Research on intelligent management and control of municipal road project progress and quality driven by multi-source data

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Abstract: As an important part of urban infrastructure, the construction efficiency and quality of municipal road projects directly affect urban development and residents' lives. However, there are some problems in the traditional project management mode, such as data fragmentation, insufficient response and resource mismatch, which lead to time overruns and increased costs. The purpose of this study is to explore the intelligent control method of municipal road engineering progress and quality based on multi-source data drive. Firstly, an "air-sky-ground" integrated data collection network is constructed, which integrates heterogeneous data such as Internet of Things (IoT), unmanned aerial vehicle (UAV), video surveillance and manual reporting, and preprocesses them to lay the foundation for subsequent analysis. Secondly, a multi-modal fusion model based on deep learning is proposed to realize the deep fusion of visual data and sensing data, and a virtual-real linkage system is constructed by combining digital twinning technology. Finally, an intelligent identification and prediction algorithm is designed to realize dynamic prediction of progress, early warning and accurate traceability of quality defects, and a resource optimization model is constructed to realize dynamic allocation of resources. Through case verification, the intelligent management and control system can effectively improve the efficiency and quality of municipal road engineering construction and reduce the comprehensive cost. This study provides theoretical and technical support for intelligent management and control of municipal road engineering, and has broad application prospects.

1. Introduction

As the key link of urban infrastructure, municipal road engineering, although the annual investment exceeds one trillion yuan, has long been plagued by problems such as data fragmentation, insufficient dynamic response and resource mismatch, which leads to time overruns and increased costs. With the application of new information technologies such as Internet of Things (IoT), Unmanned Aerial Vehicle (UAV), deep learning and digital twinning, engineering management is undergoing changes [1-2]. Through real-time collection of construction data, intelligent identification of quality defects, and mining of multi-factor correlation, a closed-loop management and control system of virtual and real linkage is constructed, which provides a brand-new path for improving the efficiency and quality of road engineering construction [3-4].

This study theoretically breaks through the traditional single-source data management mode, constructs a framework of data fusion, risk prediction and decision optimization, and fills the gap of collaborative analysis of municipal engineering multimodal data; In practice, it is expected to improve the management efficiency, ensure the construction quality and reduce the comprehensive cost by realizing the hourly time limit for a project prediction, early warning and accurate traceability of quality defects driven by real-time data, and reducing equipment idleness and material waste with the help of dynamic resource allocation algorithm.

2. Multi-source data acquisition and preprocessing

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Construct a "air-sky-ground" integrated three-dimensional data collection network, covering the whole life cycle of municipal road engineering. Data sources include IoT sensing data. By installing sensors on construction machinery, templates and materials, time series data such as equipment working condition, position, material temperature, paving speed and compaction times are collected in real time [5]. UAV and remote sensing image data are regularly taken by aerial photography, and high-resolution orthophoto images and three-dimensional real-life models are obtained for macro progress monitoring, earthwork calculation and site layout analysis. On-site monitoring video and image data Using cameras deployed at key construction sites, video streams of the construction process are continuously collected for personnel activity analysis, compliance inspection of technology and construction methods and identification of potential safety hazards. Manually fill in and integrate the structured and unstructured data generated by project management system (PM), building information model (BIM) and supervision log with business system data [6].

For the above-mentioned multi-source heterogeneous data (images, point clouds, time series data, texts, etc.), a special preprocessing pipeline will be designed, including data cleaning, denoising, labeling, space-time alignment (unifying all data in the same time stamp and coordinate system) and other steps, laying a high-quality data foundation for subsequent fusion and analysis.

3. Multi-source data fusion and key technologies

Traditional methods such as Critical Path Method (CPM) and Program Review Technique (PERT) rely on static planning and are difficult to cope with dynamic construction environments. In recent years, BIM technology has improved the level of progress visualization through 4D simulation, but lacks the integration of real-time on-site data [7]. Although the IoT based dynamic progress monitoring system can collect device status data, it has not solved the problem of semantic heterogeneity of multi-source data [8]. The application of nondestructive testing technology and mobile quality inspection system has promoted the digitalization of quality management. However, the existing research focuses on the analysis of a single data source, such as image-based crack identification or compactness evaluation monitored by sensors, and lacks the comprehensive utilization of structured data such as material inspection reports and construction logs [9]. The data model in municipal road engineering is more complex, and it is necessary to solve the problem of data alignment and correlation analysis in dynamic environment. In addition, the existing fusion models mostly use weighted average or rule engine, so it is difficult to capture the nonlinear relationship between data [10].

