BridgeSync: A Digital Twin Framework for Secure and Intelligent Smart Bridge Monitoring

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***Abstract*—This paper introduces BridgeSync, a novel digital twin framework for secure and resilient real-time bridge monitoring. BridgeSync leverages blockchain technology and edge computing to overcome the limitations of traditional bridge monitoring systems, such as security risks and high latency. The framework integrates PureEdge, an edge computing approach, to enable offline data caching and synchronization, and it integrates with PureChain, a cost-efficient blockchain network, for secure and tamper-proof sensor data storage. Additionally, BridgeSync uses 3D immersive visualization to provide an interactive and intuitive platform to monitor bridge conditions. The system was validated by modeling three bridges as digital twins and comparing them to their physical counterparts, confirming accurate structural replication. Further evaluation demonstrated BridgeSync's real-time monitoring and interactive visualization capabilities through sensor integration tests.**

***Index Terms*—digital twin, blockchain, edge computing, SHM, bridge, real-time monitoring**

I. Introduction

A. Background and Motivation

Bridges are critical components of transportation infrastructure, facilitating mobility and economic activities worldwide. However, aging infrastructure, environmental degradation, and increasing traffic loads pose significant challenges to their structural health and longevity [1]. Traditional bridge monitoring and maintenance practices rely on periodic inspections and static data collection methods, which often lead to delayed detection of structural issues and inefficient resource allocation for repairs [2]. The emergence of digital twin technology offers a promising solution by enabling real-time monitoring, predictive maintenance, and data-driven decision-making [3]–[5].

Despite advancements in digital twin applications for bridge management, existing frameworks often suffer from key limitations, including the lack of decentralized security, inefficient real-time data processing, and limited visualization capabilities [1], [6]. Many current approaches rely on centralized cloud storage, making them vulnerable to data tampering, latency issues, and inaccessibility in remote areas with poor network connectivity. Additionally, traditional structural health monitoring (SHM) systems do not provide an interactive and immersive visualization of bridge conditions, limiting their effectiveness in assisting engineers and decision-makers [2], [7]. To address these challenges, a more robust and scalable digital twin solution is required, integrating emerging technologies such as blockchain, edge computing, and high-fidelity visualization.

B. Aim and Objectives

The primary aim of this study is to develop an advanced digital twin framework that enhances real-time bridge monitoring through blockchain security, edge computing resilience, and 3D immersive visualization. The proposed system seeks to overcome the limitations of conventional digital twin models by leveraging *PureChain* [8], a cost-efficient blockchain network, for secure and tamper-proof sensor data storage, and *PureEdge* [9], an edge computing approach, to enable offline data caching and synchronization.

C. Contributions

The key contributions of this study are as follows: (i) We proposed a novel blockchain-integrated digital twin framework for bridge monitoring, enhancing data security, reliability, and automation through *PureChain*. (ii) We proposed an edge-computing-enabled architecture for digital twins, improving offline data processing and real-time synchronization using *PureEdge*. (iii) We developed an immersive and interactive 3D visualization system with Unreal Engine and WebGL, enabling real-time monitoring and intuitive decision-making for engineers and infrastructure managers. (iv) We developed a real-world validation of the proposed system through digital twin models of three bridges, designed from scratch using 3D modeling tools. (v) We presented the results of the immersive and interactive digital twin for bridge management.

D. Paper Organization

The rest of this paper is structured as follows: Section II presents a detailed review of related work on digital twins for bridge monitoring, immersive visualization, and blockchain-based SHM. Section 1 describes the proposed *BridgeSync* architecture, including its system components and implementation. Section IV discusses the experimental setup and evaluation results. Finally, Section V concludes the study and outlines future research directions.

II. Related Works

Digital twin technology has been widely explored for bridge structural health monitoring (SHM) to enhance predictive maintenance and lifecycle management. However, existing frameworks often face challenges in real-time data integration, interoperability, and automation. This section reviews prior studies and highlights how *BridgeSync* addresses these gaps.

