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Digital Twin for Road Condition Monitoring and Predictive Maintenance

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Abstract. A digital twin-based framework is developed in this paper for road condition monitoring and predictive maintenance, aiming to tackle the inefficiencies of traditional road inspection methods and the practical dilemmas in the operation of complex road infrastructure systems. Road maintenance management is confronted with prominent challenges including the spatial complexity of road networks, the nonlinear evolution of pavement damage, and the heterogeneity of multi-source monitoring data. To solve these practical problems, this research designs a three-layer digital twin architecture composed of physical space, data interaction space and virtual space, and puts forward three targeted innovative design strategies. First, autonomous inspection vehicles integrated with a multi-sensor system are deployed to realize continuous and real-time data acquisition under normal traffic conditions, without interrupting the regular road operation. Second, a unified data integration platform is constructed to standardize the format of heterogeneous monitoring data, thereby improving the interoperability and data sharing efficiency of different road monitoring systems. Third, a robotic maintenance system is designed to support targeted and automated repair operations, with maintenance decisions generated based on the predictive analysis results of the digital twin model. The case test results show that the proposed digital twin framework can significantly improve the efficiency of road condition inspection and provide reliable technical support for the formulation of predictive maintenance strategies for road infrastructure. Overall, the framework developed in this study provides a practical approach for improving road maintenance using digital twin technology. It shows potential for supporting more efficient and scalable maintenance processes in real-world applications.

Keywords: Digital Twin, Road Condition Monitoring, Predictive Maintenance, Autonomous Inspection, Data Integration.

1. Introduction

Road infrastructure is a core component of modern transportation systems, supporting daily mobility, logistics operations and regional economic development. However, road pavements are constantly damaged by heavy traffic loads, environmental factors and material aging, leading to cracks, potholes and structural deformation that compromise driving safety and increase maintenance costs [1].

Traditional road condition monitoring mainly depends on manual inspection and regular detection with professional devices. These methods are inefficient and fail to capture the early symptoms of road damage [2].

Road maintenance systems also face three key challenges in practice. Firstly, road networks have complex spatial variations driven. For example, differing traffic loads, pavement materials and structural designs. Secondly, road deterioration follows non-linear temporal patterns. This led to unpredictable damage and development over time. Thirdly, monitoring data is sourced from diverse channels. Such as inconsistent formats and metric measurement.

As a dynamic digital counterpart of physical processes, a digital twin mirrors real-world conditions in real time. It abstracts the core attributes of physical entities to perform real-time simulation. Then predict and analyze relevant processes. Finally reflecting their actual operational status [3].

This study aims to address these existing problems. It puts forward a framework based on digital twin technology. This framework is applied to road condition monitoring and predictive maintenance. It integrates multi-source sensing data and intelligent analytical models to improve road inspection efficiency, cut maintenance costs, and finally realize predictive maintenance for road infrastructure.

2. Literature review

Road maintenance monitoring has advanced from manual inspection to intelligent systems. Early manual inspection relied on visual assessment by staff, which was time-intensive and heavily reliant on human experience. With the advancement of sensing technologies, advanced detection tools like laser scanning vehicles and pavement condition monitoring systems have been adopted to boost detection accuracy [4]. Yet these systems still depend on periodic checks instead of real-time, continuous monitoring.

Digital twin technology has been widely utilized in smart manufacturing, energy systems and urban infrastructure management. It builds a virtual replica of physical assets, with real-time data enabling constant updates to support real-time monitoring, predictive analysis and intelligent decision-making. Recent research has explored digital twin applications in road infrastructure management, proving its potential to enhance maintenance efficiency and infrastructure resilience [2]. Nevertheless, most existing studies focus on data visualization and basic monitoring, with automated inspection and maintenance remaining relatively understudied [5].

3. Methodology

3.1. System architecture

This work introduces a three-layer structure built on digital twin technology. It is made up of the physical layer, data interaction layer, and virtual layer, and is used to support road monitoring and maintenance work in an intelligent way. These three parts work with each other so that data can be collected, processed, analyzed and used for decision making in real time.

3.2. Physical space

The physical layer covers real road facilities and all kinds of sensing equipment. Information about road conditions is gathered by different sensors, such as LiDAR, accelerometers and cameras. Self-driving inspection cars are used to keep track of road states without affecting normal traffic

To make data collection more efficient, this research sets several important parameters, such as sampling frequency and trigger rules. For example, vibration sensors usually work at a high frequency, while sensors that collect environmental information use a lower sampling rate.

3.3. Data interaction space

The data interaction layer works as a platform that combines data from different sources. To make different types of data work together, the system uses unified data models that follow international standards like ISO 19156 and OGC Sensor Things API.

Time synchronization methods such as NTP and PTP are used to arrange data from different sensors on the same time axis. At the same time, the system also checks data quality from aspects such as integrity, accuracy and delay.

3.4. Virtual space

The virtual layer is the digital twin part that describes the whole road network. This model is built by combining BIM and GIS information, so it can show both geometric shape and spatial distribution clearly.

