integrated theory, experimentation, and engineering projects, thereby achieving a comprehensive enhancement of students' knowledge, practical skills, and engineering competencies. Huang et al. [9] integrated the OBE concept and constructivist theory to explore and design a CDIO case-based teaching method that supports the autonomous construction of competencies. The aforementioned studies reveal the embodied cognitive rationale of engineering education and resolve the "triple disconnection" among knowledge, competencies, and resources in traditional engineering education [10].

At the National Education Conference, General Secretary Xi Jinping emphasized the need to "continuously strengthen and improve ideological and political education in the new era," "continuously expand the spaces and frontiers for practical and online education," and "deeply implement the national digitalization strategy for education." In light of the development trends of human-machine integration and virtual-physical interaction in the Industry 5.0 era, new-generation information technologies—centered on Generative Artificial Intelligence and Digital Twins—have transformed the paradigms of knowledge acquisition and ideological and political education. This has provided new driving forces for delivering customized learning experiences, implementing ideological and political education practices, and innovating personalized learning designs [11-12]. Mou et al. [13] explored the design logic and practical approaches of human-machine collaborative personalized learning modalities based on cognitive intelligence large models. To

address issues such as the restricted personalized development of students, high trial-and-error costs, and difficulties in knowledge transmission during engineering practice teaching, Li et al. [14] constructed a student-centered "design-twin-manufacturing-sharing" teaching model. Large model technologies enable the retrieval of major events related to disciplinary development and research dynamics through feature correlation; they digitally and intelligently enhance the perceptual context of ideological and political education in engineering courses, thereby achieving empathetic resonance and the generation of ideological meaning during human-machine interactions. Taking the spatiotemporal logic of the "third classroom" as a starting point, Li et al. [15] proposed an action pathway for a "third classroom" practice model that integrates ideological and political large models with intelligent agents. Furthermore, from the perspective of knowledge distillation technology, Yin et al. [16] constructed an educational closed loop of "embodied practice–behavioral reinforcement–value internalization" based on model lightweighting and scenario-adaptive mechanisms. This drives the shift in ideological and political education's value transmission from "explicit preaching" to "implicit nurturing."

Grounded in the curriculum development of Mechanical System Dynamics, this study takes practical engineering projects on the dynamic design of marine gear reducers as a carrier to reconstruct course content and design engineering cases along students' cognitive progression. This activates the dynamic interaction between the modeling stream and the application stream throughout the learning process, thereby driving learners' self-evolution from theoretical knowledge to engineering competence and fostering meaning generation. Subsequently, based on these engineering cases, the study taps into the engineering-philosophy worldview, scientific and innovative spirit, and craftsmanship spirit embedded in engineering education, precisely tailoring an engineering-science-oriented framework for ideological and political education. Finally, by combining digital twins with simulation deduction under the curriculum objective of cultivating engineering literacy, it establishes a novel digital-intelligence-enhanced domain for embodied interactive experiences in both specialized engineering education and ideological and political education, thereby effectively bridging the theory-practice gap and reinforcing value cultivation.

2. Engineering Case Design for Mechanical System Dynamics

Taking the collaborative research on marine gear reducers as the leading force, the course content of Mechanical System Dynamics is reconstructed and divided into three modules: Generalized System Dynamics, Vibro-Acoustic Coupling System Dynamics, and Vibro-Acoustic Coupling System Optimization. To address the dilemma of the theory-practice gap and the difficulty of learning through application in traditional engineering education, the research and development process of mechanical engineering equipment is integrated into the teaching design. Centered on the development of students' cognitive abilities and the design iteration process of marine gear reducers, and utilizing the three content modules as a knowledge base, the teaching content is structured into three stages, five key components, and nine engineering cases, as shown in Figure 1. This expands the practical arena for students' autonomous construction of engineering competence.