A. Digital Twins for Bridge Monitoring

Several studies have leveraged digital twins for SHM. Heng et al. [6] proposed an intelligent maintenance system for monitoring corrosion-fatigue in steel bridge hangers. While effective for predictive maintenance, it lacks real-time monitoring and relies on centralized storage. Similarly, Costin et al. [10] centralized bridge assessment data but did not integrate blockchain for security, making it vulnerable to data manipulation. Gao et al. [1] enhanced interoperability by integrating GIS and BIM but remained dependent on cloud-based architectures, leading to latency issues in poor network environments. *BridgeSync* overcomes these limitations by incorporating blockchain for tamper-proof sensor data storage, edge computing for real-time processing, and an interactive 3D visualization framework.

B. 3D Immersive Visualization in Digital Twins

3D visualization enhances digital twins by providing an intuitive representation of structural conditions. However, existing solutions often lack high-fidelity rendering or real-time sensor integration.

Fawad et al. [2] developed an AR-based platform for bridge damage assessment using a 3D game engine. Their system improves user interaction but relies on Scan-to-BIM, which limits scalability. Jiménez Rios et al. [11] highlighted interoperability and anomaly detection challenges in current digital twin frameworks, particularly the lack of real-time visual feedback on sensor data. *BridgeSync* addresses these gaps by integrating Unreal Engine and WebGL for high-fidelity 3D visualization with real-time sensor updates across multiple platforms.

C. Blockchain and Edge Computing in Smart Bridge Monitoring

Most digital twin solutions still rely on centralized cloud storage, introducing security risks, latency, and connectivity issues. While blockchain and edge computing can mitigate these challenges, few studies effectively integrate both.

Hidayat et al. [12] developed an IoT-based bridge monitoring system but lacked blockchain security and edge processing for low-latency operations. Zhou et al. [7] proposed a UAV-based monitoring approach but did not implement decentralized data validation, leaving it vulnerable to inconsistencies. Mousavi et al. [13] reviewed digital twin frameworks and identified gaps in decision support systems and the reliance on cloud storage, which introduces security risks and connectivity constraints. *BridgeSync* integrates *PureChain* blockchain for secure, decentralized sensor data storage with smart contracts for automated alerts. Additionally, *PureEdge* computing enables offline caching and local processing, ensuring uninterrupted monitoring in areas with limited connectivity.

III. Methodology

In this study, we implemented *BridgeSync* following a structured workflow that integrates digital twin modeling, real-time data handling, sensor integration, interactive visualization, and secure data management. This section details the system architecture and methodologies used.

A. BridgeSync System Architecture

The proposed *BridgeSync* framework provides a comprehensive digital twin solution for bridge infrastructure monitoring. It integrates real-time sensor data, interactive 3D visualization, and decentralized data storage to enhance structural health monitoring and decision-making, as illustrated in Fig. 1.

1) 3D Model Development: High-fidelity 3D bridge models form the foundation of the digital twin system. These models include essential architectural and structural components such as roadways, railings, supports, and sensor attachment points. The models are optimized for both Unreal Engine and WebGL to enable seamless interaction and visualization across different platforms.

2) Sensor Integration and Backend Processing: To ensure real-time monitoring, multiple sensors (e.g., strain gauges, temperature sensors, accelerometers) are deployed at key bridge locations. These sensors continuously collect structural data and transmit it to the backend system, which is implemented using *FastAPI*. The backend manages sensor metadata, processes data requests, and communicates with the visualization platforms.

3) Data Processing and Storage: The system employs a hybrid approach for real-time analytics, data security, and offline resilience:

- Edge computing for offline caching: The system integrates edge computing at sensor gateways to enable local data processing. When connectivity is disrupted, sensor readings are cached and later synchronized with the main database upon reconnection.
- Blockchain-based security with *PureChain*: Sensor data is logged on a decentralized ledger to prevent tampering and ensure traceability. Authorised validators verify the authenticity of incoming data, and smart contracts trigger alerts when critical thresholds are exceeded.

