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Construction·Driven·Evaluation: Exploration and Practice of Knowledge Graph in Scenario-Based Teaching of "Highway Electromechanical System Integration Technology"

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Abstract: *To address the challenges of the complex knowledge system, high system coupling, and the difficulty of intuitively presenting multi-dimensional relationships in traditional teaching for the course "Highway Electromechanical System Integration Technology," this paper employs a structured approach to organize core elements such as toll collection, surveillance, communication subsystems, their equipment interconnections, fault logic, and engineering specifications. This process constructs a knowledge graph with deep semantic relationships. Practical engineering scenarios are utilized to design teaching cases, driving the implementation of a scenario-based teaching model. Simultaneously, a multi-dimensional evaluation system is established to assess teaching effectiveness, validating its impact on enhancing student learning interest, knowledge mastery, and practical capabilities.*

Keywords: *Highway Electromechanical Systems; Knowledge Graph; Teaching Reform; Scenario-Based Teaching*

1. Introduction

The course "Highway Electromechanical System Integration Technology" covers equipment principles, integration logic, and engineering practices of subsystems including toll collection, surveillance, communication, and tunnel electromechanics. Its knowledge system exhibits complex characteristics of "multi-system coupling, multi-equipment interconnection, and multi-specification intersection." In traditional teaching, instructors primarily rely on static media like presentation slides, textbooks, and blueprints, making it difficult for students to intuitively grasp the multi-dimensional relationships among "equipment-fault-solution-engineering specifications." This often leads to a disconnect between theory and practice and low learning engagement.

As a visual semantic association technology, knowledge graphs can transform fragmented knowledge points into a structured "entity-relationship" network, providing intuitive support for teaching complex systems. Scenario-based teaching, anchored in real engineering scenarios, facilitates the transformation of knowledge from "cognition" to "application." This paper proposes a tripartite teaching reform framework of "Graph Construction - Scenario Driving - Multi-dimensional Evaluation." By constructing a knowledge graph for highway electromechanical systems, driving scenario-based teaching implementation, and establishing a multi-dimensional evaluation system, it explores new pathways to enhance course teaching effectiveness, offering a reference for similar course reforms.

2. Theoretical Foundation and Technical Support

2.1 Knowledge Graph Technology

A knowledge graph is a semantic network composed of entities, relationships, and attributes, visually presenting the associative logic between knowledge points. Its core value lies in breaking the linear storage mode of traditional knowledge, enabling dynamic querying and visual reasoning. The fundamental building block of a knowledge graph is the triplet, consisting of a head entity, a relationship, and a tail entity, denoted as (h, r, t).

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With the maturation of key technologies like ontology construction and entity extraction, the application of knowledge graphs in education has deepened. Educational knowledge graphs represent a specific application form of knowledge graph technology within a particular discipline or course. Compared to industry-specific knowledge graphs, educational knowledge graphs exhibit the following characteristics: (1) Diverse node types, encompassing entities, concepts, formulas, theorems, and conclusions; (2) Specialized inter-node relationships, characterized by directionality, transitivity, and reciprocity; (3) Diverse node attributes, containing various types of teaching resources such as text, video, and images. The Educational Knowledge Graph is shown in Figure 1.

