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A Proactive Maintenance Framework for Road and Bridge Infrastructure Based on Digital Twin, BIM, GIS, and IoT Integration

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Abstract. Transportation organizations face pressing issues due to the aging of road and bridge infrastructure, rising traffic demand, and tight resources. Manual inspection and reactive repair, which are frequently ineffective, expensive, and unreliable, are significant components of traditional maintenance. Therefore, a change to proactive, data-driven management is crucial. The Digital Twin, Building Information Modeling (BIM), Geographic Information System (GIS), and Internet of Things (IoT) are all integrated in this paper's proposed unified maintenance architecture. Data collection, semantic integration, analytical modules, and decision optimization make up the architecture's four tiers. Three functional modules in this system, automated defect detection, time-series performance prediction, and network-level risk assessment, cooperate to convert unprocessed data into insights that can be used. After that, a portfolio of potential treatments is assembled and assessed using economic and optimization analysis. The system is flexible and scalable, making it appropriate for both regional networks and single bridges. It gives agencies a workable option to transition from reactive repairs to preventive stewardship by integrating transparency and traceability. Throughout the whole life cycle of infrastructure assets, this proactive strategy lowers emergency interventions, improves safety, and increases cost-effectiveness.

Keywords: Digital twin, BIM-GIS-IoT integration, Structural health monitoring, Deep learning, Cost-benefit analysis

1. Introduction

Systems of infrastructure serve as the foundation for both social and economic advancement. Nonetheless, the planned service lives of many road and bridge networks throughout the world are being approached or surpassed. Most bridges in wealthy nations were built in the middle of the 20th century. However, in areas that are fast becoming more urbanized, deterioration is accelerated by high traffic and environmental stress. While resources are still limited, maintenance demands are rising. Waiting until flaws are apparent or failures happen, or reactive maintenance, frequently results in expensive emergency repairs, protracted closures, and serious safety issues [1].

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Moreover, the traditional approaches are usually based on subjective visual inspections that are difficult to replicate and are inconsistent among inspectors. Meanwhile, it is hard to estimate the impact of a single failure propagating through the system because of the complexity of modern transportation systems. Area economies, emergency response times, and freight supply chains can all be affected, for instance, by the closure of a bridge in a congested urban corridor. These aspects assert the need of proactive maintenance strategy that predict hazards before they occur [2].

New developments in digital technology offer resources to facilitate this change. Platforms for digital twins enable the development of dynamic virtual models that combine historical records with real-time sensor data. Multi-scale visualization and cross-disciplinary semantic consistency are made possible by BIM–GIS integration [3]. High-frequency measurements can be gathered at scale thanks to IoT networks, and data science advancements enhance forecasting and decision-making in the face of uncertainty [4]. However, integration is still fractured despite advancements. Predictive models are still underutilized, data is still fragmented, and technical outputs frequently do not convert into workable investment plans [5].

By creating a thorough framework that links data collecting, semantic unification, analytical modeling, and decision-making, this article addresses these issues. It is intended to provide a systematic, scalable, and policy-relevant pathway for proactive road and bridge maintenance, going beyond technical demonstrations.

2. Integrated architecture and data flow (four-tier architecture)

Data acquisition, semantic and spatiotemporal foundation, analytical modules, and decision and optimization comprise the framework's four interrelated layers.

UAV surveys, stationary sensors, vehicle-mounted cameras, and conventional field records are all integrated into the data acquisition layer [6]. Redundancy is guaranteed, and susceptibility to noise or sensor failure is decreased, by gathering data from many viewpoints and environmental circumstances. Pre-processing makes disparate data streams comparable by aligning time stamps, compressing signals, and filtering mistakes. This layer likewise prioritizes continuity: complete datasets are saved for long-term trend research, and real-time warnings can be created locally.

The spatiotemporal and semantic foundation provides interoperability. Asset identifiers are constant from design to operation, using IFC for asset components and InfraGML for geographical reference [3]. The spatiotemporal and semantic bases provide for interoperability. Identifiers for assets remain unchanged from design to operation, leveraging IFC for the asset components and InfraGML for the geographical reference [3]. Dual indexing is used to facilitate flexible retrieval, which applies geographical coordinates for mapping and linear referencing for transit corridors. Metadata ensures traceability as every data record has information related to device type, calibration history and sample frequency, traceability is assured. Role-based data access enables executives, planners, and inspectors to "cut the data in" specialized but consistent way [2]. Further this enables inter-agency collaboration, thus allowing national or regional agencies to integrate data from multiple states.

Decentralized functional modules, responsible for Risk Evaluation, Prediction and Detection, compose the Application Layer. Every module produces reported results and is auditable. By exposing the factors influencing a forecast or symmetric defect identifying parameters, explainability algorithms enable the decision maker and technical staff to validate and trust the predicted outcomes.

Finally, outputs are utilized in prospective interventions by the decision- and optimization layer. It finds a tradeoff between the policy goals, financial constraints, and technical requirements [5].