TABLE I: Comparison of Related Studies with *BridgeSync*

Study	3D Visualization	Blockchain Security	Edge Computing	Smart Contracts	Multi-Platform
Heng et al. [6]	✗	✗	✗	✗	✗
Costin et al. [10]	✗	✗	✗	✗	✓
Gao et al. [1]	✓	✗	✗	✗	✓
Fawad et al. [2]	✓	✗	✗	✗	✓
Hidayat et al. [12]	✗	✗	✗	✗	✗
Proposed *BridgeSync*	✓	✓	✓	✓	✓

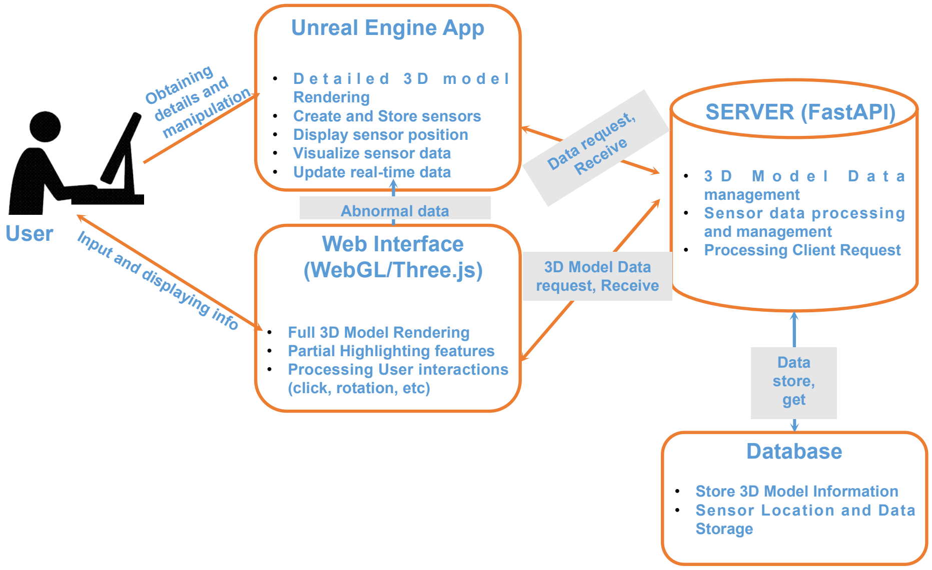


Fig. 1: System architecture of *BridgeSync*, illustrating the interaction between the user, Unreal Engine-based immersive visualization, WebGL interface, FastAPI server, and database. The system integrates real-time sensor data, edge computing, and blockchain-based security for efficient bridge monitoring

- Database management: A central database stores 3D bridge models, sensor positions, and historical monitoring data. The database interfaces with both Unreal Engine and the WebGL frontend to provide seamless data retrieval.

4) Visualization and User Interaction: The system offers two primary visualization interfaces:

- *Unreal Engine App:* Provides a high-fidelity immersive 3D experience, allowing users to inspect bridge structures, visualize sensor readings, and interact with real-time data. Features include sensor highlighting, real-time updates, and interactive manipulation.
- *WebGL Interface:* A lightweight browser-based alternative that enables 3D model rendering, basic sensor interaction (e.g., click, rotation, zoom), and real-time data display.

Users can explore the digital twin, analyze sensor readings, and toggle visibility for internal components. The interface updates dynamically based on live sensor data, ensuring an intuitive and responsive experience for engineers, researchers, and decision-makers.

5) Blockchain Integration with PureChain: To enhance data integrity and traceability across the various sensors on the bridges, we propose integrating with *PureChain*, a private blockchain network. This provides central data storage with a uniform ledger on the *PureChain*, as illustrated in Fig. 2. This enables effective management of the numerous distributed sensors across the bridges, providing auditability, traceability, and automatic critical actions in case of anomaly detection using *Smartcontracts*. Despite blockchain integration being planned for future implementation, it is notably expected to improve transparency and security in the cross-management of data from the sensors on the bridges.

