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Research on the Application of Digital Twin Technology in the Full Lifecycle Operation and Maintenance Management of Urban Road Infrastructure

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Abstract: With the continuous development of digital technology, urban management and urban construction have undergone tremendous changes, exerting a profound impact on people's lives. As a vital component of cities, urban road infrastructure is closely related to the daily lives of citizens. The application of digital twin technology can provide more support for the full lifecycle operation and maintenance management of urban road infrastructure, effectively improving the quality and efficiency of operation and maintenance management, ensuring the effectiveness of urban road infrastructure, and building a higher-quality urban life. Based on urban road infrastructure, this paper analyzes the application value of digital twin technology, proposes strategies for full lifecycle operation and maintenance management, and offers more references for urban construction.

Keywords: Digital twin technology; Urban roads; Infrastructure; Full lifecycle; Operation and maintenance management

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1. Introduction

The full lifecycle operation and maintenance management of urban road infrastructure is a comprehensive and complex management task that involves various stages, including planning, design, construction, operation, and maintenance of the infrastructure. With the accelerating process of urbanization, the demand for urban road infrastructure is also growing, highlighting the importance of its full lifecycle operation and maintenance management. Through the application of digital twin technology, real-time monitoring of the status and performance of urban road infrastructure can be achieved, enabling timely identification of issues and the implementation of targeted solutions. This promotes the construction of smart cities and provides citizens with more comfortable urban services.

1.1. Overview of digital twin technology

Digital twin technology is a product of the continuous development of digital technology. It creates corresponding virtual replicas for physical entities and uses them as platforms to effectively monitor the actual behavior and performance of these entities, thereby enabling analysis and evaluation. The concept of digital twins was first proposed by Michael Grieves in 2002 within the context of Product Lifecycle Management (PLM), and has since gradually been promoted and applied in fields such as aerospace and manufacturing [1,2]. Today, with the continuous development of artificial intelligence technology, the gradual popularization of Internet of Things technology, and the increasing maturity of big data technology, the application scope of digital twin technology has become increasingly widespread. It has become an indispensable tool for urban infrastructure management, providing more assistance to urban construction [3].

2. Application significance of digital twin technology

2.1. Improving the quality and efficiency of operation and maintenance management

Digital twin technology can provide managers with a 1:1 accurate model of urban road infrastructure, helping them more efficiently conduct performance tests on the infrastructure, design targeted operation and maintenance plans, reduce unscientific maintenance measures, ensure the efficient and high-quality operation of various infrastructure, and promote continuous improvement in the quality and efficiency of operation and maintenance management.

2.2. Ensuring the safety and reliability of operation and maintenance management

Digital twin technology can establish a real-time, dynamic monitoring system for urban road infrastructure. Through sensor networks deployed in structures such as roads, bridges, and tunnels, the system can continuously collect operational data such as deformation, stress, displacement, temperature, and humidity, and then conduct intelligent analysis and risk assessment of the operational status of the facilities. When abnormal fluctuations in monitoring data occur, the system can immediately generate warning signals, prompting managers to take targeted actions, thereby effectively reducing the probability of safety accidents.

Meanwhile, through the joint analysis of historical operational data and simulation models, the digital twin platform can identify high-risk areas and vulnerable components within the facilities, assisting management departments in formulating scientific inspection and maintenance plans. This data-driven dynamic monitoring mechanism not only enhances the real-time nature and accuracy of operations and maintenance but also provides reliable assurance for the long-term stable operation of urban infrastructure.

2.3. Achieving optimal allocation of operations and maintenance management resources

Digital twin technology can integrate with the actual conditions of urban road infrastructure operations and maintenance management to achieve optimal resource allocation, ensuring the quality of operations and maintenance management. This allows infrastructure to operate in its best possible state, providing greater assistance to urban residents in their travels. The system can scientifically allocate maintenance personnel, equipment, and financial investments based on the importance of facilities, operational loads, and risk levels, avoiding resource wastage and redundant operations. Additionally, the digital twin platform supports a quantitative evaluation mechanism based on ROI (Return on Investment), helping managers assess the input-output ratio of various operations and maintenance plans from an economic perspective and providing quantitative evidence for decision-making in urban infrastructure management. This data-driven refined management model not only improves the efficiency of operations and maintenance resource utilization but also promotes the sustainable development of the urban infrastructure operations and maintenance system [4].