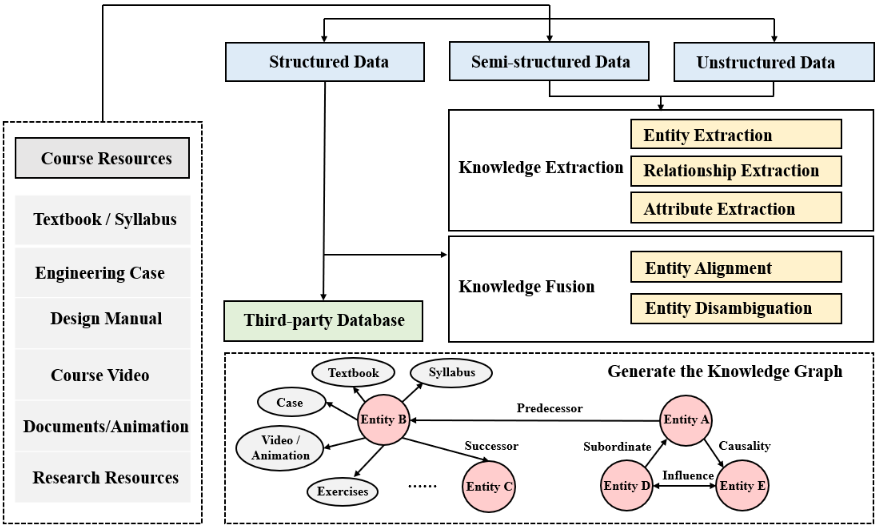

Figure 1 Schematic Diagram of an Educational Knowledge Graph

A knowledge graph serves not only as a "knowledge base" but also as a cognitive and decision-making aid. Literature [1] proposed a construction and completion strategy for a power transformer fault knowledge graph. Literature [2] established a technical architecture integrating knowledge graphs with large language models for the power domain, exploring applications in equipment operation and maintenance, power dispatch operation planning, and ultra-high voltage transmission line fault diagnosis. Literature [3] constructed a knowledge graph for organizing knowledge and enabling intelligent applications in railway signaling equipment fault diagnosis. Literature [4], focusing on highway informatization, studied the use of knowledge graph technology to integrate highway traffic information for improved traffic management efficiency.

2.2 Scenario-Based Teaching

Scenario-based teaching, anchored in scenarios, problem-oriented, and practice-centered, aligns highly with the engineering nature of the "Highway Electromechanical System Integration Technology" course. Typical course scenarios, such as toll station equipment joint debugging and surveillance system fault troubleshooting, involve clear task objectives, equipment interconnections, and operational specifications. The knowledge graph provides the "knowledge base" for scenario-based teaching, while scenario-based teaching offers the "application context" for the knowledge graph. This synergy drives students to actively explore entity relationships within the graph, achieving a closed loop from "graph to scenario" and "cognition to application," thereby addressing the issue of "knowledge fragmentation" in traditional teaching.

Outcome-Based Education (OBE) requires teaching objectives to focus on student competency attainment. The integration of knowledge graphs and scenario-based teaching aligns with the course's three core competencies: training system correlation analysis skills through graph querying, cultivating engineering problem-solving abilities through scenario tasks, and reinforcing industry standard application skills by invoking specification entities. This achieves a closed-loop connection between the teaching process and competency goals. In related research, literature [5] reconstructed teaching projects by deconstructing typical industrial projects, building an OBE-oriented course-practice integration system. Literature [6] constructed an "Imitation-Crossing" dual model to address shallow student practice and weak skill retention. Literature [7] integrated the spirit of craftsmanship into OBE courses, emphasizing value guidance and subjective education. Literature [8] utilized new technologies like

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intelligent networking and vehicle-infrastructure coordination as the core, employing OBE for backward design to support innovative talent cultivation in transportation.

The CDIO (Conceive-Design-Implement-Operate) engineering education model also highly complements knowledge graph-driven scenario teaching. The knowledge graph provides the knowledge association framework for the "Conceive" phase, scenario tasks guide practical operations in the "Design" and "Implement" phases, and the "Operate" effectiveness can be verified using specification entities within the graph [9][10]. For instance, in a surveillance system integration scenario, students need to conceive a solution based on the "equipment compatibility" relationship in the graph, design implementation steps according to the "installation specification" entity, and ultimately validate the solution's feasibility through scenario simulation.