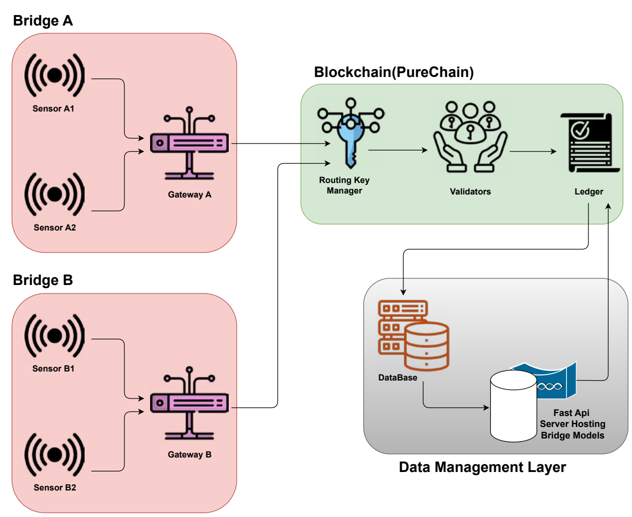


Fig. 2: Sensor data from multiple bridges is collected through IoT-enabled gateways and transmitted to the Blockchain (PureChain) for secure storage and validation. The validated data is stored in a database within the Data Management Layer, where a FastAPI server hosts bridge models for real-time monitoring and visualization.

6) Edge Computing with PureEdge: To support low-latency decision-making and ensure continued functionality in network-constrained environments, we propose that *PureEdge* computing be implemented at the sensor gateway level. This approach enhances real-time monitoring and enables seamless synchronization with cloud storage when connectivity is available. The implementation of *PureEdge* ensures robustness and resilience in digital twin-based bridge monitoring, allowing engineers and infrastructure managers to make informed decisions even in environments with intermittent connectivity.

IV. Experimental Setup & Case Study

A. Implementation of BridgeSync

1) Digital Twin Modeling: The digital twin models were created using *Autodesk Maya*, *Sketchup*, and *Blender*, focusing on high-fidelity representations of three bridges: Alpha Bridge, Gamma Bridge, and Theta Bridge *(not actual names)*. The modeling process involved

- Reference alignment: High-resolution images, drone footage, and engineering blueprints (CAD files) were used to ensure structural precision.
- Geometric Optimization: Mesh decimation was applied to reduce polygon count while maintaining structural fidelity. For bridges with complex designs, such as Gamma Bridge's duplex structure, curve extrusion techniques were used to ensure precision.
- Material and texture mapping: UV unwrapping was performed to enable realistic texturing, with road surfaces and structural materials optimized for rendering efficiency.
- Export and integration: Models were exported in *FBX* format, ensuring seamless compatibility with *Unreal Engine* and *WebGL*.

2) Backend Development with FastAPI: A *FastAPI* backend was developed to facilitate real-time sensor data management and system communication. The backend was responsible for:

- Sensor data handling: Data from strain gauges, accelerometers, and temperature sensors was collected, formatted in *JSON*, and stored in a centralized *PostgreSQL* database.
- API endpoints: RESTful APIs were implemented to allow both *Unreal Engine* and *WebGL* to fetch real-time sensor updates. The APIs supported endpoints for retrieving bridge sensor positions, historical data, and structural health trends.
- Data synchronization: Periodic synchronization mechanisms were developed to ensure seamless data flow between the edge computing layer, blockchain storage, and visualization platforms.

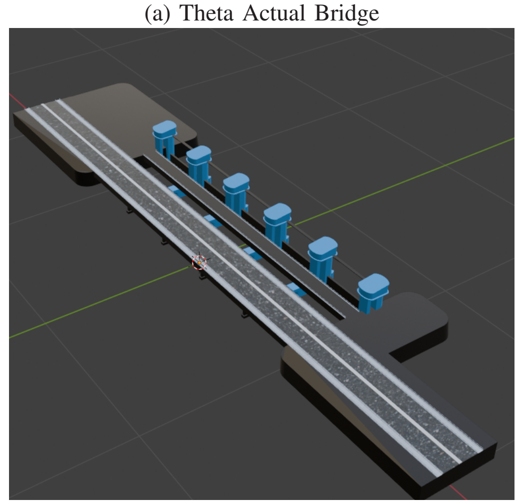
3) Unreal Engine Integration: The immersive visualization platform was developed using *Unreal Engine*, with interaction logic handled via *Blueprints*. The key features included:

