USD-Based 3D Model Database and Spatial Configuration Technologies for Digital Twins

Myeongseop Kim
Contents Convergence Research Center
Korea Electronics Technology Institute
Gyeonggi-do, Republic of Korea
myeongseopkim@keti.re.kr

Jungwook Wee
Contents Convergence Research Center
Korea Electronics Technology Institute
Gyeonggi-do, Republic of Korea
jwwee@keti.re.kr

***Abstract*—Digital twin technology creates dynamic virtual replicas of physical systems with bidirectional data exchange capabilities. This paper examines recent advances in Universal Scene Description (USD)-based 3D model database systems and spatial configuration technologies for digital twin applications. Through comprehensive analysis of related research, we identify significant progress in multi-format 3D model integration, database-driven spatial configuration, and real-time scene management. However, critical challenges persist in scalability, intelligent reconfiguration, and enterprise integration. The increasing demand for digital twin implementations in manufacturing and robotics sectors highlights the need to address current limitations. To this end, this paper proposes a comprehensive research framework identifying five critical directions for advancing USD-based digital twin technologies.**

***Index Terms*—Digital Twin, USD, 3D Model Database, Spatial Configuration, Multi-Format Integration**

I. Introduction

Digital twin technology has evolved from NASA's 2002 space mission concept to a fundamental Industry 4.0 enabler, creating continuously synchronized virtual-physical systems [1]. Spatial Digital Twins (SDTs) emphasize geospatial aspects, incorporating precise location-dimensional attributes for comprehensive spatial environment understanding [2]. The emergence of Universal Scene Description (USD) as a standardized framework for 3D content creation has created unprecedented opportunities for digital twin development, particularly through its convergence with advanced sensor fusion technologies. However, current USD-based digital twin implementations face critical challenges in scalability, real-time performance, and enterprise integration. This paper presents a comprehensive review of USD-based 3D model database systems and spatial configuration technologies, identifying key technological advances, persistent challenges, and proposing a research framework with five essential directions for advancing digital twin systems capable of supporting complex industrial applications.

This research was supported by a grant from the Korea Planning & Evaluation Institute of Industry Technology (KEIT), funded by the Ministry of Trade, Industry and Energy (MOTIE) (RS-2025-15122968, Real-time Augmented Experimentation Technology Using Digital Twin Integrated with Real World).

II. Current State and Technological Advances

A. USD-Based 3D Database Systems

Universal Scene Description has emerged as the foundational framework for 3D digital twin ecosystems, evolving beyond entertainment to become the HTML of 3D worlds [3].

3D Model Database Architecture: Recent studies demonstrate significant progress in USD-based 3D model database construction, enabling scalable asset management and retrieval systems. SyncTwin's implementation showcases the transformation of disparate data sources (Microsoft PowerPoint, Excel, PDF formats) into unified 3D digital twin databases through USD asset resolvers [4]. This approach enables complex 3D assets abstraction through storage backends and serialization, facilitating seamless integration of production processes, product catalogs, and scheduling data.

Multi-Model Integration: Recent studies reveal challenges in multi-3D model application within USD frameworks. Format conversion technologies now support diverse CAD formats, BIM models, and IoT sensor data integration into unified USD scenes [5]. However, maintaining data consistency across heterogeneous model sources remains problematic, particularly when dealing with different geometric representations, material properties, and semantic annotations.

Spatial Configuration Technologies: Database-driven spatial configuration approaches enable dynamic scene composition based on real-time operational requirements. Current implementations utilize USD's layering capabilities to non-destructively modify source data while maintaining geometric accuracy and semantic relationships [6].

B. Real-Time Environment Integration

Current literature reveals substantial progress in multi-modal sensor integration, combining accelerometers, gyroscopes, and magnetometers through feature-level fusion, decision-level fusion, and Kalman filter fusion [7]. Advanced frameworks utilize microservice architectures for data processing, decomposing information processing into independent services for easier maintenance and scaling [8]. Healthcare implementations achieve 72% accuracy in real-time staff task tracking [9], while Unity3D-based industrial platforms establish virtual-real mapping architectures for enhanced robot control [10].

III. Research Gaps and Future Directions

A. Critical Limitations

3D Model Database Scalability: While spatial database research has identified general challenges in managing complex 3D model collections [2], the scalability characteristics of USD-based database systems for large-scale 3D model repositories have not been thoroughly investigated. This gap limits our understanding of performance bottlenecks in asset indexing, version control, and metadata management.

Spatial Configuration Consistency: Multi-3D model integration within USD frameworks struggles with maintaining geometric and semantic consistency across different model sources. Format conversion from diverse CAD, BIM, and sensor data formats introduces data loss, coordinate system misalignment, and material property inconsistencies [4].

Real-Time Performance Constraints: Current USD architectures face limitations in high-speed dynamic scene updates required for millisecond-level industrial applications. Database-driven spatial reconfiguration operations create computational bottlenecks, particularly when dealing with complex object hierarchies and spatial relationships [5].

