Research on an Intelligent Training System for Highway Construction Safety Based on Cloud-Edge-End Collaboration and Knowledge Graph

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Abstract: *The highway construction environment is complex, with high personnel mobility and numerous potential hazards. Traditional safety training models commonly suffer from issues such as being overly formalized, having dull content, lacking specificity, and missing a closed loop for effectiveness evaluation, making it difficult to effectively enhance the safety awareness and skills of practitioners. To address the above problems, this paper proposes and develops a "Cloud-Edge-End Integrated Multimedia Safety Training Management System," similar to the system adopted in Shaanxi Province's highway construction projects. This system is based on a "cloud-edge-end" collaborative architecture and deeply integrates knowledge graph technology, AI recommendation algorithms, and IoT hardware technologies. On the cloud side, a highway construction safety knowledge graph covering the five-dimensional elements of "personnel, machinery, materials, methods, and environment" is constructed, and a personalized assessment and course recommendation engine is developed based on the Transformer model; this achievement is supported by research on the construction and application of a multimodal safety knowledge graph for construction based on large language models, while the application of BIM technology in highway construction safety management also provides a technical background for this work. On the edge side, a portable intelligent training toolbox integrating identity verification, multimedia teaching, and paperless assessment is developed, and seamless collection of training process data is achieved through a PPT plugin. On the terminal side, a WeChat mini-program for trainees is developed, supporting pre-/post-training assessments, personalized learning path recommendations, and interactive learning. This study elaborates in detail on the system's overall architecture, key technologies (including automatic knowledge graph construction, AOV-optimal learning path generation, and edge device integration), and business processes. The system has been successfully applied in the Hu-Zhou-Mei Highway project in Shaanxi Province. Practice demonstrates that the system effectively achieves precise, dynamic, and closed-loop management of safety training, significantly improving training efficiency and outcomes, and provides an innovative technical model and practical reference for safety production management in the field of transportation infrastructure construction.*

Keywords: *Highway Construction; Safety Training; Cloud-Edge-End Collaboration; Knowledge Graph; Intelligent Recommendation; Adaptive Learning*

1. Introduction

With the deepening advancement of China's strategy to strengthen the country through transportation, the scale of highway construction continues to expand, engineering structures are becoming increasingly complex, and unsafe factors in the construction environment have significantly increased. Statistics indicate that a substantial number of safety incidents stem from a lack of safety knowledge, weak safety awareness, and insufficient operational skills among on-site workers[1]. Although regulations such as the "Work Safety Law of the People's Republic of China" explicitly require enterprises to implement the "training before posting" system, current safety training efforts still face severe challenges. For example, according to 2019 highway construction safety training data, the safety awareness of trained workers improved by 30%, and the accident rate decreased by 25%. This demonstrates that despite regulatory requirements, the actual effectiveness of safety training still needs further enhancement and optimization[2].

In recent years, scholars both domestically and internationally have conducted numerous explorations in the informatization of safety training. Developed countries abroad, such as the United States and Germany, have established professional and systematic safety training systems[3]. Domestic research, however, has largely focused on the development of multimedia courseware or the construction of simple online learning platforms. Significant gaps remain in areas such as leveraging artificial intelligence technology to achieve precise delivery of training content, breaking down data barriers between training and on-site behavior, and constructing a comprehensive solution covering "field-cloud-mobile terminals." Existing systems often fail to deeply integrate advanced AI algorithms with hardware equipment that meets the stringent conditions of construction sites, resulting in a disconnect between theoretical research and engineering practice.

In response to the aforementioned industry pain points and research gaps, this study, supported by a scientific research project from the Shaanxi Provincial Department of Transportation, designed and implemented an "Integrated Cloud-Edge-End Multimedia Safety Training Management System." The core innovation of this system lies in its pioneering application of a knowledge graph-driven adaptive learning model to the field of highway construction safety training. Furthermore, by utilizing self-developed edge computing hardware (the Intelligent Training Toolbox) and mobile applications, it establishes a complete closed loop encompassing data collection, intelligent analysis, and precise intervention. This paper aims to systematically introduce the platform's design philosophy, technical architecture, core algorithms, and application outcomes, thereby providing a replicable and scalable technological pathway for enhancing the intrinsic safety level of transportation engineering construction.

