Exploring Digital Twin Classroom: Extended Reality for Immersive Learning

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Abstract

The development of new technologies has driven the transformation of teaching models. Extended Reality (XR) technologies, which bridge the gap between the virtual and the real world, have further evolved to incorporate digital twin and semantic technology within the immersive learning framework, creating innovative approaches for higher education. This paper formulates a Semantic-enhanced Immersive Digital Twin (SIDT) technology framework, introducing new, knowledge-driven concepts for teaching and curriculum design. The constructed system features high-fidelity interaction, cognitively-aware personalized learning, and remote distributed collaboration, encompassing the holistic design and optimization of educational objectives, teaching methods, learning environments, and instructional activities. In the teaching practice of the course *Fundamentals of Wireless Communication Technology*, this model was applied to classroom instruction with the integration of innovative assessment methods to evaluate student learning outcomes. A comparative analysis between traditional teaching and digital twin–based immersive learning environments was conducted. The study provides exploratory practice and valuable insights into the application of digital twin technology in higher education.

Keywords

Digital Twin, Higher Education, Semantic, Extended Reality(XR), Teaching Model.

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1 Introduction

In engineering and science education, foundational courses are often characterized by strong objectivity, empirical nature, and systematicity. Taking Fundamentals of Wireless Communication Technology as an example, the course is filled with highly abstract concepts and mathematical formulas, such as electromagnetic wave propagation, signal modulation and demodulation, and multipath effects. The traditional teacher-centered lecture model relies on static charts and text descriptions, making it extremely difficult to help students build intuitive physical images. Consequently, students often remain in a passive state of knowledge reception, struggling to translate theoretical knowledge into practical engineering problem-solving skills.

In recent years, educational researchers have attempted to break through this dilemma by reshaping learning spaces. Although flipped classrooms have enhanced learning initiative to some extent, they lack intervention and support in authentic physical learning environments. Conventional Extended Reality (XR) technologies, such as Virtual Reality (VR) or Augmented Reality (AR), provide highly immersive audiovisual experiences [1]; however, most virtual systems are merely "static digital sandboxes." Unlike simple interactive VR environments where students merely operate IoT devices, our approach integrates deep semantic understanding. Lacking this pedagogical semantics, conventional systems fail to provide real-time, accurate cognitive causal attribution when students explore through trial and error, i.e., they cannot explain "why it is wrong" in addition to "what is wrong". Consequently, learners' real-time exploration needs across complex spatial and temporal dimensions remain inadequately met.

To address these pain points, this paper innovatively integrates digital twin [2] with Semantic Technology [3], proposing a novel pedagogical framework aimed at bridging the cognitive gap between virtual spaces and physical learning environments. The main contributions of this study are as follows:

- Proposing the SIDT Technology Framework: Creatively integrating XR, digital twins, and the Educational Knowledge Graph (EKG) to construct an intelligent learning space with high-fidelity interaction and cognitive awareness.
- Reshaping a Knowledge-Driven Pedagogical Loop: Designing a dynamic exploration loop supporting remote collaboration and "zero-risk trial and error," anchoring behavioral feedback with deep disciplinary logic.
- Conducting Empirical Comparative Analysis: Validating the model in an engineering course, demonstrating significant improvements in knowledge mastery and complex system problem-solving capabilities.

2 SIDT FRAMEWORK AND PEDAGOGICAL DESIGN

Traditional digital simulations often function merely as "operational simulators." To elevate the learning environment into an intelligent "cognitive scaffolding," we propose the SIDT technology framework. As shown in Fig. 1, the framework is a deeply integrated, five-layer heterogeneous ecosystem.

2.1 The Five-Layer SIDT Architecture

Physical Layer (The Reality Anchor): As the cornerstone of the SIDT framework, it represents the objective real world (e.g., communication lab equipment). Grounded in Situated Learning Theory, this layer ensures that knowledge acquisition remains rooted in authentic physical constraints. It provides not only the static geometric blueprints (via CAD or 3D scanning) but also the foundational physical rules and dynamic real-time data from Internet of Things (IoT) sensors. Consequently, it serves as both the essential data source for constructing the digital twin and the ultimate validation benchmark for verifying practical teaching outcomes.