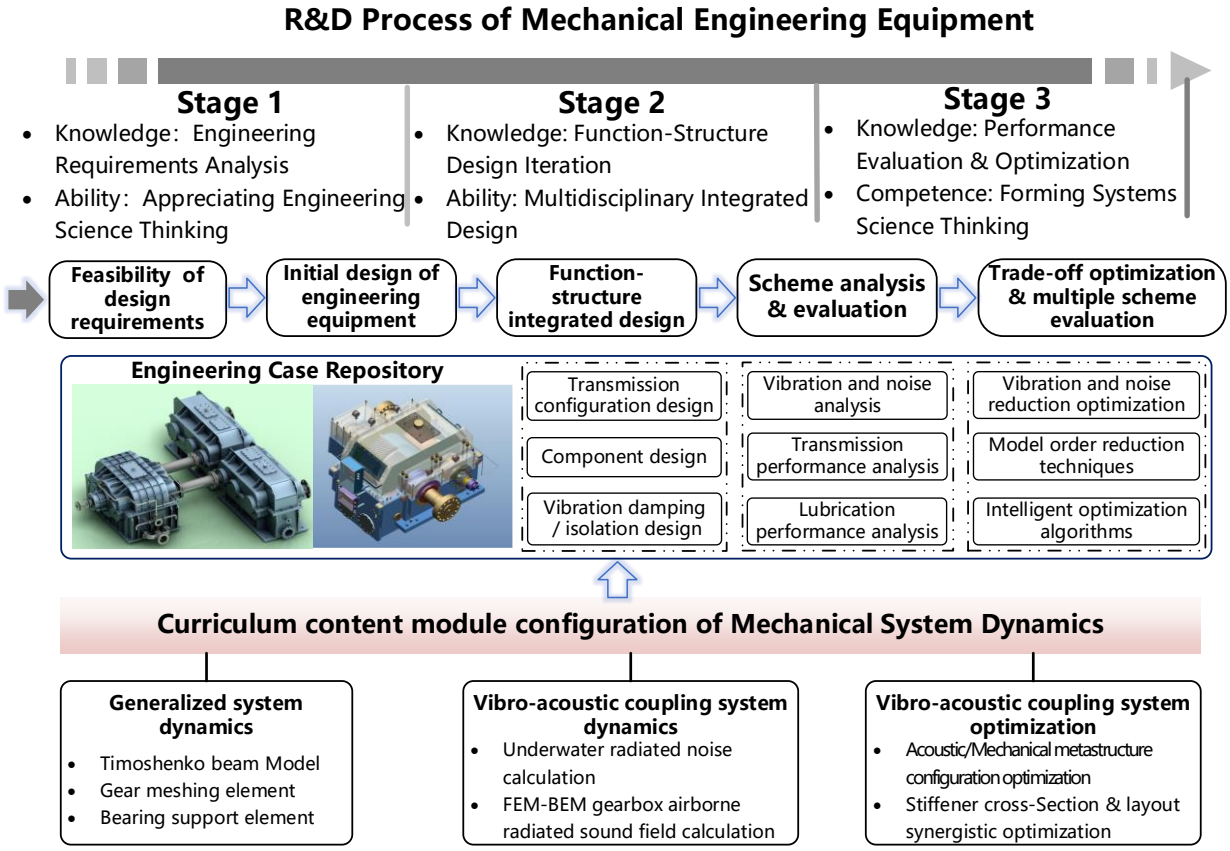


Figure 1: Engineering case repository based on the R&D process of mechanical engineering equipment

Table 1: Engineering-Science-Oriented Framework for Ideological and Political Education

	Cases of Functional-Structural Integrated Design	Cases of Scheme Analysis and Evaluation	Cases of Trade-off Optimization and Multi-Scheme Evaluation
Qualitative Research Mechanistic Research Data-Driven Research	Engineering-Philosophy Worldview	Scientific and Innovative Spirit	Craftsmanship Spirit