2. Overall System Architecture Design

To address the characteristics of highway construction, such as numerous scattered sites, extensive linear distribution, broad coverage, and highly mobile personnel, the system adopts a three-layer "cloud-edge-end" collaborative architecture. This design aims to balance the centralized management of global operations with the flexibility required for on-site training.

2.1 Cloud Platform Layer

The cloud platform serves as the system's "brain" and data center, primarily responsible for the centralized management of global resources and intelligent decision-making. Its core functions include:

Safety Training Resource Repository: It stores and manages a vast collection of multimedia courseware, question banks, and safety regulation documents. The courseware content is meticulously categorized by trade (such as electricians, blasters, scaffolders, etc.) and construction process.

Knowledge Graph and AI Engine: This is the core intelligent module of the system. By constructing a knowledge graph for the highway construction safety domain and integrating deep learning models like Transformer, it achieves a precise profile of trainees' knowledge mastery and drives personalized course recommendations.

Management Backend System: It provides comprehensive management functions, including user management, project management, course management, learning progress statistics, and effectiveness evaluation, for use by safety management personnel.

Microservices Support Platform: Built on the SpringCloud framework, it encompasses four major business support platforms: data exchange, message center, and permission authentication, ensuring high availability, high concurrency, and security for the system.

2.2 Edge Computing Layer

The edge layer serves as the crucial link connecting cloud-based intelligence with on-site practical operations. Its physical carrier is the self-developed "Portable Cloud-Edge-End Integrated Multimedia Safety Training Toolbox." This toolbox integrates various hardware modules, enabling independent training activities in environments with no or weak network connectivity and synchronizing key data to the cloud. Its main hardware components include:

Main Control System: It employs an industrial-grade touch all-in-one computer, featuring wide voltage input and electromagnetic interference resistance, making it adaptable to complex construction site environments.

Identity Information Recognition Module: It integrates a high-precision OCR-based ID card reader, capable of quickly reading and verifying information from second-generation ID cards.

Biometric Information Recognition Module: It combines dynamic facial recognition and non-membrane optical fingerprint recognition technologies to achieve efficient, anti-cheating, real-name attendance tracking.

Intelligent Projection Module: It has a built-in DLP projector, supporting wireless screen mirroring, auto-focus, and keystone correction, enabling the creation of mobile training classrooms anytime and anywhere.

Wireless Response Module: Based on 2.4GHz RF technology, it supports up to 200 response devices operating simultaneously, enabling paperless, real-time classroom assessments.

Furthermore, a dedicated PPT plugin has been developed and embedded within the training toolbox. When instructors deliver lessons, the plugin automatically captures interactive data such as courseware playback, trainee check-ins, and in-class tests, and uploads this data to the cloud in real-time via a message queue, achieving digitalization and automation of the training process.

2.3 Terminal Application Layer

The terminal layer, serving as the direct interaction interface for trainees, adopts a lightweight WeChat mini-program format, significantly lowering the barrier to user adoption. The primary functions of the trainee client include:

Scan-to-Check-in: Trainees complete real-name check-in by scanning a dynamic QR code generated by the PPT plugin, with their geographical location information recorded.

Pre-/Post-Training Assessments: Trainees complete assessment questionnaires pushed by the system before and after learning, providing analytical data for the AI engine.

Personalized Learning: Trainees receive learning plans and courses recommended by the system based on assessment results and can engage in online learning anytime, anywhere.

Interaction and Feedback: Trainees participate in classroom tests, view scores, submit learning reflections, and more, fostering two-way interaction.

This three-layer architecture effectively overcomes the limitations of traditional training regarding time and venue, establishing a new safety training model characterized by "offsite mobile training, online centralized management, on-site real-time querying, and intelligent safety access control."

3. Core Technologies and Algorithm Research

3.1 Construction of the Intelligent Adaptive Learning Model

The Intelligent Adaptive Learning System is a system supported by an educational knowledge graph and designed to serve the intelligent adaptive learning paradigm. This system comprises six components: a learning content database, a knowledge graph, a learner database, a learner cognitive profile, an intelligent adaptive learning engine, and learning applications.