To this end, this stage aims to open up data islands and explore the deep association between multimodal data. The main key technologies include:

3.1 Multimodal fusion model based on deep learning

A neural network model is constructed to deeply integrate visual data (UAV images, surveillance videos) and sensing data. The project image progress identified by UAV is correlated with the compaction times and speed data sent back by compaction equipment to comprehensively evaluate the quality and progress of compaction process.

3.2 Virtual-real linkage driven by digital twins

Based on the BIM model, the high-fidelity digital twin of the construction site is constructed by integrating data such as tilt photography and laser scanning [11]. This twin is not only a visual "digital mirror image", but also a carrier of data fusion and simulation, which realizes real-time interaction and two-way mapping between physical entities and virtual models.

3.3 Intelligent identification and prediction algorithm

3.3.1Schedule management

Computer vision (CV) technology (semantic segmentation, target detection) is used to automatically identify the key nodes of the project (subgrade completion, pipeline laying), and based on historical data and real-time data, time series prediction model is used to realize the dynamic prediction of short-term construction period in hours/days.

3.3.2 Quality management

Train a deep learning model to analyze images and videos in real time, intelligently identify quality defects such as cracks, lack of flatness, honeycomb pits, etc., and locate the processes, equipment and teams where defects occur through traceability analysis to achieve early warning and accurate accountability.

3.3.3 Resource optimization

Based on the fused global data, an optimization model is constructed with time limit and cost as two objectives, and resources such as manpower, machinery and materials are dynamically allocated by using operational research algorithms and reinforcement learning to reduce idleness and waste.

4. Design and implementation of intelligent management and control system

The above research results are integrated into a unified intelligent management and control platform for engineering implementation. The system architecture is shown in Figure 1. Using micro-service architecture, a system including data center, algorithm center and business application front-end is designed. The data center is responsible for accessing, managing and storing massive multi-source data; The middle platform of the algorithm encapsulates all kinds of fusion, recognition and prediction models, and provides intelligent capabilities in the form of API services; The business front end provides visual progress, quality, resources and safety control dashboards for different users (owners, construction parties and supervisors).

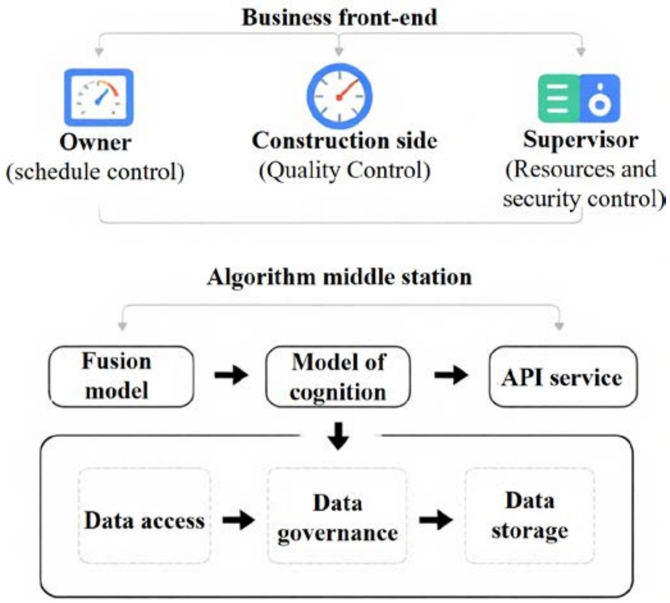

Figure 1 Intelligent management and control system architecture

The system constructs a closed-loop control mechanism of "perception-analysis-decision-execution". Real-time data is used to sense the site state, and after intelligent algorithm analysis, optimization decisions (issuing quality early warning and adjusting resource scheduling plan) are generated, and the instructions are fed back to the site for execution, thus forming an intelligent management closed loop with virtual and real linkage and continuous optimization. Through the above three interlocking research stages, a set of overall solutions of intelligent management and control of municipal road engineering with solid theory, advanced technology and strong practicality is finally formed.

5. Case verification and analysis

In order to verify the actual effectiveness of the multi-source data-driven intelligent management and control system proposed in this study, a city road widening and reconstruction project was selected as a pilot project for a three-month empirical study. The experimental group (section K) with intelligent management system was compared with the control group (section L) with traditional management method.