Taking into account industrial demands for graduates' R&D competence, the design of engineering cases supports the cultivation of students' interdisciplinary innovation capabilities across three dimensions of dynamic design in engineering equipment: qualitative research, mechanistic research, and data-driven research. Qualitative research grasps the causal relationships and principal contradictions within technical systems, ignores secondary factors, and simplifies complex dynamics problems, thereby obtaining several qualitative conclusions to guide subsequent dynamics modeling. In the modeling preparation stage, the coupling characteristics of internal and external excitations in gear transmission are qualitatively analyzed to predict potential non-linear vibration behaviors of the system, such as attractor transitions. Mechanistic research proceeds from dynamics modeling, presenting engineering cases such as the rigid-flexible coupling system of the marine gear reducer and the vibro-acoustic coupling system in underwater/air-radiated sound fields. This reveals the impact of non-linear behaviors, such as chaos and bifurcation, on transmission efficiency, vibration and noise, and lubrication performance. Data-driven research introduces new methods such as the DeepSeek large model, knowledge distillation, and proper orthogonal decomposition. This cultivates students' abilities to establish deep learning models for the design iteration of marine gear reducers by utilizing mechanics knowledge, data modeling, and Generative Artificial Intelligence, thereby enhancing their capacity for the autonomous construction of engineering literacy.

Starting from three aspects and three perspectives, the engineering case design comprises a total of 9 items, including: three cases in the aspect of functional-structural integrated design (transmission configuration design, component design, and vibration damping/isolation design); three cases in the aspect of scheme analysis and evaluation (vibration and noise analysis, transmission performance analysis, and lubrication performance analysis); and three cases in the aspect of trade-off optimization and multi-scheme evaluation (vibration and noise reduction optimization, model order reduction techniques, and intelligent optimization algorithms), thereby establishing a multi-level, progressive practical teaching case system grounded in "learning by doing."

3. Engineering Case Design for Mechanical System Dynamics

3.1 Engineering-Science-Oriented Framework for Ideological and Political Education

Grounded in working through the full R&D process of marine gear reducer engineering design, proceeding from the three aspects and three perspectives of engineering case design, and permeating the connotations of science, technology, and engineering, this course progressively establishes an engineering-science-oriented framework for ideological and political education, as shown in Table 1, through reshaping students' engineering-philosophy worldview, nurturing their scientific and innovative spirit, and forging their craftsmanship spirit of crafting major equipment for the nation.

Large and medium-sized surface warships, such as destroyers, frigates, and amphibious assault ships, are equipped with high-power marine gear reducers in their main propulsion systems to transmit power from the main engine to the propeller. With the continuous increase in China's requirements for ship maneuverability, payload capacity, and acoustic stealth performance, marine gear reducers are developing toward higher output power, lower space occupancy, and lower vibration. As vital equipment for the nation and core machinery in naval power transmission, high-power-density marine gear reducers embody rich dynamics content and ideological and political connotations throughout their R&D process. The aforementioned engineering cases, designed along this R&D chain, adhere to the engineering science thought advocated by Qian Xuesen, which helps inspire students' mission of strengthening the military and empowering the nation to serve major national needs, as well as fostering their scientific spirit of daring to innovate and tackle challenges.

3.2 Integration of the Engineering-Philosophy Worldview into Engineering Cases

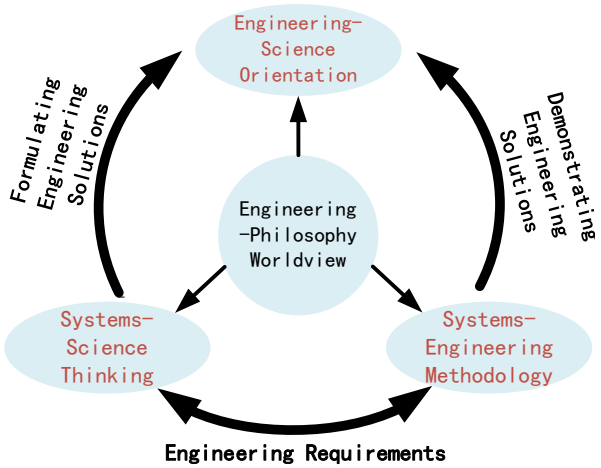


Figure 2: Basic logic of the engineering-philosophy worldview

In this course, the way in which the relationship between mechanical system dynamics and engineering equipment design is deconstructed through particular orientations and modes of thinking constitutes the engineering-philosophy worldview. Its underlying logic consists of three levels: an engineering-science orientation, systems-science thinking, and systems-engineering methodology. From a philosophical perspective, with engineering science as the guiding orientation, the synergistic and co-constructive relationship between engineering practice and theoretical research is examined from the perspective of systems-science thinking,

thereby enabling the formulation of iterative engineering solutions. At the same time, systems-engineering methodology is employed to explore the potential application space of theories for meeting engineering requirements and to demonstrate the feasibility of engineering solutions. In this way, the basic logic of the engineering-philosophy worldview is established, as shown in Figure 2.