- *BP_Character*: The primary controller for sensor interactions, camera movements, and real-time environmental adjustments.
- *BP_Dynamic_Sensors*: Managed the dynamic spawning of sensors and their respective interactions, including hover effects, pop-up metadata displays, and state changes based on sensor conditions.
- *Transparency Toggles*: Bridges with internal sensors were designed with adjustable transparency, enabling users to reveal embedded structural elements.
- *Sensor Zoom-on-Click*: Clicking a sensor automatically adjusted the camera view, providing a closer inspection of the sensor's data and condition.

4) WebGL Frontend Development: For cross-platform accessibility, a lightweight *WebGL* frontend was developed using *JavaScript* and *Three.js*. This web-based visualization provided:

- Interactive 3D Models: Users could manipulate bridge models, zoom in/out, and switch between different sensor views.
- Live Sensor Data Visualization: Sensor readings were mapped directly onto the 3D model, updating dynamically as new data was received from the FastAPI backend.
- Cross-Platform Compatibility: The WebGL interface was optimized for desktop and mobile browsers, ensuring accessibility for engineers in the field.

(a) Theta Actual Bridge



(b) Theta 3D Model

Fig. 3: Comparison of the Theta Bridge: (a) actual bridge, (b) 3D digital twin model.

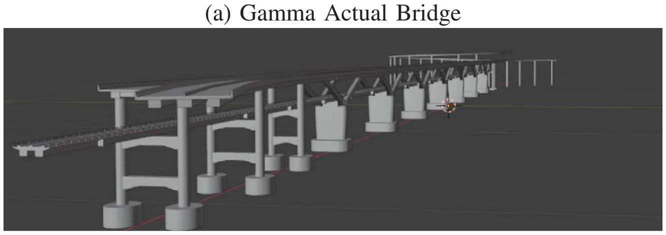
B. Case Study Results

This section presents the outcomes of the *BridgeSync* framework, showcasing digital twin development, real-time sensor data visualization, and user interaction in both the WebGL-based interface and the Unreal Engine-based application. The results highlight how the system enables interactive monitoring, ensuring sensor alignment and consistency across different platforms.

1) 3D Models: The development of accurate digital twins is crucial for effective structural monitoring. Figs3, 4, and 5 illustrate the actual bridges alongside their corresponding 3D digital twin models. These models replicate structural details with high precision, capturing essential architectural elements such as support piers, roadways, and railings.

In the 3D model of the Theta bridge, as illustrated in Fig. 3, the structure of the geometry of the bridge was successfully captured. This includes key features such as support columns and accurately represented road textures.

(a) Gamma Actual Bridge



(b) Gamma 3D Model

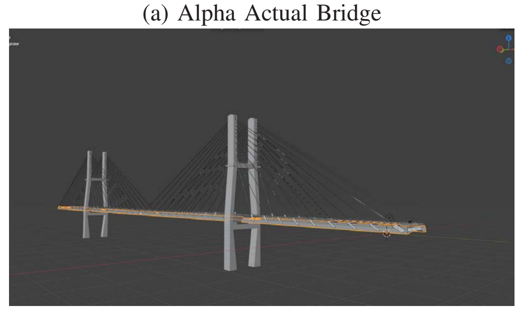
Fig. 4: Comparison of the Gamma Bridge: (a) actual bridge, (b) 3D digital twin model.

Gamma bridge's 3D model (Fig. 4) includes key structural elements such as the bridge's piers and multi-lane roadway system.

The digital twin for Alpha bridge (Fig. 5) provides a faithful representation of the cable-stayed bridge, ensuring accurate visualization for monitoring and analysis. The developed models enable engineers and decision makers to virtually inspect bridge conditions, facilitating early detection of structural problems.