Cross-Platform Database Integration: Limited standardization exists for integrating USD-based 3D model databases with existing enterprise systems [4]. Native connections to PLM, ERP, and IoT platforms remain underdeveloped, creating data silos and workflow inefficiencies.

B. Proposed Research Framework

(1) Scalable USD-Based 3D Model Database Architecture: Developing distributed database systems optimized for large-scale 3D asset management with efficient indexing, version control, and metadata handling for heterogeneous model collections. (2) Intelligent Spatial Configuration Systems: Creating AI-driven spatial configuration algorithms that automatically optimize object placement, spatial relationships, and scene composition based on operational requirements and real-time constraints.(3) Multi-Format Integration Framework: Establishing standardized conversion pipelines for seamless integration of diverse 3D model formats (CAD, BIM, point clouds) while preserving geometric accuracy and semantic annotations. (4) Database-Driven Real-Time Scene Management: Developing efficient algorithms for dynamic scene updates and spatial reconfiguration operations that minimize computational overhead while maintaining consistency. (5) Enterprise System Integration: Creating standardized APIs and protocols for connecting USD-based 3D model databases with existing PLM, ERP, and IoT enterprise systems

IV. Conclusion

This paper establishes the current state of USD-based 3D model database and spatial configuration technologies for digital twin applications. While USD has emerged as a promising standard for 3D digital twin ecosystems, significant challenges persist in achieving scalable, real-time systems suitable for complex industrial applications.

Through systematic examination of recent advances, we identified progress in multi-format 3D model integration, database-driven spatial configuration, and real-time sensor fusion. However, limitations persist in four key areas: (1) database scalability for large-scale 3D model repositories, (2) spatial configuration consistency across heterogeneous model sources, (3) real-time performance for millisecond-level industrial applications, and (4) cross-platform integration with enterprise systems.

To address these challenges, we propose a research framework comprising five directions: scalable USD-based 3D model database architecture; intelligent AI-driven spatial configuration systems; multi-format integration frameworks preserving geometric and semantic fidelity; database-driven real-time scene management; and standardized enterprise system integration protocols for PLM, ERP, and IoT platforms.

Advancing these research directions will be crucial for next-generation digital twin systems supporting Industry 4.0 applications. The identified gaps and proposed framework provide clear pathways for developing robust USD-based technologies enabling seamless virtual-physical integration in manufacturing and robotics domains.

Acknowledgment

This research was supported by a grant from the Korea Planning & Evaluation Institute of Industry Technology (KEIT), funded by the Ministry of Trade, Industry and Energy (MOTIE) (RS-2025-15122968, Real-time Augmented Experimentation Technology Using Digital Twin Integrated with Real World).

References

[1] W. Liu, M. Wu, G. Wan, and M. Xu, "Digital twin of space environment: Development, challenges, applications, and future outlook," *Remote Sensing*, vol. 16, no. 16, pp. 3023, 2024.

[2] M. E. Ali, M. A. Cheema, T. Hashem, A. Ulhaq, and M. A. Babar, "Enabling spatial digital twins: Technologies, challenges, and future research directions," *PFG–Journal of Photogrammetry, Remote Sensing and Geoinformation Science*, vol. 92, no. 6, pp. 761-778, 2024.

[3] NVIDIA Corporation, "Universal Scene Description as the Language of the Metaverse," NVIDIA Technical Blog, 2022.

[4] NVIDIA Developer, "Transforming Microsoft XLS and PPT Files into a Factory Digital Twin with OpenUSD," Technical Blog, 2024.

[5] NVIDIA Developer, "Creating Immersive Events with OpenUSD and Digital Twins," Technical Blog, 2024.

[6] J. Wang, F. Mo, S. Qiao, H. Feng, and Z. Lyu, "Spatial computing in digital twins," *Digital Twin*, Art. no. 2508268, 2025.

[7] B. Momoh and S. Yahaya, "Data sensor fusion in digital twin technology for enhanced capabilities in a home environment," 2025, arXiv:2502.08874. [Online]. Available: https://arxiv.org/abs/2502.08874

[8] C. Yang, Q. Guo, H. Yu, Y. Chen, T. Taleb, and K. Tammi, "Semantic-enhanced digital twin for industrial working environments," in *Proc. Int. Summit Global Internet of Things and Edge Computing*, Springer Nature Switzerland, 2024, pp. 3-20.

[9] G. D. K. Kuruppu Appuhamilage, M. Hussain, M. Zaman, and W. Ali Khan, "A health digital twin framework for discrete event simulation based optimised critical care workflows," *npj Digital Medicine*, vol. 8, no. 1, Art. no. 376, 2025.

[10] W. Chang, W. Sun, P. Chen, and H. Xu, "Construction and validation of a digital twin-driven virtual-reality fusion control platform for industrial robots," *Sensors*, vol. 25, no. 13, Art. no. 4153, 2025.