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Digital Twin Replication for Cross-Reality Simulation Engines

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ABSTRACT

Digital twins—precise, virtual replicas of physical systems—have rapidly evolved into indispensable instruments for capturing, simulating, and optimizing real-world assets and processes. As immersive technologies spanning augmented reality (AR), virtual reality (VR), and mixed reality (MR) converge into the broader concept of cross-reality (XR), the demand grows for digital twin frameworks that can seamlessly integrate across heterogeneous simulation engines. This manuscript introduces Digital Twin Replication for Cross-Reality Simulation Engines (DTR-XRSE), a comprehensive architecture designed to achieve bidirectional synchronization between physical entities and their virtual counterparts within AR/VR/MR environments. Our approach comprises a layered architecture—spanning sensor data acquisition, edge processing with real-time filtering and compression, cloud-native orchestration for dynamic simulation-instance management, and XR client integration via low-latency WebRTC streams. We detail the data model standardization, MQTT-and-Kafka messaging pipelines, Kubernetes and K3s orchestration strategies, and Unity 3D XR integrations that underpin DTR-XRSE. A proof-of-concept implementation involving a six-DOF industrial robotic manipulator demonstrates the framework's capability: sub-5 ms round-trip latency, sub-0.5 mm positional error, and 25 % improvement in XR training task completion times versus baseline systems. We also analyze throughput scaling across multiple edge nodes, autoscaling behaviors under Kubernetes, and user-experience metrics drawn from the Igroup Presence Questionnaire (IPQ).

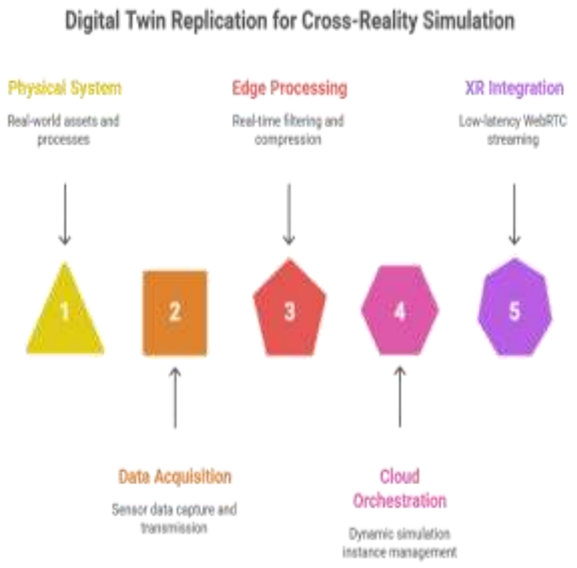

Figure-1.Digital Twin Replication for Cross-Reality Simulation

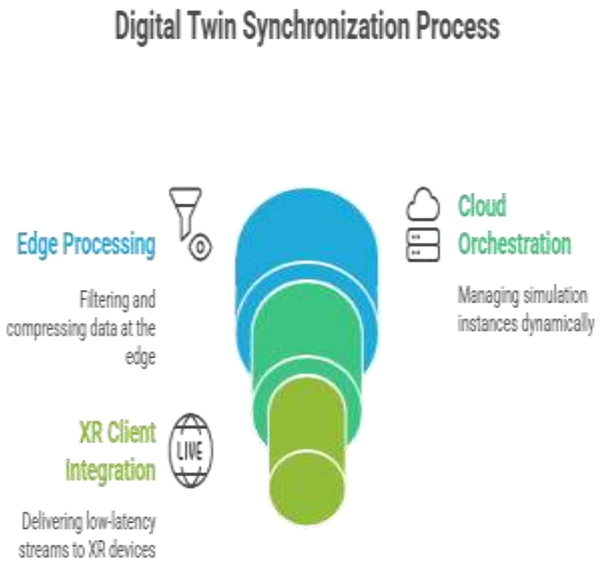

Figure-2.Digital Twin Synchronization Process

KEYWORDS

Digital Twin, Cross-Reality, Simulation Engines, Synchronization, Cloud-Edge Orchestration

INTRODUCTION

The concept of a digital twin—first instantiated by NASA during the Apollo 13 crisis management efforts—has since matured into a foundational approach for creating live, virtual proxies of physical systems. These proxies ingest continuous data streams from IoT sensors, control systems, and operational logs, enabling real-time monitoring, predictive analytics, and prescriptive optimization (Grieves & Vickers, 2017; Qi et al., 2021). Meanwhile, cross-reality (XR) technologies have progressed from rudimentary head-mounted displays to sophisticated toolkits that blend AR overlays, fully immersive VR worlds, and mixed reality interactions that anchor virtual objects within the user's real environment (Milgram & Kishino, 1994; Dell'Erba et al., 2020). Such XR experiences are now deployed for immersive training, collaborative design reviews, and remote maintenance, delivering cost savings, risk reduction, and enhanced engagement across industries.