3. Application of digital twin technology

3.1. Application in urban road infrastructure construction

3.1.1. Design phase

During the design phase of urban road infrastructure construction, digital twin technology can assist designers in optimizing design plans more conveniently [5]. Designers can use digital twin technology to create models of urban road infrastructure based on design requirements, analyzing potential climate conditions, usage requirements, and maintenance needs that the infrastructure may face in different virtual environments. By comparing the advantages and disadvantages of different design plans, designers can promptly identify issues and deficiencies in the design plans and take targeted measures for optimization. Through this virtual experimentation approach, design flaws can be identified in advance, construction rework can be minimized, construction costs can be reduced, and project timelines can be shortened [6].

Digital twin technology can also facilitate multidisciplinary collaboration in the design process of urban road infrastructure, enabling designers to complete scheme designs more efficiently. Urban road infrastructure is a comprehensive project that requires the joint participation of professionals from various fields, such as structural engineering and civil engineering. On the digital twin platform, engineers from different disciplines can enter the same virtual environment, enabling real-time information sharing and jointly driving continuous design optimization. This approach helps overcome information silos in traditional design models, further enhancing the feasibility of design schemes and promoting the continuous improvement of urban road infrastructure [7].

The design drawings completed through digital twin technology can also provide more comprehensive technical support for subsequent construction and operation and maintenance. During the design phase, designers need to consider the requirements for the operation and maintenance of urban road infrastructure throughout its entire lifecycle and incorporate potential maintenance issues into the design model. This approach allows for corresponding optimizations during the construction phase and facilitates the design of emergency response plans within the system, enabling timely access in case of unexpected issues and effectively mitigating severe consequences [8].

Additionally, operation and maintenance personnel can accurately understand the structure and function of various infrastructure components based on the system models uploaded by designers on the platform, thereby improving the quality and efficiency of infrastructure operations and ensuring that the overall performance of the infrastructure better meets the needs of different groups.

3.1.2. Construction phase

Digital twin technology enables real-time monitoring of the construction process of urban road infrastructure and simulates subsequent construction procedures through virtual simulation. This not only provides more precise guidance for construction but also significantly enhances construction efficiency and quality [9]. Construction personnel can also leverage digital twin technology platforms to simulate and analyze potential construction issues that may arise in the future, effectively predicting risks inherent in the construction process. This enables the formulation of more targeted strategies, ensuring the quality of urban road infrastructure construction and laying a solid foundation for subsequent operation and maintenance efforts.

Digital twin technology also facilitates the real-time collection of various types of data during the construction process and enables rapid sharing within the platform. Numerous sensors are often installed at construction sites, transmitting real-time construction data to the digital twin platform. Models are then constructed based on construction drawings and specific progress, allowing managers to visually observe the construction status of road infrastructure and evaluate construction effectiveness. This facilitates timely adjustments to construction plans in line with project deadlines and usage requirements [10].

Digital twin technology also provides construction personnel with a more convenient environment and conditions for equipment learning. On the platform, construction personnel can use virtual models to practice operating specific equipment, enabling them to better familiarize themselves with operational processes and related techniques while also mastering necessary emergency response measures. As a result, construction personnel can approach actual construction with confidence and promptly address unexpected situations, preventing any adverse impact on infrastructure projects [11].

Additionally, based on the construction needs of different infrastructure projects, digital twin technology can monitor the usage of various resources in real time, providing more comprehensive resource allocation plans in line with construction progress to ensure the efficient utilization of engineering resources. This not only significantly enhances construction quality and efficiency but also facilitates the operation and maintenance management of urban road infrastructure, effectively reducing cost consumption during the operation and maintenance process.