3. Highway Electromechanical System Knowledge Graph Construction

3.1 Entity Classification and Relationship Definition

This section, based on the course syllabus and engineering practice requirements of "Highway Electromechanical System Integration Technology," combines "top-down" framework design with "bottom-up" element extraction. This approach enables the structured organization of core elements within the toll collection, surveillance, and communication subsystems, completing the definition of the entity-relationship model.

Entity classification covers key elements from teaching content and engineering scenarios: Equipment entities encompass hardware (e.g., lane controller, high-definition camera, network switch) and software components (e.g., billing software). Fault entities are classified by system (e.g., ETC recognition failure in toll systems, video lag in surveillance systems, route flapping in communication systems). Solution entities primarily refer to troubleshooting procedures and operations for faults. Specification entities cite national and industry standards.

Relationship definitions must reflect semantic associations between elements. Five core relationship types were identified: Subordinate, Connection, Causality, BasedOn, and Influence. The core relationship types in this course knowledge graph are presented in Table 1.

Table 1 Description of Core Relationship Types in the Course Knowledge Graph

Relationship Type	Definition	Specific Course Example
Subordinate	Hierarchical or containment relationship between entities	Lane controller, toll terminal subordinate to toll system; High-definition camera subordinate to surveillance system; Optical transceiver subordinate to communication system.
Connection	Physical or logical connection link between entities	Toll terminal connects to lane controller; High-definition camera connects to video surveillance platform via network.
Causality	Causal association between entities, often reflecting fault and cause	Heavy rain causes fogging on surveillance camera lens; Network switch port offline causes toll terminal network disconnection.
BasedOn	Entity execution based on another entity as a standard or reference	"Port restart" based on Article 7.4 of GB/T 21671-2018; Surveillance equipment installation based on JT/T 1091-2016 specification.
Influence	Effect of one entity on the function of another	Insufficient network bandwidth influences surveillance video transmission fluency; Equipment compatibility influences toll and surveillance system integration effectiveness.

3.2 Course Knowledge Graph Construction

3.2.1 Data Preprocessing

Entities and relationships were extracted through multi-source data fusion: Structured information like equipment selection parameters and fault types was extracted from textbooks and engineering design manuals; "Fault-Solution" association data was extracted from engineering case documents; Equipment attributes (e.g., optical transceiver transmission rate, camera protection level) were supplemented from manufacturer product manuals; High-frequency fault patterns were extracted from desensitized operational data (e.g., fault work orders). This process formed structured data tables containing entity ID,

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name, attributes, and relationship types, providing data support for building the knowledge graph.

3.2.2 Key Technologies for Knowledge Graph Construction

This mainly comprises four parts: Knowledge Extraction, Knowledge Fusion, Knowledge Processing, and Knowledge Storage.

(1) Knowledge Extraction: As the primary step in knowledge graph construction, knowledge extraction aims to extract the required entities, relationships, and attributes from multi-source heterogeneous data (structured, semi-structured, and unstructured) to form the knowledge representation of the knowledge graph ontology. This process is prone to generating duplicate and erroneous information, necessitating knowledge fusion to eliminate redundancy and errors, ensuring knowledge graph quality.

(2) Knowledge Fusion: Also known as entity alignment, its core task is to integrate knowledge from multiple source databases. As different knowledge bases may represent the same knowledge differently, entity alignment requires achieving a unified description of heterogeneous knowledge, primarily covering relationship alignment and attribute alignment. Common methods include similarity calculation and knowledge representation learning.

(3) Knowledge Processing: Knowledge processing can be viewed as a knowledge quality assessment process. After the above steps, basic knowledge representations are obtained, but they are not yet a structured, networked knowledge system. Quality assessment is needed to filter qualified entries before inclusion in the knowledge base, often conducted manually.

(4) Knowledge Storage: The constructed knowledge base is the knowledge graph itself, which requires specific storage methods to form a computer-recognizable or visualizable knowledge graph. Currently, there are two main storage types: One is storage based on RDF, RDFS, and OWL data models, all XML-based metadata standards focusing on machine understandability; The other is storage based on graph databases, emphasizing efficient querying, retrieval, and visual presentation, clearly showing dependencies between data nodes.