2) Interactive Visualization and Sensor Integration: The 3D models of the respective bridges were developed to full digital twin scale in *Unreal Engine* and *WebGL*. Figs. 7 and 6 demonstrate these interactive visualization platforms in the *BridgeSync* framework. The *WebGL*-based visualization interface enables real-time interaction with sensor data. When a sensor is hovered over, its coordinates are displayed, allowing users to verify sensor placement accuracy. The user can highlight different bridge sections and examine sensor positions dynamically. The system fetches live sensor readings from the backend, ensuring up-to-date monitoring.

(a) Alpha Actual Bridge



(b) Alpha 3D Model

Fig. 5: Comparison of the Alpha Bridge: (a) actual bridge, (b) 3D digital twin model.

Fig. 6: *WebGL* Interface with Alpha Bridge selected

The *Unreal Engine*-based application illustrated in Fig. 7 offers an immersive experience where users can freely explore the bridge environment. Sensor coordinates are also displayed when hovered over, ensuring consistency in data representation. The camera can be manipulated to zoom into specific sensors for closer examination. The *Unreal Engine* implementation provides additional depth perception, allowing users to analyze structural deformations and spatial relationships better.

3) Challenges with Implementation: One of the critical challenges in multi-platform visualization is ensuring sensor coordinate consistency between the WebGL and Unreal Engine environments. In both interfaces, sensor positioning

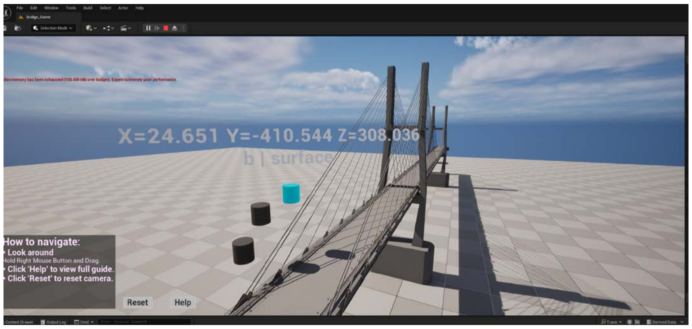


Fig. 7: *Unreal Engine* Interface with Alpha Bridge selected

must match real-world locations for effective monitoring and decision-making. To achieve this:

- Coordinate mapping: We ensured that the sensor data, including X,Y,Z positions were retrieved from a common JSON file stored on the FastAPI server. Both platforms read the same data.
- Real-time updates: The *WebGL* and *Unreal Engine* applications periodically synchronize with the backend, ensuring changes in sensor placement are reflected consistently.
- Hover-based coordinate display: When a sensor is hovered over, its real-time coordinates are retrieved and displayed, allowing users to validate positions.
- Data transformation and scaling: Since *WebGL* and *Unreal Engine* operate with different rendering scales, a coordinate transformation algorithm was applied to normalize positions. This ensures that sensor placements in *Unreal Engine* align with *WebGL*, preventing discrepancies.

V. Conclusion & Future Work

This study introduced BridgeSync, a digital twin framework for smart bridge monitoring, addressing security, latency, and interactivity limitations in existing structural health monitoring (SHM) systems. It integrated real-time sensor data, 3D visualization via Unreal Engine and WebGL, and a hybrid architecture with edge computing and blockchain. Unlike centralized, cloud-dependent systems, BridgeSync ensures secure, decentralized data management, low-latency processing, and multi-platform access, enhancing infrastructure safety and efficiency. Its features, compared to prior studies in Table. I set a new standard for digital twin applications in civil engineering. Experiments on the Alpha, Gamma, and Theta bridges produced accurate digital twins with effective real-time data visualization and user interaction. Sensor coordinate consistency across platforms was achieved through standardized mapping and synchronization. These results confirm BridgeSync's reliability and utility, surpassing traditional SHM methods with its multi-platform design and edge computing resilience. Blockchain integration is still pending and requires further development.