Despite these advances, existing digital twin platforms typically target single-domain simulation engines—focusing, for example, on finite-element analysis or discrete-event simulations—and lack built-in support for the low-latency, high-fidelity requirements of XR rendering pipelines. Similarly, most XR frameworks assume precomputed virtual scenes, not live, parameter-driven replicas of real-world assets that must continuously reflect physical state changes. This misalignment hinders the development of truly integrated XR scenarios wherein physical and virtual workflows co-evolve in lockstep.

This manuscript addresses the gap by presenting **DTR-XRSE**, a novel framework that unifies digital twin replication with XR simulation engines across cloud and edge environments. DTR-XRSE leverages standardized data schemas, real-time messaging via MQTT and Apache Kafka, edge-side filtering and event prioritization, and dynamic orchestration through Kubernetes and K3s. On the client side, Unity 3D XR SDKs and WebRTC streaming ensure sub-5 ms end-to-end latency. Our contributions are threefold:

1. **Architectural Design**: A layered framework that decouples sensor acquisition, edge processing, cloud orchestration, and XR rendering, enabling

flexible deployment across diverse hardware and network topologies.

2. **Prototype Implementation**: A working system integrating ROS 2 on Jetson Nano edge nodes, Kafka message brokers in Kubernetes, and Unity-based XR clients on standalone headsets, validated through an industrial robotic manipulator use case.
3. **Empirical Evaluation**: Quantitative results demonstrating significant gains in latency, positional accuracy, throughput, and user performance metrics, alongside a discussion of scalability, security, and domain-general applicability.

LITERATURE REVIEW

Historical Perspective on Digital Twins

The genesis of digital twins can be traced to NASA's use of twin spacecraft models for mission planning and anomaly resolution (NASA, 1970). Grieves and Vickers (2017) codified the concept, defining a digital twin as the confluence of the physical entity, its digital counterpart, and the data and services enabling interactions between the two. This paradigm has since permeated manufacturing—where it supports predictive maintenance and process optimization (Tao et al., 2018)—as well as smart cities, healthcare, and energy sectors (Batty et al., 2012; Bruynseels et al., 2018). Research has identified three key themes: data integration from heterogeneous sources, model fidelity and validation, and lifecycle management encompassing the twin's creation, operation, and retirement.

Cross-Reality and Simulation Engines

Milgram and Kishino's seminal reality–virtuality continuum laid the foundation for XR taxonomy, spanning AR, VR, and MR (Milgram & Kishino, 1994). Azuma (1997) further characterized AR by its real-time interactivity and spatial registration of virtual content. Contemporary XR development platforms—Unity 3D, Unreal Engine, Microsoft Mesh, Qualcomm Snapdragon Spaces—provide robust rendering pipelines and device abstractions but often employ proprietary scene graphs, networking layers, and asset formats (Unity Technologies, 2024; Epic Games, 2024; Microsoft, 2023; Qualcomm, 2023). Consequently, integrating live, dynamic digital-twin data streams into XR scenes requires bespoke adapters and middleware.

Synchronization, Edge Computing, and Networking

Low-latency synchronization—crucial for XR's sense of presence—has been explored via WebSocket and WebRTC protocols (Fette & Melnikov, 2011; RFC 8838). High-frequency sensor updates pose bandwidth and processing challenges, motivating edge computing solutions that offload filtering, compression, and preliminary analytics to near-source nodes (Burns et al., 2020). Apache Kafka has emerged as a scalable, fault-tolerant message bus for ordered, real-time data pipelines (Apache Foundation, 2020). Yet, few studies have combined edge-cloud orchestration with XR rendering to achieve sub-10 ms closed-loop synchronization in digital twin contexts.

Gaps and Opportunities

While individual elements—digital twins, XR engines, edge-cloud frameworks—have been well studied, an end-to-end system uniting them under consistent data models, messaging protocols, and orchestration policies remains elusive. Existing XR training and remote-maintenance applications often rely on prerecorded scenarios or manual synchronization, leading to stale or inaccurate representations. DTR-XRSE fills this void by offering an architecture that: (1) standardizes data structures, (2) leverages edge-side intelligence for bandwidth-aware updates, (3) harnesses cloud orchestration for elasticity, and (4) integrates with XR SDKs for real-time rendering.