Learning Content Database: This component is responsible for collecting and storing text information closely related to knowledge, learning resources, and learning objectives. It serves as the primary data source for knowledge graph development.

Knowledge Graph: This component is responsible for the comprehensive planning and visual representation of the disciplinary knowledge system and learning resources, guided by learning objectives, to ensure alignment between learning objectives and learner capabilities.

Learner Database: This component is responsible for storing and managing learners' cognitive foundations and learning behavior information, providing comprehensive static and dynamic data support for constructing learner cognitive profiles.

Learner Cognitive Profile: This component is responsible for modeling individual cognitive characteristics across four dimensions: knowledge state, knowledge structure, cognitive style, and metacognitive ability. It involves a multidimensional analysis of learners' basic information and learning behavior data.

Intelligent Adaptive Learning Engine: This component is responsible for mapping learners' cognitive profiles onto the knowledge graph, facilitating the presentation of personalized cognitive states, designing individualized learning paths, and providing learning resource recommendations. This engine plays a key role in supporting personalized learning services.

Learning Application Module: This module serves as the human-computer interaction interface of the Intelligent Adaptive Learning System, providing personalized learning services to learners. Its functions include pre-assessment, visual cognition, learning path guidance, access to learning resources, intelligent question-answering, and learning evaluation.

Automatic Construction and Optimization of Knowledge Graph

The knowledge graph serves as the foundation for intelligent adaptive learning. This study proposes a three-stage construction method that integrates ontology modeling and deep learning.

Stage 1: Data Acquisition and Preprocessing

Text data is crawled from authoritative sources such as highway construction safety regulations, operating procedures, and accident reports, with batch collection performed using the Scrapy framework. Processes such as word segmentation, noise removal, and entity annotation are performed on the raw text. The text is then converted into word vector sequences using BERT's WordPiece tokenizer and divided into training and test sets in a 7:3 ratio.

Stage 2: Ontology Construction and Entity-Relation Annotation

The Protégé tool is used to define the core concepts, attributes, and relational constraints within the safety training domain, forming a top-level ontology model. The ME+R+BIESO labeling schema is adopted to perform joint annotation on text sequences:

ME (Main Entity): Labels core safety knowledge concepts (e.g., "work at height").

R (Relation): Labels semantic relationships between entities (e.g., "requires" indicates a prerequisite condition).

BIESO Tags: Identify entity boundaries (B/I/E denote beginning, inside, and end respectively, while S denotes a single-word semantic unit).

For example, the sentence "Work at height requires wearing a safety harness" is annotated as:

[work at height/B-ME, requires/O, wearing/B-R, safety harness/E-R]

Stage 3: Entity and Relation Synchronous Extraction

A BiLSTM-CRF model is constructed for end-to-end entity and relation extraction (Figure 4). The model structure includes:

BERT Embedding Layer: This layer encodes the input text into 768-dimensional vectors, capturing contextual semantic features.

BiLSTM Layer: A bidirectional LSTM network extracts forward and backward dependencies from the sequence and outputs hidden state vectors.

CRF Layer: This layer uses the Viterbi algorithm to find the optimal label sequence. The loss function is defined as:

$$L=-\sum \log \sum y' eS(X,y') eS(X,y)$$

where S(X, y) represents the score of label path y for sequence X.

The performance evaluation of the model on the test set is shown in Table 1, achieving an F1-score of 89.7%, indicating its high accuracy in entity and relation extraction.

Table 1 Performance of the Entity-Relation Extraction Model

Metric	Precision(%)	Recall(%)	F1-Score(%)
Entity Recognition	91.2	88.5	89.8
Entity Recognition	87.6	86.3	86.9
Overall Performance	89.4	88.1	89.7

The extracted triples are stored in the Neo4j graph database, which supports multi-hop queries and reasoning. For example, to query the prerequisite knowledge points for "scaffolding erection," it can be achieved using a Cypher statement:

MATCH (a:Knowledge)-[:PREREQUISITE]->(b:Knowledge name: "Scaffolding Erection") RETURN a

Learning Path Recommendation Algorithm Based on AOV Network

To generate personalized learning paths that conform to knowledge logic, this study proposes a recommendation algorithm based on an AOV (Activity on Vertex) network.

