실시간 공동 시뮬레이션과 안정적 동기화를 위한확장형 디지털 트윈 아키텍처

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An Expanded Digital Twin Architecture for Real-Time Co-Simulation, Secure Synchronization, and Edge-Resilient Operation

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Abstract

Digital Twin (DT) systems are increasingly deployed to support monitoring, diagnosis, and decision-making in complex cyber-physical systems. However, many existing DT implementations remain tightly coupled to specific applications or software platforms, limiting scalability, interoperability, and deployment robustness. This paper presents a Phase-2 Digital Twin core architecture that extends foundational twin models toward real-time data synchronization, co-simulation, browser-based visualization, and edge-resilient operation. The proposed architecture integrates OPC UA and MQTT for real-time data exchange, supports co-simulation between physics-based models and interactive virtual environments, enables WebGL-based browser access, and incorporates edge caching to ensure offline continuity. Secure event logging is included to preserve fault traceability and system integrity. The resulting framework establishes a future-ready DT core that supports interactive access, fault-aware simulation, and resilient deployment across heterogeneous computing environments.

Keywords - Digital Twin, Co-Simulation, OPC UA, MQTT, WebGL, Edge Computing.

I. Introduction

Digital Twins (DTs) have evolved from static simulation replicas into dynamic systems that synchronize with physical assets in real time [1]. As DTs transition from laboratory prototypes to operational systems, architectural challenges related to interoperability, accessibility, and resilience become increasingly critical. Many DT implementations prioritize high-fidelity modeling while overlooking system-level concerns, including distributed communication, interactive visualization, and robustness under network disruptions. These limitations constrain scalability and impede real-world deployment, particularly in environments that require remote access or edge operations. Building on a previously validated hybrid IoT-based Digital Twin framework for real-time parameter estimation and predictive maintenance in hydraulic excavators [2], this paper addresses these challenges by proposing an expanded DT core architecture that emphasizes system integration rather than application-specificity. The focus is on real-time synchronization, co-simulation, browser-accessible visualization, and fault-aware resilience, forming a foundational layer for advanced diagnostic and intelligent DT systems.

II. Methodology

The proposed Phase-2 architecture extends the baseline DT into a multi-layer system that comprises real-time data synchronization, co-simulation, browser-based visualization, and edge-resilient operation, as illustrated in Fig. 1. Live synchronization between physical systems and the DT is achieved via OPC UA and MQTT. OPC UA provides structured and secure communication for industrial environments [3], while MQTT enables lightweight publish--subscribe messaging suitable for constrained or wireless networks [4]. This dual-protocol approach enables flexible deployment across heterogeneous devices while maintaining low latency. The architecture supports co-simulation between physics-based models and interactive virtual environments.

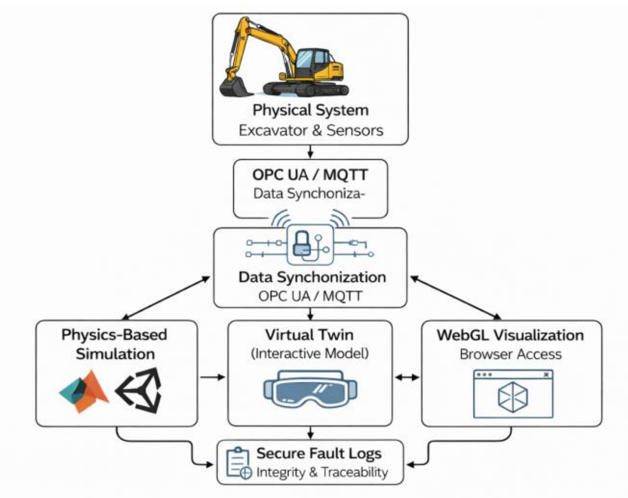

Fig. 1 - Phase-2 Digital Twin core architecture for an excavator system, illustrating real-time data synchronization via OPC UA/MQTT, co-simulation between physics-based models (Simulink) and interactive virtual environments (Unity), browser-based visualization using WebGL, secure fault logging, and edge-resilient operation

Physics-driven simulation engines operate in parallel with virtual representations, while a synchronization bridge ensures consistent propagation of system states, fault injections, and response signals. This enables fault-mode simulation and scenario evaluation within a unified DT environment. To enhance accessibility, the DT is visualized using WebGL-based browser interfaces. Virtual scenes exported from the simulation environment allow users to inspect system behavior, replay events, and interact with the DT remotely, eliminating dependence on specialized local software installations. To address intermittent connectivity, the architecture incorporates edge caching mechanisms that store DT snapshots, event logs, and lightweight models locally [5]. During network outages, the DT continues to operate in a degraded yet functional mode. Cached data are synchronized upon reconnection, preserving continuity and fault awareness. Reliable DT deployment requires diagnostic traceability and system integrity. The proposed architecture includes secure logging mechanisms that record fault events, simulation states, and system responses. These logs support auditability, post-event analysis, and trustworthy diagnostic reasoning, particularly in safety-critical environments. The proposed Phase-2 DT architecture enables:

1. Real-time synchronization across distributed systems,
2. Interactive co-simulation of physical and virtual models,
3. Browser-based DT access via WebGL,
4. Resilient operation under network disruptions, and
5. Secure and traceable fault diagnostics.

III. Conclusion

This paper presented a Phase-2 DT core architecture designed to support real-time synchronization, co-simulation, secure diagnostics, and edge-resilient operation. By emphasizing interoperability and architectural robustness, the framework overcomes key limitations of application-bound DTs. Future work will integrate explainable artificial intelligence to enable health-state prediction, root-cause analysis, and human-interpretable decision support, thereby transforming the DT into an intelligent and transparent reasoning platform.

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