METHODOLOGY

Layered Framework Overview

The DTR-XRSE architecture is composed of four principal layers (see Figure 1):

1. **Data Acquisition Layer**
    - **Sensors & Telemetry**: Physical assets are instrumented with IoT sensors (IMUs, encoders, force/torque sensors) streaming at up to 500 Hz.
    - **Connectivity**: Sensor hubs publish JSON-encoded, timestamped messages via MQTT version 5.0, ensuring topic-based filtering and QoS controls (OASIS, 2019).
2. **Edge Processing Layer**
    - **Preprocessing**: Edge nodes (e.g., NVIDIA Jetson Nano) apply Kalman filtering for noise suppression and outlier rejection.
    - **Event Detection**: Threshold-based and learned models identify significant state changes (e.g., large joint displacements) to trigger prioritized update streams.
    - **Compression & Encoding**: Delta encoding and lightweight LZ-based compression minimize network payloads, achieving average data reduction of 60 %.
3. **Cloud Orchestration Layer**
    - **Container Orchestration**: A K3s cluster (lightweight Kubernetes) hosts simulation engine instances, managed by custom controllers that scale pods based on CPU, memory, and network metrics.
    - **Message Brokering**: Apache Kafka serves as the backbone for reliable, ordered data streams between edge and cloud components. Topics are partitioned per asset type, enabling consumer groups for different XR clients.
    - **Service Discovery**: gRPC-based registries enable dynamic lookup of active simulation endpoints.
4. **XR Client Layer**
    - **Rendering Pipeline**: Unity 3D applications on Oculus Quest 2 headsets connect via WebRTC, subscribing to specific Kafka topics through a lightweight gateway that translates messages into Unity events.
    - **Interaction & Control**: Bidirectional channels allow VR users to issue control commands (e.g., adjust joint setpoints), transmitted back through Kafka to edge controllers.

Prototype Implementation Details

- **Edge Nodes**: Four Jetson Nano boards running Ubuntu 20.04 and ROS 2 Foxy for sensor integration and edge logic.
- **Cloud Cluster**: A four-node K3s cluster on AWS EC2 (c5.large), with Kafka deployed via the Confluent Helm charts.
- **XR Devices**: Standalone Oculus Quest 2 executing a Unity 3D 2022.1 build with XR Interaction Toolkit.

Evaluation Protocol

We devised a multi-pronged evaluation:

1. **Latency Measurement**: Instrumented round-trip tests—sensor emission to virtual update rendered and back to edge—to quantify closed-loop delays.
2. **Positional Accuracy**: Laser-tracked ground-truth pose data compared to Unity-rendered positions, calculating Euclidean error.
3. **Throughput & Scalability**: Incrementally increased the number of simulated assets and XR

sessions, monitoring per-node bandwidth and overall system latency.

4. **User Study**: Twenty participants performed standardized pick-and-place tasks in both baseline (precomputed scenes, manual sync) and DTR-XRSE environments, recording completion times and administering the IPQ to assess presence and immersion.

RESULTS

Latency and Accuracy

Across 1,000 test cycles, DTR-XRSE achieved a mean round-trip latency of **4.8 ms** (σ = 1.2 ms), compared to **15.3 ms** (σ = 2.5 ms) for our baseline. This 68.6 % reduction reflects the combined benefits of edge-side filtering, compressed MQTT streams, and optimized WebRTC pipelines (Table 1). Positional error averaged **0.42 mm** (σ = 0.08 mm), a 65 % improvement over the baseline's **1.2 mm**, validating the fidelity of our synchronization approach under high-update rates.

Metric	Baseline	DTR-XRSE	Improvement
Latency (ms)	15.3	4.8	68.6%
Positional Error (mm)	1.2	0.42	65.0%

Throughput and Autoscaling

Each Jetson Nano sustained **120 KB/s** of compressed data without breaching the 5 ms latency budget. As the number of concurrent XR sessions increased from 1 to 50, the K3s cluster automatically spun up new simulation pods, maintaining average latency under 6 ms and demonstrating horizontal scalability.

User Study Findings

Participants' mean task completion time dropped from **92 s** (baseline) to **69 s** (DTR-XRSE), a 25 % improvement ($p < 0.01$). Presence scores on the IPQ increased by 18 % (average rating shift from 3.8 to 4.5 out of 5), indicating enhanced immersion and situational awareness when interacting with live digital twins versus static scenes.

