

Web3D 2026

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Human-Centered Digital Twins: A Bidirectional WebXR-Based Architecture for Immersive Interaction

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Agenda Overview

1. Introduction
2. Research Questions & Objectives
3. Conceptual Architecture Design
4. Implementation
5. Evaluation
6. Conclusion & Future Work

Introduction

- Digital Twins: What are they and why are they important?
- Existing Architectures: Current approaches and technologies
- Limitations: Scalability, interoperability, and domain dependency
- Research Gap: Need for a reusable, domain-agnostic architecture



Research Questions

RQ1: Can a browser-based DT architecture enable real-time, interoperable synchronization?

RQ2: How well does a WebXR-based DT perform on consumer hardware?

RQ3: Can one domain-agnostic framework support diverse application domains?

Research Objectives

- ✓ Design a browser-native, open-standard Digital Twin architecture.
- ✓ Enable real-time visualization, synchronization, and interoperability.
- ✓ Present a domain-agnostic architecture with a unified runtime.
- ✓ Evaluate performance and demonstrate reuse across diverse domains.



Universal Digital Twin architecture

Continuous Closed Loop:
Physical → Virtual: Data & Updates ↔ Virtual → Physical: Decisions & Control

Layer 5: WebXR Visualization & Interaction



5a- Visualisation

5b- Human Control

Human Feedback & Decisions

Virtual Insights, Models & Recommendations

Layer 4: Intelligence & Decision
Generate insights through analytics, prediction, optimization, and AI-assisted decision support.

Layer 3: Digital Twin Core (synchronization)
Maintain consistency between physical and virtual systems through real-time synchronization, data fusion, and state updating.

Layer 2: Data Processing & 3D Modeling
Process raw data into structured information, 3D models, and digital representations for virtual system updates.

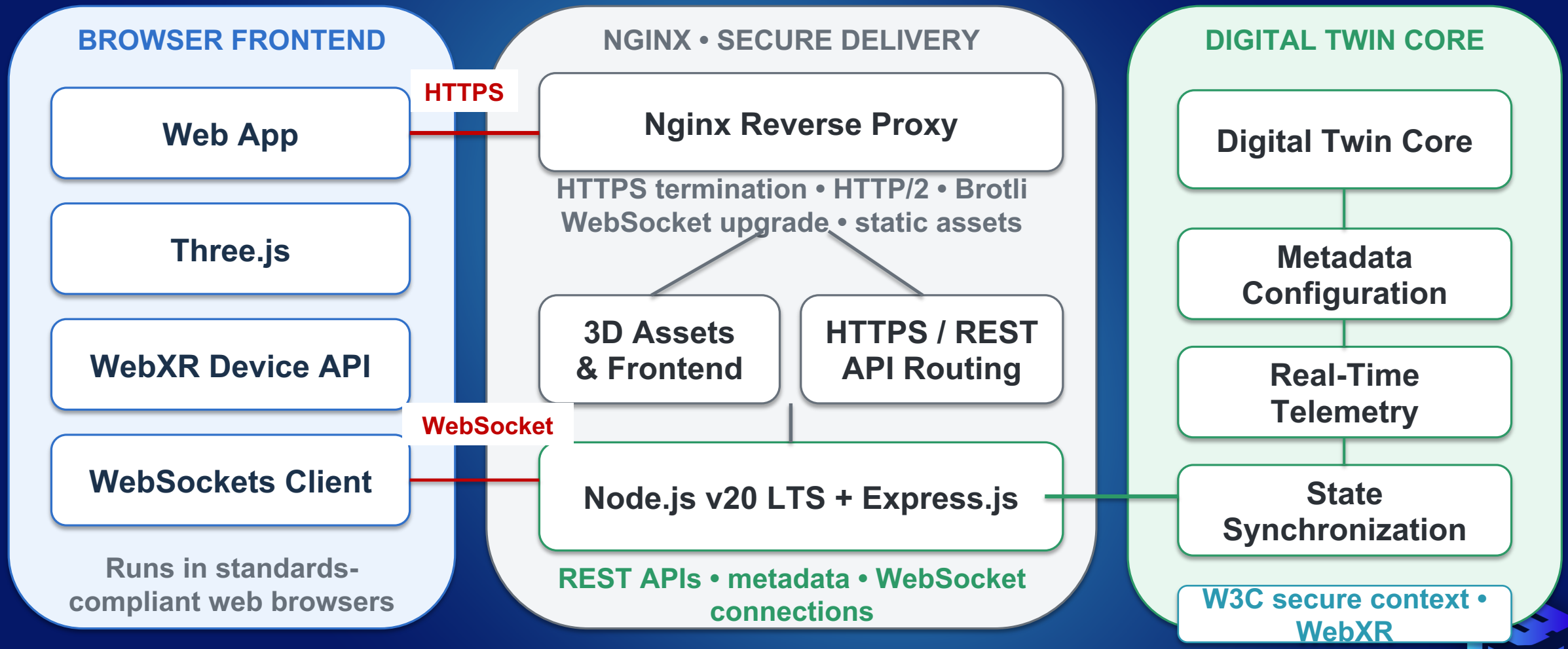
Layer 1: Sensing & Data Acquisition
Capture real-world data, including sensor measurements, operational states, and environmental parameters.