The key technologies for constructing the knowledge graph and their relationships are illustrated in Figure 2.

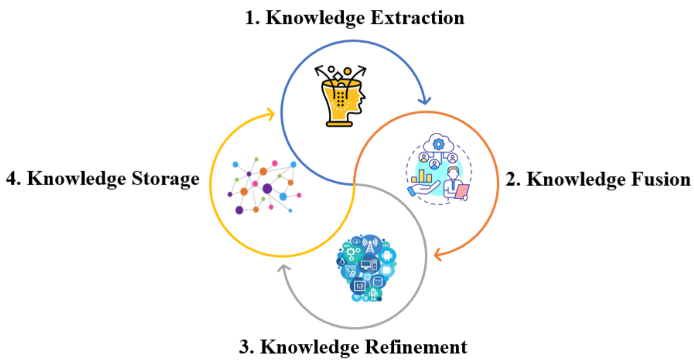

Figure 2 Key Technologies for Knowledge Graph Construction

3.2.3 Constructing the Course Knowledge Graph

Bottom-up and top-down are the two mainstream approaches for knowledge graph construction. The bottom-up approach collects data in triplet form, gradually refining the model based on data, mainly suitable for creating general-purpose knowledge graphs. The top-down approach first defines the knowledge graph data model, populates data according to the model, and finally constructs the graph, primarily used for building domain or industry-specific graphs. This paper focuses on constructing the "Highway Electromechanical System Integration Technology" knowledge graph. Centered on core course content (e.g., system architecture, equipment parameters, fault correlations, specification standards), this graph has clear knowledge boundaries, prominent domain characteristics, and well-defined knowledge association structures like equipment subordination and fault causality logic. As a typical domain-specific knowledge carrier, the top-down approach is more suitable. The primary step in top-down construction is ontology construction.

The specific process for constructing the course knowledge graph in this study is as follows:

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(1) Course ontology data originates from the planned textbooks "Highway Electromechanical System Integration and Application" and "Highway Electromechanical System Integration Technology," supplemented by self-compiled practical training guides;

(2) Based on textbooks, professional training plans, teaching syllabi, engineering design manuals, engineering cases, and equipment product manuals, knowledge point extraction and knowledge concept acquisition were completed, and the ontology of the knowledge graph was analyzed and determined;

(3) Based on the "Chapter-Section-Knowledge Point" hierarchical structure, a multi-level classification system for knowledge concepts was constructed using the "top-down" method;

(4) Knowledge points were annotated with attributes and learning requirements;

(5) Associations between extended knowledge points and cross-system knowledge points were established, and data was constructed into triplets;

(6) Data import was completed, and the course knowledge graph was visualized using a graph database;

(7) Utilizing entity linking technology, the knowledge graph was integrated with multi-modal resource entities. The supporting resource library includes teaching resources (course videos, presentations, animations), industry cases, and research resources (core journal articles, theses).

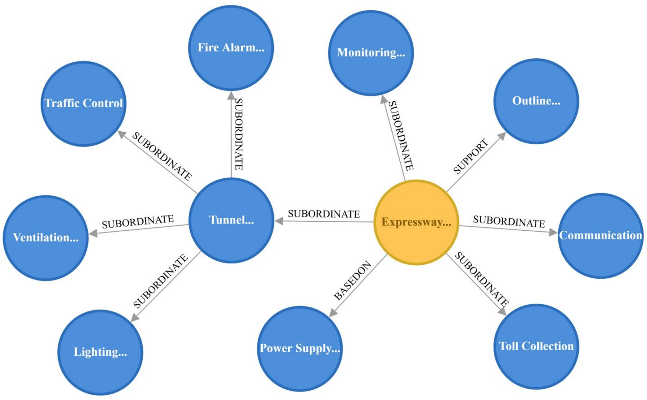

Figure 3 Knowledge Graph of Chapter Outline for Highway Electromechanical System Integration Technology Course