In the engineering case design of Mechanical System Dynamics, the engineering-philosophy worldview is integrated into the course design of ideological and political integration, thereby accurately aligning it with students' autonomous construction of engineering competence and achieving the practical unity of knowledge reinforcement, competence development, and value internalization. Marine gear reducers operate in complex broadband vibro-acoustic environments, and their vibration responses vary over time; therefore, they fall within the category of generalized dynamic systems. In response to the engineering requirements of high power density and low noise for marine gear reducers, students are cultivated to independently apply generalized dynamic system theory to demonstrate the feasibility of engineering solutions and identify the optimal technical pathways for their implementation. The engineering cases designed in this course are derived from authentic engineering contexts, providing a practice arena guided by engineering science and strengthening the role of scientific research in driving students' engineering practice competence. Given that generalized dynamic systems exhibit coupled technical and non-technical characteristics, including integrity, purposiveness, dynamism, openness, and human-centeredness, they involve complex technical and physical contradictions. Therefore, solving engineering problems requires systems-science thinking. Based on the "three-element" relationship among science, engineering, and technology, students are guided to integrate five research paradigms—experimental observation, theoretical deduction, computational simulation, data-driven approaches, and artificial intelligence—to construct a systems-engineering methodology grounded in systems-science thinking and demonstrate engineering solutions that meet practical engineering requirements.

3.3 Case Design for Cultivating the Scientific and Innovative Spirit

Using the gearbox plate-and-frame structure of a marine gear reducer as the base structure, a periodic metamaterial viscoelastic coating is applied to the surface. By exploiting the damping and energy-dissipation characteristics of the coating, airborne noise near the walls of the gearbox is attenuated, thereby enabling low-noise design of the marine gear reducer, as shown in Figure 3. First, students are guided to employ topology optimization to determine the optimal configuration of the metamaterial unit cell. Second, students use 3D printing technology to fabricate the unit cells of the metamaterial viscoelastic coating. Finally, through experimental performance testing of the marine gear reducer system, students are supported in mastering a series of research skills, including experimental methods, experimental data modeling, and performance evaluation. In engineering practice, the integration of multiple scientific paradigms drives the interaction between the modeling process and the application process, encouraging students to combine experimental, theoretical, computational, data-driven, and artificial intelligence paradigms to model engineering problems, thereby generating new knowledge points and knowledge relationships and achieving an educational effect analogous to that of a "cognitive intelligence large model."