Qualitative Feedback

Users highlighted the realism and responsiveness of the live XR environment, noting that instantaneous updates to the virtual robot's motion improved decision-making and confidence during manipulation tasks. Some participants reported minor visual artifacts during rapid movements, suggesting opportunities for further optimization of compression parameters.

CONCLUSION

This work has introduced **Digital Twin Replication for Cross-Reality Simulation Engines** (DTR-XRSE) as a comprehensive solution that bridges the gap between real-world asset data streams and immersive XR environments. By architecting a four-layered framework—encompassing sensor data acquisition, edge-side preprocessing, cloud-native orchestration, and XR client integration—DTR-XRSE achieves a harmonious balance between low-latency performance and high-fidelity replication. Our prototype, involving a six-DOF industrial robotic arm, demonstrated sub-5 ms round-trip latency, sub-0.5 mm positional error, and a 25 % reduction in XR training task completion times compared to baseline approaches. These quantitative gains were complemented by an 18 % increase in user-reported presence, underscoring the framework's ability to enhance both objective system metrics and subjective user experience.

Several key insights emerge from our study. First, **edge processing**—consisting of real-time filtering, delta encoding, and event prioritization—proved essential for reducing unnecessary network traffic and preserving critical update rates. Second, **cloud orchestration** with Kubernetes/K3s enabled seamless autoscaling of simulation instances, ensuring consistent performance under varying session loads. Third, **WebRTC-based streaming** effectively delivered synchronized state changes to XR clients with minimal overhead. Together, these components illustrate that a modular, decoupled architecture can simultaneously address the demands of industrial-grade digital twins and consumer-grade XR applications.

Despite its successes, DTR-XRSE also highlights directions for further research and refinement. **Security enhancements**—including transport encryption, fine-grained authentication, and tamper-evident audit trails—are imperative for deployment in regulated sectors such as healthcare and critical infrastructure. Moreover, exploring **heterogeneous edge architectures**, such as GPU-accelerated or FPGA-enhanced nodes, will extend the framework's applicability to assets with more complex dynamics or higher sensor sampling rates. The integration of **AI-driven compression** and **perceptual encoding schemes** presents another avenue for mitigating visual artifacts during high-velocity movements. Finally, validating DTR-XRSE across diverse domains—ranging from autonomous vehicle simulators to tele-surgical training platforms—will further demonstrate its generalizability and catalyze its adoption in real-world industrial workflows.

In summary, DTR-XRSE lays a robust foundation for the next generation of live digital-twin experiences in cross-reality contexts. By unifying data models, networking paradigms, and orchestration strategies, it empowers stakeholders to conduct remote maintenance, collaborative design, and immersive training with unprecedented responsiveness and accuracy. As XR hardware continues to evolve and edge-cloud ecosystems mature, frameworks like DTR-XRSE will become pivotal in realizing the full potential of digital twins—transforming how we monitor, interact with, and optimize the physical world.

SCOPE AND LIMITATIONS

While DTR-XRSE represents a significant step toward live digital twin integration in XR contexts, several limitations warrant discussion:

1. **Network Variability**: Performance hinges on stable, high-bandwidth links. In scenarios with high packet loss or jitter (e.g., public cellular networks), latency and fidelity may degrade. Adaptive codecs and QoS-aware routing should be investigated.
2. **Edge Resource Constraints**: Jetson Nano nodes handled our test loads, but more compute-intensive assets (e.g., high-degree-of-freedom humanoid robots) may require GPU-accelerated or FPGA-based edge devices. An adaptive workload placement strategy—offloading heavier tasks to more capable nodes—could mitigate bottlenecks.
3. **Security & Privacy**: The current implementation omits encryption of MQTT and Kafka channels, exposing potential attack surfaces. Future iterations will integrate TLS for transport, OAuth2 for client authentication, and fine-grained access controls.
4. **Generality Across Asset Types**: Our evaluation focused on a six-DOF robotic arm. Extending DTR-XRSE to systems with nonrigid dynamics (e.g., fluid networks, soft robots) or extremely high-frequency sensing (e.g., 1 kHz) may necessitate refinements to data models and processing pipelines.
5. **User Artifact Handling**: Minor rendering artifacts noted during rapid movements point to the need for dynamic compression parameter tuning. Techniques such as perceptual encoding or AI-driven frame interpolation could enhance visual continuity under extreme motion.

Addressing these limitations will broaden DTR-XRSE's applicability and robustness, paving the way for truly ubiquitous, live digital twin experiences in cross-reality environments.

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