Step 1: Construction of the Knowledge Point Association Graph

By applying association rule mining (such as the FP-Growth algorithm) to analyze trainee answer data, the support and confidence between knowledge points are calculated. For instance, if most trainees who answer a question on "safety harness usage" incorrectly also subsequently answer a question on "work-at-height procedures" incorrectly, a rule is generated as follows:

Safety Harness Usage--Work-at-Height Procedures (with a confidence of 0.85)

Knowledge points are treated as vertices and rules as directed edges to construct the AOV network.

Step 2: Learner Clustering and Grouping

The k-means algorithm is employed to cluster trainees based on their knowledge mastery vectors (score rates across various knowledge points), thereby dividing them into k groups. The clustering objective function is:

$$J=\sum_{i=1}^{k}\sum_{x\in C_i}\|x-\mu_i\|^2$$

where C_i is the i-th cluster, and μ_i is the cluster center.

Step 3: Topological Sorting and Path Optimization

For each group's AOV network, the Kahn topological sorting algorithm is applied to generate a linear learning sequence. Knowledge points whose mastery level exceeds a threshold θ (e.g., θ =0.8) are pruned from the path. The final optimal path must satisfy the following conditions:

$$Path=\arg\min\sum_{i=1}^{n}(1-p_i)\cdot d_i$$

where p_i is the mastery level of the knowledge point, and d_i is the learning difficulty coefficient.

Step 4: Dynamic Adjustment Mechanism

The Transformer model is used to monitor trainees' real-time learning behaviors (such as video completion rates and test accuracy rates). The attention weights are employed to dynamically update path priorities:

$$\alpha_i=\frac{\exp(score(h_i,h_q))}{\sum_j \exp(score(h_j,h_q))}$$

where h_i is the feature vector of the knowledge point, and h_q is the query vector.

4. System Application Demonstration and Effectiveness Analysis

The Hu (Huyi)-Zhouzhi-Mei County Expressway project is a critical component of the Xi'an Ring Expressway and the Zhou-Feng Expressway within Shaanxi Province's "2367" expressway network plan. It is a key construction project in the province's 14th Five-Year Plan. The route starts at Shuizhai Village in Huyi District and ends at Huaoya Town in Mei County, with a total length of 71.465 kilometers. It is designed as a two-way, six-lane expressway with a design speed of 120 kilometers per hour. The total excavation volume for the subgrade along the entire route is 4.4177 million cubic meters, and the fill volume is 14.1936 million cubic meters. The total length of bridges is 9,073.73

meters across 57 structures, accounting for 12.69% of the route length. The entire route includes 8 interchanges, 1 monitoring sub-center, 1 maintenance area, and 1 service area, with a total estimated investment of 9.617 billion yuan. This project provides a typical scenario and data foundation for the engineering validation of the proposed system.

The project team deployed portable multimedia safety training toolboxes at the construction site, implementing an online-offline integrated training model. Construction personnel can engage in learning anytime via mobile terminals, building a five-dimensional knowledge graph covering "personnel, machinery, materials, methods, and environment." By integrating the Transformer model to identify individual knowledge gaps, the system achieves "tailored-to-each-individual" assessment analysis and personalized resource delivery.

The system significantly enhances safety levels in high-risk scenarios such as specialized operations. By delivering targeted operational standard videos and interactive tests via mobile terminals, it strengthens the safety awareness of construction personnel. The system tracks learning progress and test results in real time, shortens the "identify issues-deliver courses-assessment feedback" closed-loop cycle, improves training efficiency, reduces ineffective training time, and achieves precise and closed-loop management of safety training.

A comparison of key indicators between the traditional training model and the system proposed in this study validates its effectiveness:

Table 2 Comparative Analysis of Training Effectiveness

Metric	Traditional Training Model	Proposed System	Improvement
Training Completion Rate(%)	72.5	95.8	+23.3%
Average Assessment Score (Percentage)	68.3	86.7	+18.4
High-Risk Behavior Reduction Rate(%)	15.2	41.6	+26.4%
Training Record Completeness（%）	60.1	98.5	+38.4%

The results indicate that the system significantly enhances trainee engagement and knowledge mastery levels through personalized recommendations and interactive training.

Fund Projects

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