Digital Twin Layer (The Dynamic Sandbox): Acting as a high-fidelity, computable dynamic simulation engine, it continuously receives data from the Physical Layer for calibration and real-time synchronization. It accurately replicates the physical entities' geometric appearance, behavioral logic, and systemic evolution in a digital space. Its core pedagogical value lies in supporting Problem-Based Learning (PBL) by providing a zero-risk environment for trial and error. Furthermore, it enables advanced spatiotemporal compression, making inherently invisible or abstract physical processes (such as multipath signal attenuation) directly manipulable and visually observable for learners.

Semantic Layer (The Intelligent Brain): This layer constitutes the core innovation distinguishing SIDT from conventional virtual labs. It is built upon an EKG constructed *a priori* via Natural Language Processing (NLP) techniques—such as Named Entity Recognition (NER) and Relation Extraction (RE)—to autonomously extract pedagogical relations from unstructured textbooks and expert syllabi, ensuring high causal reasoning accuracy. By semantically linking digital objects to EKG entities, it operates as a sophisticated causal reasoning engine and a metadata index for personalized cognitive diagnosis. For instance, if a student erroneously configures an excessively high signal rate causing the Bit Error Rate (BER) to skyrocket, the layer reasons: *Excessive Rate* → *violates* → *Channel Capacity Principle* → *leads to* → *Severe Signal Distortion*. It thus provides deep, context-aware cognitive scaffolding rather than rudimentary binary feedback.

Interaction Layer (The Immersive Bridge): Composed primarily of XR technologies, this layer forms the bi-directional sensory system connecting human cognition with the digital ecosystem. It superimposes computable information from the Digital Twin and Semantic layers directly onto real-world equipment via XR, or provides full spatial immersion via VR. Crucially, it captures students' behavioral intents in real-time through controllers and gesture recognition. This virtual-physical fusion effectively transforms taxing memory-recall tasks into intuitive recognition tasks, significantly reducing cognitive load and facilitating true "embodied cognition" by shifting learning from passive observation to active physical manipulation.

Pedagogical Layer (The Control Hub): Functioning as the central teaching support environment, this layer aggregates heterogeneous learning telemetry and real-time simulation statuses into an intuitive visual dashboard. Requiring minimal specialized training, this transparent data orchestration empowers teachers to transition from traditional knowledge transmitters to proactive process facilitators. By instantly identifying class-wide or individual cognitive bottlenecks, instructors can utilize this centralized system to seamlessly push EKG-guided interventions, targeted hints, or global parameter modifications directly to specific students across the distributed virtual learning space, closing the dynamic teaching loop.