3.1.3. Operation and maintenance phase

Upon completion of construction, digital twin technology can conduct real-time analysis of the operational status of infrastructure, effectively monitoring the performance of various facilities and equipment. This can not only help operation and maintenance personnel more accurately grasp the basic structure and main functions of infrastructure, but also enable them to understand the service effectiveness of the infrastructure, so as to adopt more targeted strategies to design maintenance plans and effectively establish a virtuous cycle of operation and maintenance. Under this real-time monitoring mode, operation and maintenance personnel can not only detect abnormal phenomena in facilities and equipment, but also observe the status of these new facilities and equipment in the surrounding environment, so as to assess whether further environmental modifications and optimizations are required, thereby effectively reducing safety risks arising during the operation of infrastructure [12].

Digital twin technology can also predict the lifecycle of infrastructure. By combining relevant historical usage data and equipment performance reports, it can predict potential future failures through computational models and design more targeted maintenance plans, thereby supporting the extension of the service life of infrastructure.

3.2. Application in the maintenance and repair of urban road infrastructure

Maintenance and repair work is a crucial aspect of the entire lifecycle operation and maintenance of urban road infrastructure, largely determining its service effectiveness and lifespan. Therefore, through the application of digital twin technology, infrastructure can be maintained in a relatively good operational state, laying the foundation for improving urban service quality [13].

3.2.1. Preventive maintenance

Preventive maintenance is a key focus in infrastructure operation and management, requiring managers to regularly inspect the basic status of infrastructure during daily operations and take corresponding maintenance measures to ensure that equipment performance remains stable and good. The application of digital twin technology can further enhance the quality and efficiency of preventive maintenance. Building digital twin models on the platform enables effective monitoring of operational parameters for various infrastructure facilities, such as temperature, humidity, vibration, and so on. When abnormal values are detected, the system automatically sends alerts to management personnel and indicates the locations where the abnormal values have occurred, helping managers quickly locate and inspect them so that effective remedial measures can be taken.

Digital twin technology also enables managers to conduct in-depth analysis of historical data to explore the historical operational status of urban road infrastructure. For example, by combining historical maintenance records, managers can understand the main fault issues of the infrastructure and evaluate its overall operational performance through historical operational data. This approach allows for more precise identification of potential risks in the infrastructure and summarizes early characteristics of various faults, thereby facilitating more effective implementation of preventive maintenance and avoiding severe consequences caused by sudden failures [14].

Additionally, digital twin technology facilitates remote diagnosis and maintenance. Maintenance personnel can directly observe the actual state of the infrastructure through virtual models and perform remote operations via technical platforms. By leveraging the self-diagnostic capabilities provided by digital twin technology, they can more quickly locate faulty components in the infrastructure and complete repairs through remote guidance or operations, accelerating the restoration of infrastructure operations. This maintenance model not only reduces the time required for fault diagnosis but also lowers labor costs, enabling 24/7 uninterrupted monitoring of infrastructure. It ensures the normal operation of infrastructure and enhances urban service levels.

3.2.2. Emergency response

Emergency response is also a crucial aspect of the full lifecycle operation and maintenance of infrastructure, with digital twin technology further enhancing its efficiency. Digital twin models can directly provide managers with real-time parameters and status of infrastructure operations in the event of an emergency, helping them quickly grasp changes in the surrounding environment of the infrastructure, the functional status of its internal structure, and its operational conditions, among others. This enables managers to make rapid emergency decisions and formulate more efficient rescue and recovery plans.

Digital twin technology can also provide emergency response teams with different simulation scenarios to help them evaluate potential infrastructure failures and their consequences under various scenarios. This allows for the quickest possible response to rescue and fault handling in real-life scenarios that may arise in the future [15]. This not only significantly improves the reaction speed of emergency response teams but also ensures the accuracy of their emergency handling, effectively reducing losses and social impacts caused by emergencies. Additionally, digital twin technology can provide dynamically adjustable handling plans for emergency response teams based on the specific implementation of emergency responses, ensuring optimal allocation of resources and helping teams restore normal operation of various infrastructures more quickly.