Future works will implement PureChain for tamper-proof storage and smart contracts, optimize PureEdge for robust operation, and explore AI for predictive analytics, potentially expanding applications to other infrastructure types.

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References

[1] Y. Gao, G. Xiong, Z. Hu, C. Chai, and H. Li, "Bridge digital twin for practical bridge operation and maintenance by integrating gis and bim," *Buildings*, vol. 14, no. 12, 2024. [Online]. Available: https://www.mdpi.com/2075-5309/14/12/3731

[2] M. Fawad, M. Salamak, Q. Chen, M. Uscilowski, K. Koris, M. Jasinski, P. Lazinski, and D. Piotrowski, "Development of immersive bridge digital twin platform to facilitate bridge damage assessment and asset model updates," *Computers in Industry*, vol. 164, p. 104189, 2025. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0166361524001179

[3] J. N. Njoku, E. C. Nkoro, R. M. Medina, C. I. Nwakanma, J.-M. Lee, and D.-S. Kim, "Leveraging digital twin technology for battery management: A case study review," *IEEE Access*, vol. 13, pp. 21 382–21 412, 2025.

[4] A. Fuller, Z. Fan, C. Day, and C. Barlow, "Digital twin: Enabling technologies, challenges and open research," *IEEE Access*, vol. 8, pp. 108 952–108 971, 2020.

[5] J. Nkechinyere Njoku, C. Ifeanyi Nwakanma, and D.-S. Kim, "Explainable data-driven digital twins for predicting battery states in electric vehicles," *IEEE Access*, vol. 12, pp. 83 480–83 501, 2024.

[6] J. Heng, Y. Dong, L. Lai, Z. Zhou, and D. M. Frangopol, "Digital twins-boosted intelligent maintenance of ageing bridge hangers exposed to coupled corrosion–fatigue deterioration," *Automation in Construction*, vol. 167, p. 105697, 2024. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0926580524004333

[7] C. Zhou, D. Xiao, J. Hu, Y. Yang, B. Li, S. Hu, C. Demartino, and M. Butala, "An example of digital twins for bridge monitoring and maintenance: Preliminary results," in *Proceedings of the 1st Conference of the European Association on Quality Control of Bridges and Structures*, C. Pellegrino, F. Faleschini, M. A. Zanini, J. C. Matos, J. R. Casas, and A. Strauss, Eds. Cham: Springer International Publishing, 2022, pp. 1134–1143.

[8] D.-S. Kim, I. S. Igboanusi, L. A. C. Ahakonye, and G. O. Anyanwu, "Proof-of-Authority-and-Association Consensus Algorithm for IoT Blockchain Networks," in *The 43rd IEEE International Conference on Consumer Electronics (ICCE 2025)*, 2025.

[9] D.-S. Kim and S. Rizal, "Pureedge: Redundant edge computing system for internet failover," in *Korean Institute of Communications and Information Sciences Summer Conference*, 2024, pp. 467–468.

[10] A. Costin, A. Adibfar, and J. Bridge, "Digital twin framework for bridge structural health monitoring utilizing existing technologies: New paradigm for enhanced management, operation, and maintenance," *Transportation Research Record*, vol. 2678, no. 6, pp. 1095–1106, 2024. [Online]. Available: https://doi.org/10.1177/03611981231208908

[11] A. Jiménez Rios, V. Plevris, and M. Nogal, "Bridge management through digital twin-based anomaly detection systems: A systematic review," *Frontiers in Built Environment*, vol. 9, 2023.

[12] F. Hidayat, S. H. Supangkat, and K. Hanafi, "Digital twin of road and bridge construction monitoring and maintenance," in *2022 IEEE International Smart Cities Conference (ISC2)*, 2022, pp. 1–7.

[13] V. Mousavi, M. Rashidi, M. Mohammadi, and B. Samali, "Evolution of digital twin frameworks in bridge management: Review and future directions," *Remote Sensing*, vol. 16, no. 11, 2024. [Online]. Available: https://www.mdpi.com/2072-4292/16/11/1887