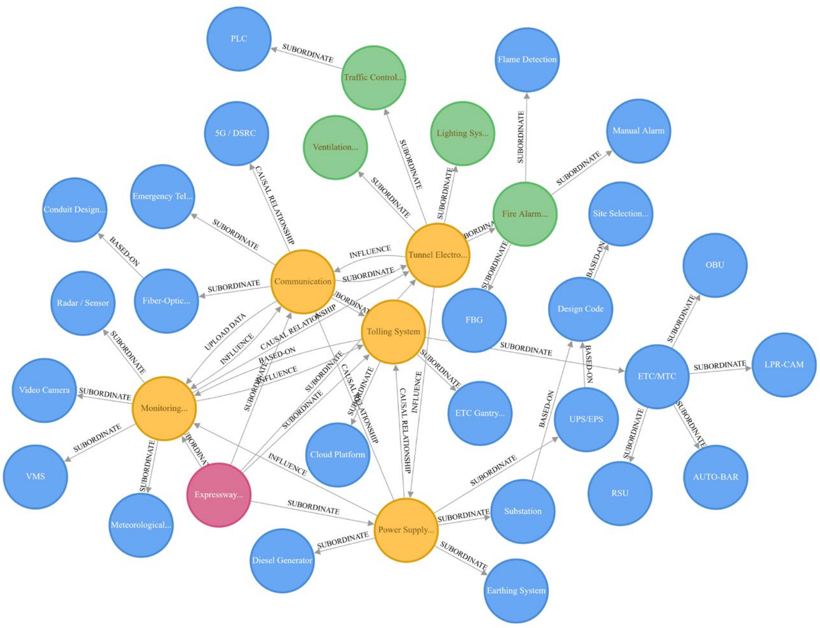

Figure 4 Course Knowledge Graph (Partial) of Highway Electromechanical System Integration Technology

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Based on the steps above, the knowledge graph of the chapter outline for Highway Electromechanical System Integration Technology Course is presented in Figure 3, and the partial knowledge graph of the Highway Electromechanical System Integration Technology course is shown in Figure 4.

4. Knowledge Graph-Driven Scenario-Based Teaching Implementation and Evaluation

4.1 Graded Teaching Scenario Design

Centered on the progressive competency development pattern of "Cognition - Application - Innovation," this paper divides teaching scenarios into three difficulty gradients: Basic Cognition, Comprehensive Application, and Innovation Challenge. Each gradient increases in difficulty, with the knowledge graph serving as the core support, embedding task-driven approaches and specification requirements throughout, precisely aligning with the OBE-oriented core competencies: system correlation analysis, engineering problem-solving, and industry standard application.

4.1.1 Basic Cognition Scenarios

Emphasis is placed on the connectivity between individual devices within foundational scenarios. Taking "Fault Location for Network Disconnection of Toll Terminals" from Highway Electromechanical System Integration Technology Course as an example, students search for the "Toll Terminal" node on the graph interface; the system displays its relationship chain: Toll Terminal - Lane Controller - Network Switch. Students click on each node sequentially, simultaneously checking the status attributes of the node's equipment. When a student locates a specific port showing "Offline" status, clicking the port node in the knowledge graph displays associated teaching resources like technical standards and operation manuals, along with suggested operational guidance. Students start from the equipment status, actively explore along the relationship chain, precisely locate the fault point based on real-time equipment status, and learn to obtain operational instructions by leveraging specification resources, establishing foundational cognitive abilities for fault tracing and standardized handling.

4.1.2 Comprehensive Application Scenarios

The comprehensive application scenario targets multi-system coupled faults, developing students' ability to collaboratively analyze and resolve complex failures stemming from cross-system interactions. Within this framework, the knowledge graph functions as a centralized information hub and relationship visualization engine across systems.