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Using scenario-based planning, managers can create conservative, moderate, and aggressive plans to accommodate constraints such as seasonal limitations, staff availability, and maximum allowable budget. This layer acts as an interface between technical evidence and governance, as well as an analytical instrument.

3. Models and algorithms

The defect identification component identifies rust, bending, surface cracking and fractures with images captured by UAV and vehicle [7]. The results are connected to the semantic base and stored in structured defect lists containing information on location, kind and severity. This enables rapid planning of interventions and to visualize them in a GIS. Most importantly, the module confers greater consistency and saves manpower by mitigating the need for subjective examinations. Feedback loops allow inspectors to verify findings and enhance their performance over time. From detection to budgeting, the module streamlines the procedures by estimating engineering quantities such as repair area or sealing length.

Deflection, strain, and fracture width are examples of environmental and structural time series that are analyzed by the performance prediction module [4,8]. It makes a distinction between short-term fluctuations brought on by weather or traffic and long-term degradation. Uncertainty intervals in forecasts help avoid over-maintenance and false warnings. The module supports tiered warnings: long-term estimates for budget planning, stronger alarms for preventive activities, and early signals for monitoring. It can also evaluate future scenarios like heatwaves or traffic growth by combining climate and traffic forecasts.

The transport network is handled as a graph by the network risk assessment module. Connections represent routes and detours, whereas assets serve as nodes characterized by condition, utilization, and redundancy [9]. The module detects single-point vulnerabilities as well as cascading dangers. For example, if a little bridge in a rural area supplies critical freight, its shutdown may have huge regional ramifications but little local impact. Risk is assessed using both systemic impact and failure probability to ensure that priorities reflect both engineering and societal value. Using live dashboards, decision-makers may see how rankings shift and adjust weights for safety, mobility, and economics.

4. Budget constraint, scheduling, and economic assessment

Maintaining service, reducing risk, and adhering to budgets are all conflicting goals that must be balanced during maintenance planning. The framework uses a decision-making process with multiple stages.

The results are then arranged into a library of potential interventions. Asset, defect, or risk type, intervention choices, costs, time windows, anticipated benefits, and uncertainty are all specified in each record [5].

The feasible portfolios are then chosen using multi-objective optimization. Maximizing risk reduction and minimizing user disruption are among the goals; seasonal work times, crew capacity, and policy requirements are among the restrictions [6]. This guarantees that solutions are not only ideal in principle but also practical in practice.

Benefit-cost analysis is used in economic evaluation. Indirect advantages (shorter closures, increased safety) as well as direct effects (fewer emergency repairs, longer asset life) are taken into account [10]. Metrics like NPV and B/C ratios offer a quantitative foundation for comparison. Life-

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cycle comparisons show that preventive measures are more cost-effective in the long run than reactive ones [11].

Lastly, robustness is tested using scenario and sensitivity analysis [12]. Managers can identify important uncertainties by altering inputs like cost inflation, traffic increase, and climate impacts. It is simpler to convey risks and trade-offs to stakeholders when results are presented using visual aids like scenario dashboards or tornado diagrams.

5. Conclusion

This study suggests a proactive maintenance system that combines decision optimization, analytical modules, semantic harmonization, and data collection into a single architecture. The framework contributes by outlining an open procedure that converts unprocessed monitoring data into investment plans supported by evidence. The integration of interoperability, redundancy, and explainability guarantees the reliability of data, the interpretability of analysis, and the accountability of decisions.

The customer defection, performance forecasting, and network risk assessment analytical models are integrated into three interdependent modules that feed into a pipeline linking observation to action. Risk assessment contextualizes outcomes at the system level, prediction provides foresight with quantified uncertainty, and detection reduces manual work and enhances reliability. These components ensure that priorities are commensurate with the systemic importance of mobility and safety, as well as with the condition of the assets.

Economic evaluation and optimization support decision-making to ensure maintenance portfolios meet economic and social viability criteria. Using sensitivity analysis and benefit-cost analysis, the methodology supports agencies in developing robust plans under uncertainty. It adds to technical development; it is a strategy as a governance tool that promotes accountability and transparency.

Considering this notion in design and practice can enhance resilience, extend service life, and reduce the need for emergency measures. Reactive, piecemeal sequences of action can be transitioned to integrated, preventive strategies by instituting proactive management. Proactive agency management enables agencies to transition from fragmented, reactive cycles of activity to a coherent, prescriptive strategy. This evolution will enhance user satisfaction, reduce life-cycle costs, and advance public safety.

In the future, research should focus on the automation of semantic mapping, the inclusion of interpretable AI within the framework, and its extension to cross-jurisdictional networks. The development of legislation that would incentivize investment in prevention is also important. At a time of growing complexity and uncertainty, this paradigm offers a pathway to sustainable infrastructure management by harmonizing technical development with governance and finance.

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