Feedback Loop

Cross-Cutting Concerns
Data storage and management with cloud/edge computing, IoT connectivity, security, APIs, and monitoring.

Universal Digital Twin WebXR Architecture

Standards-compliant browser client • HTTPS • Node.js/Express backend • Nginx reverse proxy



Nginx serves cached static/3D resources directly, isolating real-time API and synchronization traffic on Node.js.

Demonstration Scenarios



Demo: https://live.cloud.cerist.dz/demo/

Evaluation

Evaluation Methodology

- **Tools:** Chrome Performance Tools were used to evaluate the efficiency and responsiveness.
- **Core Web Vitals** : Measured: **LCP, INP, and CLS** to assess user experience and runtime performance.
- **Test Environments:** Conducted under three conditions to simulate device variation:
  1. Baseline (High-performance)
  2. 4x CPU slowdown + Fast 4G (Moderate-performance)
  3. 6x CPU slowdown + Fast 4G (Resource-constrained)



Performance Evaluation Results and Render-Blocking Analysis

Aspect / Resource	Diagnostic Observation / Latency Duration
Loading Performance	Excellent across all configurations (LCP ≤ 1.26 s)
Visual Stability	Perfect stability (CLS = 0.00)
Rendering Efficiency	Rendering and painting costs remained low in all tests
Network Performance	Fast TTFB (19 ms) and minimal loading delays
Main Performance Bottleneck	JavaScript execution and system processing
Critical Resources	three.min.js and external font loading contribute to render-blocking delays
Interaction Responsiveness	Excellent under normal conditions (72 ms), but degraded under 6× CPU slowdown (712 ms)
Critical Asset: three.min.js	Key render-blocking contributor introducing an initial delay of 337.53 ms
Critical Asset: Google Fonts	External network font dependency introducing an initial delay of 321.88 ms
Total Assessment	Strong visualization and loading performance under constrained environments



Conclusion

- The study presents a WebXR-based Digital Twin architecture, which is adaptable across various domains and supports real-time synchronization, immersive visualization, and browser accessibility.
- Prototype evaluation confirms the feasibility of the approach, offering responsive visuals, efficient synchronization, and interactive experiences using standard web technologies.
- The architecture promotes scalability, interoperability, and adaptability by separating sensing, modeling, intelligence, synchronization, and interaction layers.
- Empirical findings stem from controlled experiments with simulated data streams, indicating a need for further evaluation in large-scale operational contexts.
- The infrastructure exhibits potential applications in medical training, industrial robotics real-time monitoring, and interactive 3D educational environments.



Future developments

- ✓ Integrating domain-specific data acquisition and 3D reconstruction workflows.
- ✓ Supporting multi-user WebXR synchronization for real-time interaction among distributed users.
- ✓ Exploring distributed edge computing and AI-assisted services for enhanced platform intelligence.



Thank You!

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