In the scenario of 'Highway Tunnel Video Feed Loss,' students initiate cross-system fault diagnosis across power supply and distribution, communication, and monitoring systems by querying the knowledge graph with the 'High-Definition Camera' entity as the retrieval node.

Subordination Hierarchy: High-Definition Camera → Tunnel Monitoring System → Tunnel Electromechanical System

Connection Traceability: High-Definition Camera → Fiber Transceiver → Tunnel Communication Ring → Monitoring Center Server

During this process, the knowledge graph unifies heterogeneous data scattered across blueprints, manuals, work orders, and standards into an entity-relationship-attribute network. Students proactively drive the diagnostic progression by: first pinpointing the hierarchical position of high-definition cameras within the tunnel surveillance system and their associated subsystems, then conducting hop-by-hop troubleshooting along the connectivity paths.

4.1.3 Innovation Challenge Scenarios

Within the Innovation Challenge Scenario, which focuses on knowledge graph-driven system-level innovation planning, the 'ETC Free-Flow Tolling' use case exemplifies the methodology: First, the scenario is mapped to a four-layer architecture (Vehicle → RSU → Edge Server → Clearing Center), with each node encapsulating domain-specific devices, protocols, and regulatory specifications. Students then iteratively validate solution compatibility, cost-effectiveness, and regulatory compliance, establishing equilibrium among technical feasibility, cost control, and standard adherence to ultimately generate an executable system design.

4.2 Multi-dimensional Teaching Evaluation

This study evaluates student efficacy in course participation through three dimensions: Learning Engagement, Knowledge Integration proficiency, and Engineering Practice Capability, and Table 2 presents a comparative evaluation of teaching effectiveness across three dimensions under the two instructional approaches.

Table 2 Multi-dimensional Teaching Performance Comparison: Traditional vs. Knowledge Graph-Driven Scenario Teaching

Evaluation Dimension	Core Evaluation Points	Traditional Teaching Performance	Knowledge Graph-Driven Scenario Teaching Performance
Learning Engagement	Interaction Initiative	Primarily teacher-led, students mostly passive responders	Increased frequency of student-initiated questions and discussions, proactive problem exploration using the graph
	Task Engagement	Moderate participation in complex scenario tasks, prone to discouragement	Sustained engagement around scenario tasks, active use of graph to validate ideas
Knowledge Integration	System Correlation Understanding	Fragmented understanding of inter-system relationships, prone to confusing equipment subordination	Ability to clearly trace "Equipment-Fault-Specification" association chains, fluent cross-system knowledge invocation
	Specification Application Awareness	Fragmented referencing of engineering specifications, low matching with actual problems	Ability to precisely associate relevant specifications with scenarios, forming a "Problem-Solution-Basis" closed loop
Engineering Practice Capability	Fault Handling Logic	Singular troubleshooting approach, reliance on empirical judgment, lack of standardization	Ability to reason fault causality chains based on the graph, handling processes compliant with industry standards
	Solution Rationality	Solutions lack completeness, rarely consider equipment compatibility and cost-effectiveness	Solutions balance technical feasibility and engineering specifications, able to weigh multi-dimensional factors

5. Conclusion and Outlook

By constructing a knowledge graph for highway electromechanical systems, this paper provides effective support for the implementation of scenario-based teaching, successfully addressing the core problems of abstracted knowledge associations and weakened practice orientation in traditional teaching. The study confirms that this teaching model can effectively enhance students' learning interest, knowledge integration ability, and engineering practice literacy.

Future research can focus on two areas for optimization: First, we can extend the graph's coverage dimensions by incorporating emerging technological entities such as intelligent O&M. Second, we can develop a dynamic update mechanism to achieve real-time synchronization between the instructional knowledge graph and evolving industry standards and actual engineering cases.

Acknowledgments

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