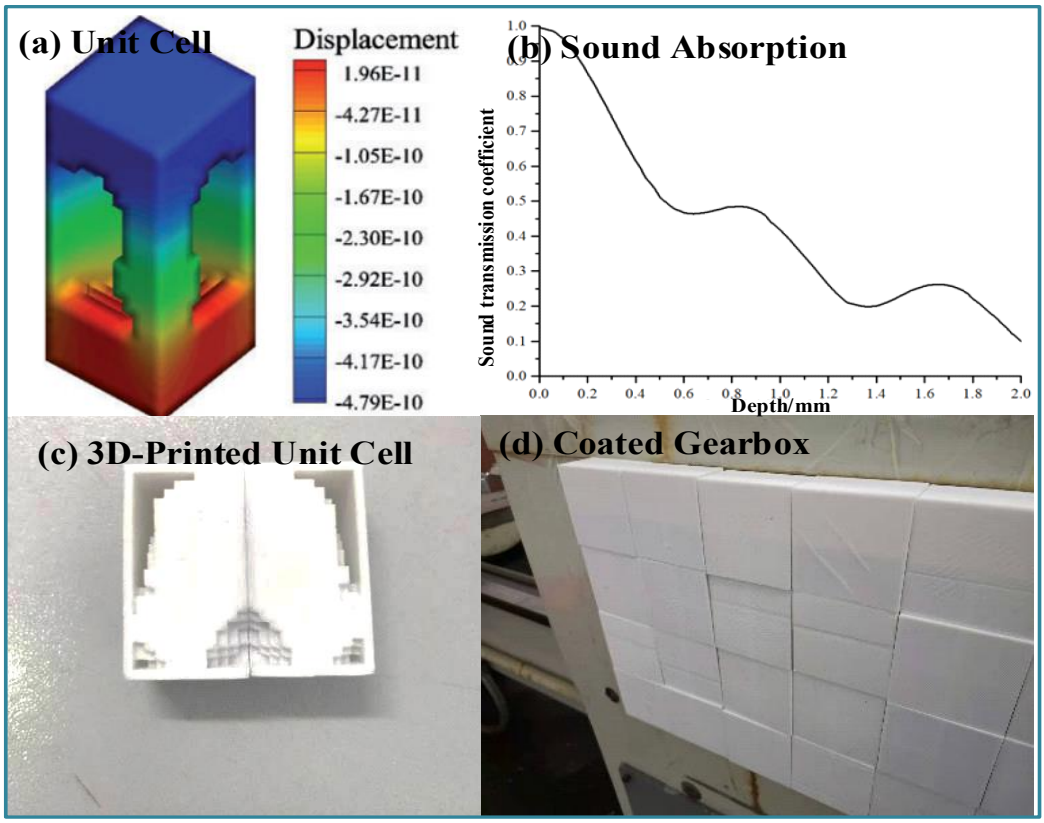


Figure 3: Low-noise design of marine gear reducers

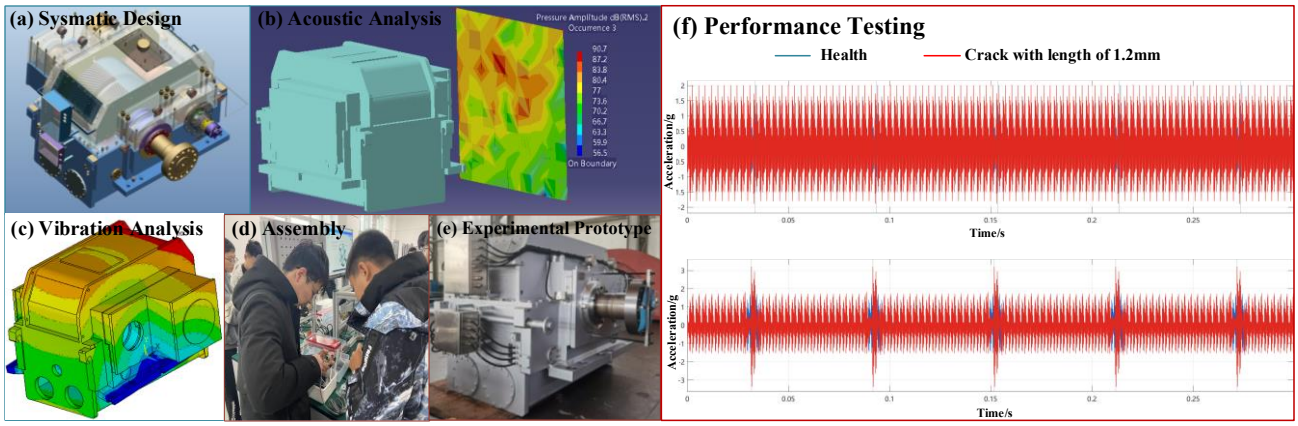


Figure 4: Integrated engineering case practice for the design, analysis, manufacturing, and testing of marine gear reducers

Engineering practice based on metamaterial topology optimization enables students to move beyond the empirical paradigm of conventional material configurations. Driven by functional objectives, the spatial distribution of materials is reconstructed to realize extraordinary physical properties that do not exist in nature, reflecting an innovative capacity to break through established cognitive boundaries and undertake original exploration in unexplored domains. Meanwhile, students are encouraged to anchor their innovative activities in the major national strategic needs associated with building China into a maritime power, thereby elevating professional cognition toward the value dimension of taking responsibility for serving the nation. Ultimately, this achieves the practical unity of knowledge reinforcement, competence development, and value internalization, fostering engineering literacy characterized by the pursuit of truth and pragmatism, adherence to fundamental principles while pursuing innovation, and a steadfast commitment to serving the nation.