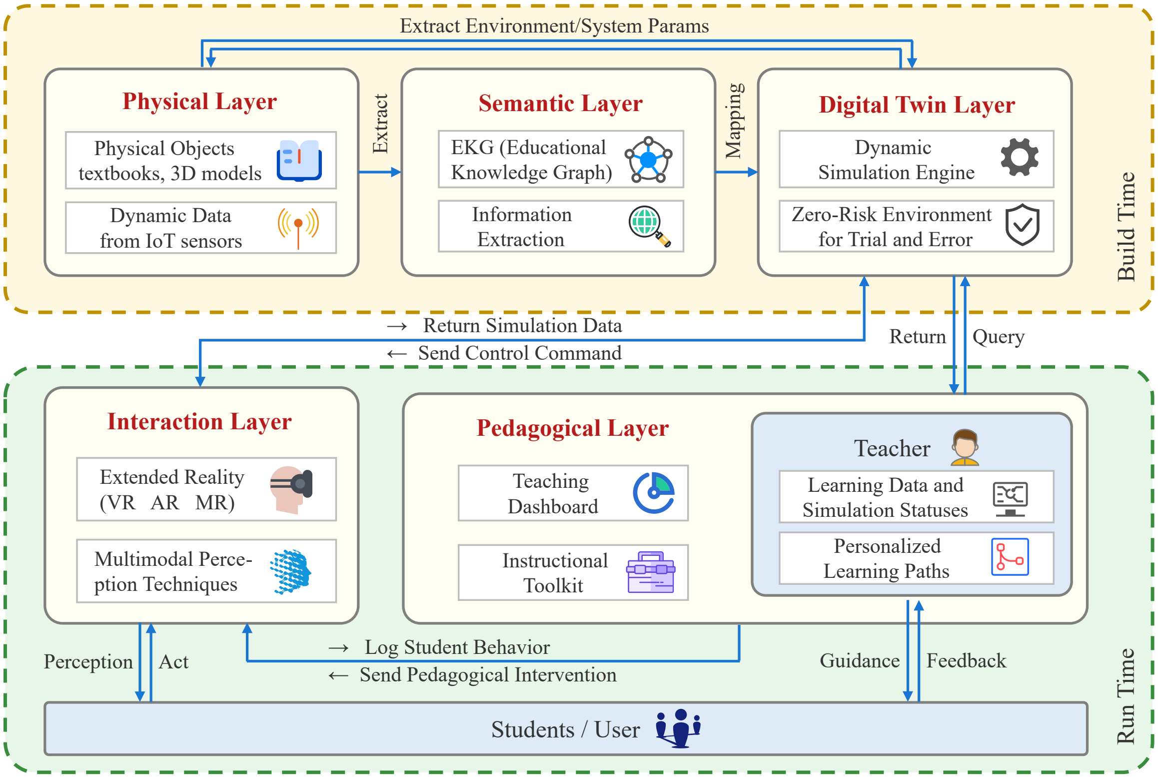
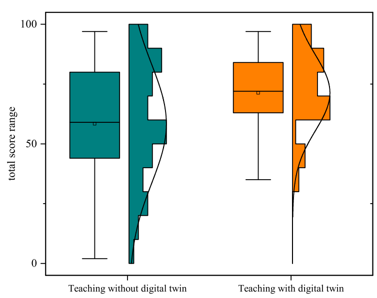
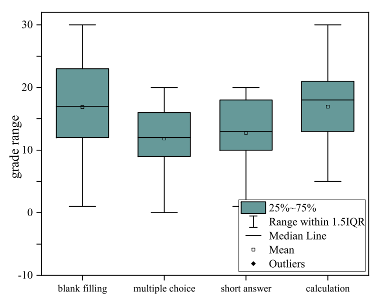


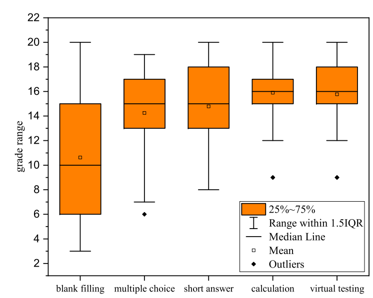
Figure 1: SIDT Framework.



(a) Grade comparison



(b) Teaching without digital twin



(c) Teaching with digital twin

Figure 2: Grade comparison and test score box diagram of different question types.

2.2 Pedagogical Affordances and Iterative Exploration

The systemic synergy between XR interfaces and computable digital twins introduces profound pedagogical affordances that address the epistemological bottlenecks of STEM education. By integrating high-fidelity simulations with real-time interaction, the SIDT framework achieves advanced spatiotemporal scaling, rendering invisible physical processes (e.g., multipath fading) as manipulable 3D structures. This transforms taxing cognitive-recall tasks into intuitive visual-recognition experiences, significantly reducing students' cognitive load.

Furthermore, this convergence reshapes the pedagogical paradigm from linear theoretical instruction to a non-linear, knowledge-driven exploration loop. Traditional lab constraints are eliminated by a zero-risk digital sandbox that explicitly leverages trial-and-error. When students execute erroneous parameters, the digital twin visualizes the realistic adverse consequences, while the Semantic Layer intelligently

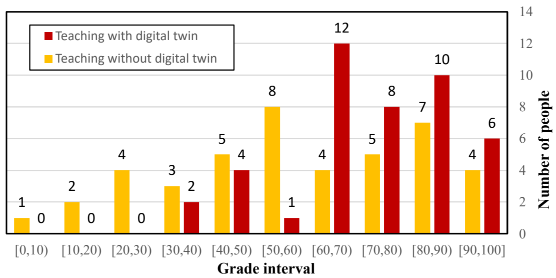


Figure 3: Test score distribution in digital twin learning space teaching.

recommends EKG-guided knowledge points to explain the failure mechanism. This "learning from failure" methodology [4] prompts an iterative cognitive cycle of hypothesis generation, real-time operation, instantaneous data feedback, and analytical refinement.