The system realizes the automatic identification and prediction of progress by fusing the daily orthophoto image of UAV and the data of IoT sensor. As shown in Figure 2, the actual progress of the experimental group (section K) is highly consistent with the progress predicted by the system, and the average deviation rate is only 2.5%. However, the control group (section L) relies on manual reporting, and the data update lags behind, which leads to a great disconnect between the management decision and the actual situation on the spot.

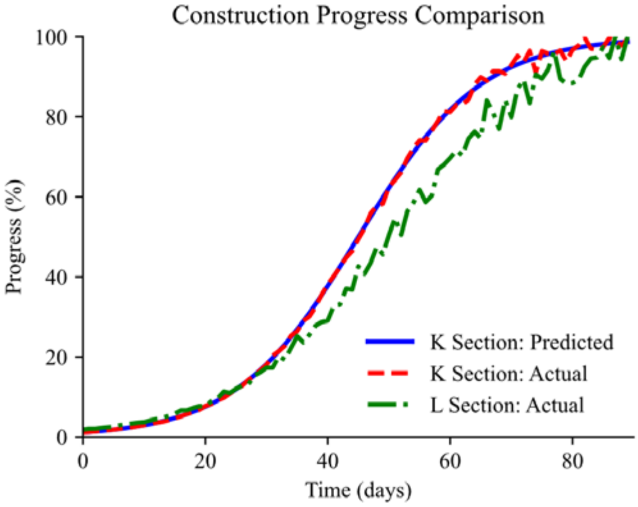

Figure 2 Comparison curve of project progress

In the aspect of quality control, the system successfully realized the early detection of quality defects in the experimental section through AI visual recognition technology. As shown in Table 1, the system proactively warned 12 quality hidden dangers in the stages of base compaction and surface paving, such as insufficient local compaction and abnormal paving temperature, of which 95% hidden dangers were rectified before the start of subsequent processes, thus avoiding rework.

Table 1 Statistical table of quality defect identification and treatment

Construction process	System AI recognition early warning number	Number of confirmed effective early warnings	Early rectification completion number	Estimate of avoiding rework (ten thousand yuan)
Subgrade construction	8	8	8	15.0
Base compaction	15	14	13	28.5
Surface paving	10	9	9	20.0
Total	33	31 (93.9%)	30 (96.8%)	63.5

Through the dynamic optimization algorithm, the system makes real-time task scheduling recommendations for the main equipment such as road rollers and pavers in the experimental section (section K). Results As shown in Table 2, the utilization rate of the main construction equipment in the experimental group has been significantly improved, and the idle rate has decreased by 22% on average compared with that in the control group (L section), and the construction period delay caused by equipment waiting has been avoided. Case verification shows that the multi-source data-driven intelligent management and control system constructed in this study can effectively solve the problems of data fragmentation and slow response in traditional municipal road engineering management.

Table 2 Key equipment utilization ratio comparison table

Device type	Average utilization rate of control group (section L)	Average utilization rate of experimental group (section K)	Promotion percentage
Spreading machine	68%	85%	+17%
Double steel roller	61%	80%	+19%
Rubber wheel roller	58%	78%	+20%
Average	62.3%	81.0%	+18.7%

6. Conclusion

Aiming at the problems of data fragmentation, insufficient dynamic response and resource mismatch in municipal road engineering management, an intelligent management and control system driven by multi-source data is proposed. By constructing a three-dimensional data collection network integrating "air-sky-ground", the comprehensive coverage of the construction process is realized. Using deep learning technology to fuse multi-modal data, a digital twin model is established, and an intelligent identification and prediction algorithm is developed, which effectively improves the accuracy of schedule prediction and quality defect early warning. The empirical study shows that the application of the system in the experimental group (section K) significantly improves the accuracy of the project progress prediction, with an average deviation rate of only 2.5%. By identifying and rectifying the quality hidden dangers at an early stage, rework is avoided and costs are saved. At the same time, the system significantly improves the utilization rate of equipment and reduces idleness and waste through dynamic optimization algorithm. To sum up, the intelligent management and control system provides a set of solutions with solid theory, advanced technology and strong practicality for municipal road engineering, which effectively solves many problems in traditional management methods and has broad application prospects and promotion value.

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