3.4 Case Design for the Craftsmanship Spirit

General Secretary Xi Jinping once urged young students: "What you have learned must not remain just in books or only in your minds; it must be put into action to achieve the unity of knowledge and action." Centered on the practical engineering project of collaborative research on marine gear reducers, and crucially supported by digital and intelligent technologies, an integrated engineering case practice architecture for the design, analysis, manufacturing, and testing of marine gear reducers is established, as shown in Figure 4. By conducting innovative activities at industry-university-research practice bases, the craftsmanship spirit is nurtured, enabling students to profoundly understand the principle that practice is the root of innovation.

Starting with open-ended, authentic engineering tasks, students collaborate in groups to autonomously conduct requirements analysis, scheme evaluation, and detailed design. At the industry-university-research practice bases, enterprise mentors guide students in transforming creative ideas into feasible technical solutions by providing design constraints, organizing scheme discussions, and introducing engineering standards. In the design practice of low-noise gear profiles, students implement iterative design optimization through self-developed dynamics simulation software and testing systems. This approach breaks away from the traditional multidisciplinary engineering design paradigm driven by manual experience, allowing students to profoundly understand the principle that genuine knowledge comes from practice. During the assembly and commissioning practice of the experimental prototype, performance degradation in the vibration characteristics of the marine gear reducer occurred due to insufficient installation precision. Nationally recognized technical experts were invited to guide the installation and debugging. The meticulous operational process of these master craftsmen inspired students, fostering a craftsmanship spirit characterized by the pursuit of excellence, a dedication to detail, and perseverance.

4. Embodied Cognition Design for Cultivating Engineering Competence

By combining digital twins with simulation deduction, taking the design practice of marine gear reducers as a carrier, and targeting the cultivation of engineering literacy, this study constructs an embodied cognition design model, as shown in Figure 5, that encompasses immersive situational experiences, visualized cognitive modes, multimodal communication and interaction, and creative self-expression. This model reconstructs traditional linear and discrete pedagogical activities into a metacognitive process characterized by interdisciplinary integration and sustainable improvement. Drawing upon the theory of technology-enhanced learning, it promotes the co-evolution of virtual-physical learning environments, thereby realizing a capability leap from intellectual rationality to engineering literacy. Furthermore, digital twins establish a new domain for ideological and political education, enabling historical milestones associated with vital equipment for the nation—such as aircraft carriers, LNG carriers, and large cruise ships—to transcend constraints of time and space, while guiding value cultivation to permeate all scenarios across the engineering education metaverse, effectively bridging the theory-practice gap in transforming knowledge into action and reinforcing value guidance.

The embodied cognition design for the cultivation of engineering competence adopts a structured "dual-loop nested" iterative architecture. Based on constructivist learning theory, the outer loop on the teacher's side creates immersive and iterable human-machine interactive engineering contexts, guiding students to identify, analyze, and express engineering problems, and to propose solutions. Utilizing the data profiles of students' learning processes, the teaching design undergoes evidence-based diagnosis and improvement to accommodate

learners' personalized learning. Based on embodied cognition theory, the inner loop on the student's side activates learners to propose engineering conjectures and hypotheses, allowing them to explore, deduce, observe, and reflect upon engineering schemes through embodied experiences within the digital twin system of marine gear reducers. Taking 'knowledge acquisition – context construction – practical application – reflective iteration' as the main thread, this approach deeply integrates constructivist theory and embodied cognition theory, thereby establishing a dynamic spiral cycle of deep learning in engineering education supported by the integration of digital twins and simulation deduction.