For predicting the trend of road damage, models like LSTM and Transformer are used in this study. The performance of these models is measured by indicators such as RMSE and MAE. The model will keep being updated and adjusted according to real-time data.

3.5. Maintenance decision and execution

The system has a module that can automatically give maintenance decisions based on digital twin results. Once road damage reaches a certain limit, the system will produce a detailed maintenance plan. This plan includes the best time for maintenance, expected work time and materials that are needed. Then automatic vehicles with maintenance robots will be sent to finish jobs like repairing cracks and filling potholes. Algorithms for task arrangement and path planning are used to improve the working efficiency of robots. The system can also communicate with the traffic control system to reduce influence on normal road use.

4. Case study

Data Normalization: Case study of Frequency Synchronization

To demonstrate how data harmonization works in practice we will use a use case of combining high-granularity vibration data and low-granularity environmental data feeds. For example, in the case of an urban road, an accelerometer might generate vibration data at 100Hz (100 records a second) for a dynamic passing vehicle event, but a temperature sensor might generate data at 0.016Hz (1 record an minute) [6].

In order for the multitude of diverse data streams to be cross analyzed, the solution must perform the following steps.

Data Resampling / Interpolation: Down sampling of the high granularity vibration data feed or interpolation of the low-granularity temperature data feed in order to provide a common time axis.

Time Alignment / Resampling: High Speed and Low Speed data streams are resampled to a common time axis so that temperature can be correlated against vibration that occurs at a specific moment in time.

Data Harmonization: Heterogeneous data such as (Fahrenheit to Celsius or different naming conventions) is automatically converted into a normalized schema. The "data silos" are virtually eliminated.

Other similar data discrepancies can be found in Table 1.

Table 1. Examples of common file name differences

Data Source	Raw Filename Example	Data Integrity Risks
Manufacturer A (Sensors)	SENS_001_20231024.csv	Uses internal IDs only. Lacks geospatial metadata
Manufacturer B (UAV/Drones)	DJI_2023_10_24_IMG99.j9	Default camera naming. Lacks distress type or road segment ID.
Manual Inspection Reports	2026-03-11-MainRoad-Survey-John.xlsx	Non-standardized characters; difficult for automated scripts to parse.
Pavement Models (CAD)	Road_Structure_Final_v2_updated.dwg	Ambiguous versioning; impossible for machines to track the latest "Ground Truth."

To address the specific data integrity risks identified in the previous analysis, the proposed framework integrates a set of targeted solutions. These solutions aim to ensure high-quality data fusion and improve the reliability of the digital twin system, as summarized in Table 2.

Table 2. Data integrity challenges and corresponding solutions

Challenge	Description	Solution
Lack of Geospatial Metadata	Manufacturer A sensors do not include GPS location information in raw data streams.	Mapping Sensor IDs to pre-recorded GPS coordinates during installation
Missing Semantic Information	UAV/drone data lacks distress types and road segment identification.	Object detection model (e.g., YOLOv8) assigns the correct road segment ID [7]
Different Model Versioning	CAD models have inconsistent version control.	Each model update is recorded with a unique version

Table 2 shows the integration of metadata enrichment, AI-driven data processing, and standardized data management mechanisms. It ensures heterogeneous data can be effectively aligned and utilized within the digital twin framework.

The feasibility of the proposed framework is substantiated by integrating established technologies into infrastructure digitalization. Previous studies on computer vision-based inspection are given in [8]. They show that deep learning can be used for automated anomaly detection. This method can identify pavement distress with an accuracy higher than 90%. Compared with manual patrolling, it also reduces inspection time by roughly 30%. Besides, Digital Twin maintenance strategies can transition from reactive to proactive. According to global industry benchmarks [9], this shift can optimize resource allocation and reduce maintenance costs.

However, there are also several challenges remaining. Such as the high cost of sensing equipment, data infrastructure requirements, and regulatory issues related to autonomous vehicles. In the Future, large-scale implementation is supposed to address the establishment of standardized legal frameworks for unmanned maintenance operations [10].

5. Conclusion

The framework proposed in this study has many advantages for intelligent road maintenance. That is, the autonomous inspection device can monitor the road condition in a constant way. It eliminates the long delays commonly found in traditional manual inspections. The data from different sources are combined into one data platform. It enhances the overall efficiency of data analysis. The automated maintenance equipment can also achieve predictive maintenance. It replaces the old maintenance mode of post-damage repairing with proactive prevention. The digital twin technology can enhance the overall economy of the system. The early discovery of road defects can save 20% of the long-term maintenance cost. The real-time synchronization between physical and virtual space can optimize the maintenance time. It shortens road closure and reduces the economic loss caused by traffic. There are still some challenges existing in the system. It still needs large amount of investment to deploy the sensing device and data infrastructure. The large scale of heterogeneous data brings certain scalability problems. The regulations issue of autonomous vehicles also hinder its real application.

In the future, the research should focus on better data processing scalability. The standard rule of unmanned maintenance operation should also be constructed.

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