Finally, this collaborative virtual workspace breaks individualized learning constraints. Remote student cohorts can co-inhabit the synchronized environment for group-based troubleshooting. Simultaneously, teachers transition from traditional knowledge transmitters to proactive facilitators, utilizing the Pedagogical Layer's data dashboard to provide targeted interventions, thereby seamlessly merging knowledge acquisition with collaborative emotional objectives.

3 Implementation and Evaluation

3.1 Experimental Setup

To validate the effectiveness of the SIDT framework, an empirical study was conducted in the course Fundamentals of Wireless Communication Technology, involving a sample size of 43 junior undergraduate students. To mitigate practice effects and content familiarity, the experiment utilized a within-subjects design where the two teaching cycles (a traditional lecture model and an SIDT-based immersive model) were applied to different curricular modules of equivalent difficulty. Furthermore, a baseline pre-test was conducted prior to the intervention to ensure the homogeneity of students' prior knowledge.

Unlike traditional assessments that heavily favor conceptual memory, this study aligned assessment dimensions with complex cognitive tasks. In the VR/AR environment, students performed hands-on tasks such as selecting virtual antennas, configuring network controllers, and adjusting signal collection frequencies.

Specifically, within the immersive learning space, students were divided into collaborative groups equipped with XR devices. Beyond merely selecting hardware, they were required to dynamically configure underlying parameters such as collection frequencies and data transmission methods to construct a comprehensive wireless communication system. Leveraging the real-time interactivity of the digital twin, students then extracted and analyzed dynamic data directly from these virtual instruments to perform system-level troubleshooting.

The final evaluation included multiple-choice (assessing cognitive judgment), fill-in-the-blank (knowledge construction), short-answer (systematic problem dismantling, e.g., reconstructing data fusion topology maps), and virtual testing (dynamic parameter adaptation).

This structured evaluation framework was deliberately engineered to mirror complex cognitive tasks rather than rote memorization. For instance, while multiple-choice queries tested cognitive application, short-answer questions required students to utilize packet data across nodes to reconstruct data fusion topology maps, thereby assessing their capacity to dismantle and analyze complex network systems.

3.2 Results and Analysis

The evaluation data reveals a significant performance shift under the new paradigm, as detailed in Fig. 2 and Fig. 3. In the SIDT group, student scores were highly concentrated in the higher ranges, with a noticeable increase in the 80-100 score bracket compared to the traditional group (see Fig. 3). The box plot analysis, illustrated in Fig. 2, indicates that the immersive learning environment particularly improved students' performance in short-answer and virtual practical questions.

This substantial improvement can be attributed to two main factors: First, XR visualization drastically reduced the cognitive load associated with abstract spatial topologies, such as multipath routing; second, the zero-risk digital twin encouraged extensive trial-and-error, allowing 75% of learners to significantly enhance their complex troubleshooting skills. Furthermore, 81.3% of students demonstrated improved abilities in independent knowledge construction by effectively consulting EKG-guided resources to solve virtual anomalies, while virtual collaborative tasks led to a 35% increase in team communication efficiency.

This collaborative dynamic fundamentally broke the limitations of individualized traditional learning. Within the virtual environment, group roles naturally diversified—spanning practical execution, technical support, and coordination—with almost zero passive participation observed. By utilizing virtual communication tools like voice chat and spatial visual notes, students seamlessly integrated diverse perspectives to solve problems collectively, significantly driving the overall performance shift observed in the higher score distributions.

4 Conclusion

This paper introduces the SIDT framework, a novel pedagogical approach synergizing XR, digital twins, and Educational Knowledge Graphs. By upgrading the virtual learning space from a static replica to a semantically aware cognitive scaffolding, the framework successfully transforms passive reception into active, iterative exploration, significantly enhancing engineering students' systemic troubleshooting capabilities. Furthermore, leveraging cloud-edge synergized deployment ensures the system's cost-effectiveness and scalability for large classrooms. Future research will explore integrating Large Language Models (LLMs) to overcome the current bottleneck of multimodal semantic extraction (e.g., parsing complex mathematical formulas and system block diagrams), thereby enabling low-cost, automated EKG construction across broader multidisciplinary domains.

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