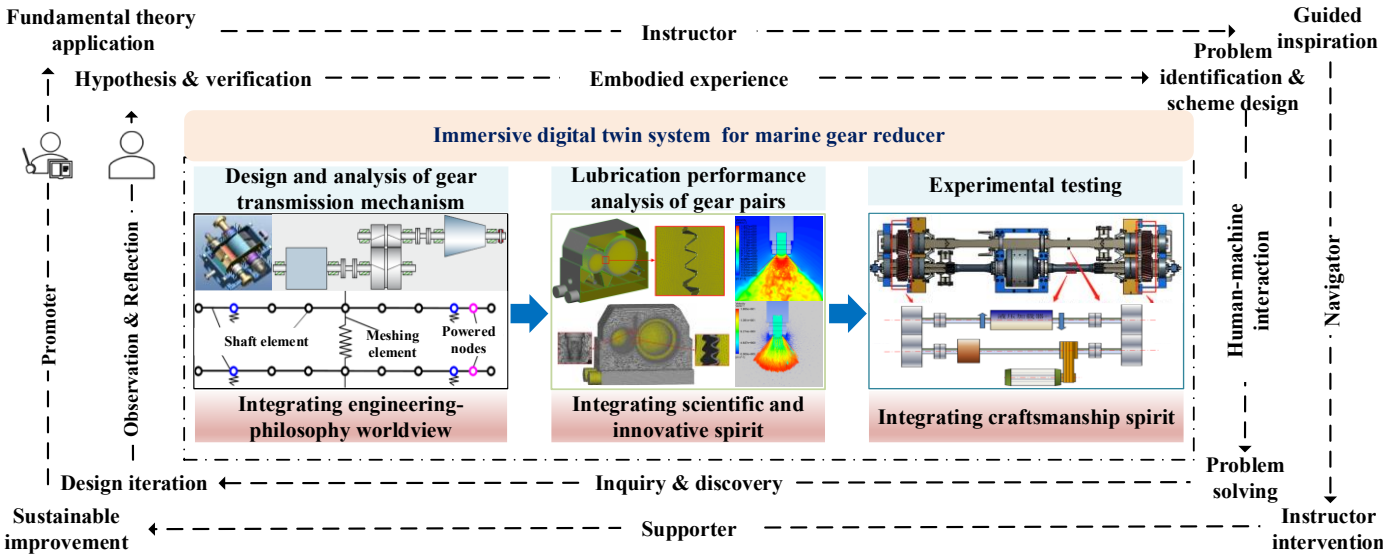


Figure 5: Embodied cognition design for engineering literacy development

5. Conclusion

Focusing on the engineering design practice of marine gear reducers, the content of Mechanical System Dynamics is reconstructed from three perspectives of engineering equipment dynamics design: qualitative research, mechanistic research, and data-driven research. Centered on the development of students' cognitive abilities and the design iteration process of marine gear reducers, the three content modules are used as the knowledge base, and nine engineering cases are designed along the three stages and five key components of the equipment R&D process. Consequently, a teaching case system of multi-level progressive practice through learning through application is established.

Building upon the aforementioned nine engineering cases, the "three-element" relationship among science, technology, and engineering in the engineering design process of marine gear reducers is deconstructed. By reshaping students' engineering-philosophy worldview, cultivating their scientific and innovative spirit, and fostering the craftsmanship spirit of building major national engineering equipment, an engineering-science-oriented framework for ideological and political education is progressively established.

By integrating digital twins with simulation deduction, a new virtual-physical interactive environment for engineering education and ideological and political education is constructed, enabling the multidimensional and comprehensive reconstruction of learners' engineering literacy for engineering practice. A structured "dual-loop nested" iterative architecture is adopted to implement the embodied cognition design for engineering literacy development. Following the main line of "knowledge acquisition–context construction–practical application–reflective iteration," engineering education elements are reconstructed and ideological and political education elements are embedded within the twin space. This transforms engineering education from extensive instruction toward personalized guidance, thereby significantly enhancing the effectiveness of engineering competence development and value formation.

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