Digital twin technology can not only provide emergency response teams with real-time captured on-site videos but also offer various precise data references through on-site sensors. It can also generate historical operation reports of infrastructure to help teams analyze the causes of infrastructure failures from different perspectives, more accurately determine maintenance considerations and potential risks, and provide scientific guidance for emergency actions. Furthermore, digital twin technology can provide remote command functions for emergency response services, allowing emergency personnel to further enhance the quality and efficiency of fault handling through remote guidance, providing more assistance in restoring road infrastructure to normal operation.

3.2.3. Performance optimization

Performance optimization is also an important aspect of the lifecycle management and operation of infrastructure, enabling managers to monitor the operational status and performance changes of infrastructure in real-time, thereby providing referenceable data for the optimization and upgrading of infrastructure. Digital twin technology can more accurately evaluate the energy efficiency and capacity of infrastructure, assess changes in it carrying capacity, and ensure its safe operation with normal parameters after upgrades and optimizations.

Meanwhile, managers can utilize digital twin technology to simulate the impacts of different upgrade and optimization plans on infrastructure and determine whether changes in maintenance plans affect the performance of infrastructure. This way, managers do not need to conduct multiple validations on the infrastructure through practical means, which not only saves optimization resources and time but also avoids causing damage to the infrastructure, providing a new approach for the upgrading and renovation of urban road infrastructure.

4. Challenges in the application of digital twin technology

Although digital twin technology demonstrates significant advantages in urban infrastructure management, its widespread adoption still faces multiple challenges. These issues are concentrated at the technical implementation and data governance levels, constraining the system's stability, scalability, and economic efficiency. To achieve sustainable development of digital twins, collaborative efforts are required in engineering practices, institutional design, and data ecosystem construction.

4.1. Technical implementation: Resource constraints in high-precision modeling and real-time simulation

Current city-level digital twin models often require the integration of multi-source heterogeneous data (geographic information, traffic flow, sensor data, etc.), resulting in high computational demands, long update cycles, and high operational costs. Particularly in high-precision 3D modeling and multi-physics field simulation, the return on investment (ROI) exhibits diminishing marginal returns, making it difficult to support long-term operations. Additionally, insufficient model standardization and interoperability of interfaces hinder the seamless integration of data and models across different departments, limiting the system's scalability.

4.2. Data governance: Institutional conflicts between privacy protection and data sharing

Digital twin systems rely on large-scale real-time data collection. However, in the context of smart cities, the widespread deployment of sensing devices involves public spaces and individual activity trajectories, which can easily lead to data security and privacy breaches. The existing data governance frameworks often prioritize security controls while overlooking the value of data reuse, exacerbating the phenomenon of "data silos". Additionally, the absence of unified data standards and evaluation systems results in inconsistent data quality, undermining the accuracy of model simulations and predictions.

4.3. Institutional and operational levels: Lagging standard systems and lack of management mechanisms

Urban-level digital twin projects generally lack top-level design guidance, with technical standards, evaluation indicators, and responsibility boundaries yet to be clearly defined. Some projects tend to prioritize construction over operation and maintenance, lacking sustained financial and talent support, which leads to a decline in system efficiency and delayed data updates in the later stages of operation.

Conclusion

In summary, during the entire lifecycle of operation and maintenance of urban road infrastructure, digital twin technology plays an increasingly vital role. It can effectively enhance the quality and efficiency of operation and maintenance, reduce costs and consumption, and assist managers in accurately locating faults, scientifically formulating plans, promptly responding to issues, and reasonably optimizing upgrades, thereby improving the operational performance of urban road infrastructure.

Disclosure statement

The authors declare no conflict of interest.

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