A Review: Digital Twin Application in Bridge Fire Engineering and Management

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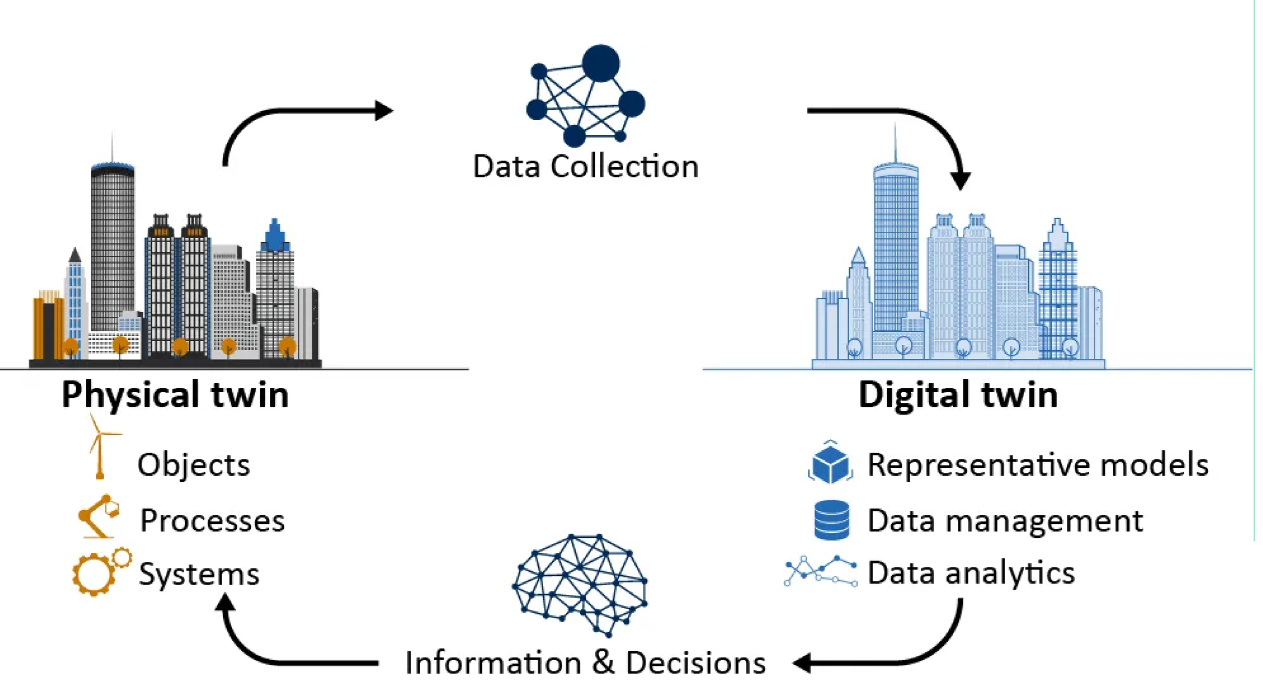
Research Background

- Bridge fires lead to extensive economic damage and safety threat
- Existing fire models do not track sever fire propagation and structural response in real time
- Increasing DT application in structural engineering, but least progress in bridge fire engineering

Research Objectives

- Conduct a review of available literature on DT concepts, focusing on bridge engineering application
- Identify the research needs and gaps in bridge fire engineering
- Summarize DT potential in bridge fire engineering and form a DT framework for bridge fire management study

Overview: Physical and Digital Twins



Source: https://www.gao.gov/products/gao-23-106453

Basic Components of Bridge DT

- A physical bridge structure, as the reference system
- A virtual DT, an evolving computational model representing the bridge's real-time condition
- Data acquisition systems, integrating IoT-based sensors to capture structural, environmental, and operational parameters
- AI-driven analytics, enabling predictive modeling and anomaly detection
- A feedback control mechanism, allowing real-world interventions based on DT-driven insights

Fire Hazards in Bridges

- Fire Behavior of Bridge Materials

Material Type	Thermal Response	Fire Resistance	Major Failure Mode	Mitigation Strategies
Steel	Rapid heat absorption, thermal expansion	Low (loses 50% strength at 600°C)	Buckling, loss of load capacity	Fireproof coatings, heat-resistant alloys
Concrete	Heat insulation, potential spalling	Moderate to high	Cracking, loss of rebar integrity	Fiber reinforcement , fire-resistant aggregates
FRP Composites	Low thermal resistance, combustibility	Low	Melting, ignition, toxic emissions	Self-extinguishing resins, thermal barriers

Comparison of Traditional vs. DT Based Fire Simulations

Feature	Traditional Fire Models	DT-Based Fire Simulations
Fire Exposure Assumption	Prescriptive heat exposure	Real-time sensor-driven fire progression modeling
Structural Response	Simplified material degradation models	AI-enhanced, real-time material deterioration tracking
Computational Efficiency	High computational demand	Hybrid cloud-edge computing for faster simulations
Predictive Capabilities	Static assessments	Dynamic, self-learning fire risk evaluation
Integration with Emergency Response	Manual intervention required	Automated risk assessment and response optimization

Challenges in Implementing DT for Fire Applications

- Computational complexity and real-time simulation constraints

Computing Approach	Processing Power	Real-Time Feasibility	Key Limitation
CFD-Based Fire Modeling	High	Limited	Computationally expensive
AI-Driven Surrogate Models	Moderate	High	Required extensive training datasets
Edge Computing	Moderate	High	Limited processing for complex models
Cloud Computing	High	Moderate	Network dependency

- Lack of standardization and validation in fire simulations
- Cybersecurity and data privacy concerns
- Data Integration and Sensor Reliability Challenges

Challenge	Description	Proposed Solution
Sensor Data Variability	Differences in sensor precision and calibration	AI-driven auto-calibration
Data Format Inconsistencies	Variations in fire resistance test data	Standardized DT data protocols
Lack of Empirical Fire Case Studies	Limited real-world bridge fire data	Creation of a global fire incident database

Opportunities for Advancing DT in Fire Engineering

- AI and ML for enhanced prediction
- Next-generation IoT sensors and smart infrastructure
- Cloud computing and edge computing for real-time processing
- Standardized DT frameworks and open-source fire modeling
- Evaluating the reliability of digital twin in fire applications
- Data fidelity and accuracy of sensor inputs
- Model validation and experimental benchmarking
- Predictive accuracy in dynamic fire scenarios and real-time synchronization and computational efficiency