Special Issue on Digital Twins

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This issue features eight articles that explore diverse aspects of digital twin (DT) research. Several works focus on the foundational frameworks and computational advancements of DTs: The first article presents a scalable cloud-native platform for deploying universal DTs, while the second introduces a multifidelity data fusion (MDF) mechanism for integrating real-time Internet of Things (IoT) sensor data with historical simulation models. Other contributions emphasize industrial and infrastructure applications: The third article develops a generative modeling approach for DT-based shop floor management, and the fourth investigates DT-enabled location-based services for smart buildings. In the realm of sustainability and energy optimization, the fifth article proposes a cognitive DT for microgrid energy management, and the sixth applies DT technology to cultural heritage preservation, specifically for the Great Wall of China. Finally, two articles highlight emerging trends: The seventh explores human DTs (HDTs) to enhance interactions within intelligent ecosystems, and the eighth presents the Internet of Twins framework as a scalable DT platform for diverse industrial applications. Together, these contributions showcase the evolving capabilities of DTs and their expanding role in bridging the physical and digital worlds.

DTs have emerged as a transformative technology, revolutionizing industries by providing a dynamic digital counterpart to physical systems. By leveraging real-time data integration, simulation, and artificial intelligence, DTs enable predictive maintenance, system optimization, and enhanced decision making across sectors, such as manufacturing, health care, energy, and transportation. The increasing convergence of IoT, cloud computing, and machine learning has significantly expanded the capabilities of DTs, allowing for more sophisticated, scalable, and adaptive implementations. As organizations strive for greater efficiency and resilience, DTs are becoming a key enabler of next-generation intelligent systems.

Despite their growing adoption, several challenges hinder the full realization of DT potential, including real-time data processing, interoperability, security, and scalability. Addressing these challenges requires innovative frameworks, robust architectures, and interdisciplinary collaboration. This special issue explores recent advancements in DT technology, showcasing state-of-the-art research that enhances system intelligence, operational efficiency, and human–machine collaboration. The articles included in this issue provide valuable insights into the latest computational models, application-driven implementations, and emerging trends shaping the evolution of DTs. We hope this special issue inspires further research and innovation in the field of DTs, paving the way for smarter, more autonomous, and highly optimized digital–physical systems.

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APPENDIX: RELATED ARTICLES

A1. T. Häußermann, J. Lehmann, A. Rache, F. Kolb, F. Wühler, and J. Reichwald, "UniTwin: Pushing universal digital twins into the clouds through reconfigurable container environments," *IEEE Internet Comput.*, vol. 29, no. 1, pp. 8–15, Jan./Feb. 2025, doi: 10.1109/MIC.2024.3489876.

A2. H. Wang, X. Song, and C. Zhang, "Multifidelity data fusion mechanism for digital twins via the Internet of Things," *IEEE Internet Comput.*, vol. 29, no. 1, pp. 16–23, Jan./Feb. 2025, doi: 10.1109/MIC.2024.3483831.

A3. Y. Wu, Y. Sun, X. Wen, X. Liu, J. Bao, and S. Wang, "A generative modeling method for digital twin shop floor," *IEEE Internet Comput.*, vol. 29, no. 1, pp. 24–31, Jan./Feb. 2025, doi: 10.1109/MIC.2024.3522301.

A4. A. Chambon, A. Rachedi, A. Sahli, and A. Mebarki, "From IoT networks deployment to robust location-based services using the digital twin of a building," *IEEE Internet Comput.*, vol. 29, no. 1, pp. 32–38, Jan./Feb. 2025, doi: 10.1109/MIC.2024.3502631.

A5. B. Sivaneasan, K. T. Tan, and W. Zhang, "Cognitive digital twins for the microgrid: A real-world study for intelligent energy management and optimization," *IEEE Internet Comput.*, vol. 29, no. 1, pp. 39–47, Jan./Feb. 2025, doi: 10.1109/MIC.2024.3488896.

A6. Z. Zhang, A. Dang, J. Huang, and Y. Chen, "Advancing conservation methods of the great wall cultural heritage through digital twin," *IEEE Internet Comput.*, vol. 29, no. 1, pp. 48–55, Jan./Feb. 2025, doi: 10.1109/MIC.2025.3539367.

A7. S. Laso, J. L. Herrera, J. Galán-Jiménez, and J. Berrocal, "Human digital twins: Enhancing interactions with digital ecosystems," *IEEE Internet Comput.*, vol. 29, no. 1, pp. 56–64, Jan./Feb. 2025, doi: 10.1109/MIC.2024.3509672.

A8. L. V. Cakir, M. Özdem, H. Ahmadi, T. Q. Duong, and B. Canberk, "Internet of twins approach: Digital-twin-as-a-platform architecture," *IEEE Internet Comput.*, vol. 29, no. 1, pp. 65–74, Jan./Feb. 2025, doi: 10.1109/MIC.2024.3491915.

IN THIS ISSUE

The special issue presents eight high-quality articles that explore the latest advancements in DT technology across diverse domains, including industrial applications, urban planning, energy management, and human-centered digital ecosystems. Below, we summarize each article's contributions and impact.

The first article[A1] presents UniTwin, a cloud-native framework for deploying and managing universal DTs in containerized environments. The framework is designed to address scalability, modularity, and domain-independence challenges through a composite design pattern and Kubernetes-based orchestration. The study demonstrates UniTwin's effectiveness in supporting scalable DT management across different application domains, paving the way for broader adoption of DT technology in cloud computing environments.

The second article[A2] introduces an MDF mechanism for DTs that integrates real-time IoT sensor data with historical finite element method simulation results. The authors propose the improved hierarchical regression for the MDF method, which enhances prediction accuracy by leveraging both high-fidelity and low-fidelity data sources. Numerical experiments validate the approach, demonstrating its effectiveness in maintaining a low normalized root mean square error and computational efficiency. The proposed mechanism offers significant potential for improving DT applications across industrial and smart infrastructure domains.

The third article[A3] presents a novel generative modeling approach for DT-based shop floor management, leveraging large language models and ontology-based information models. The proposed framework extracts domain knowledge dynamically, enabling real-time construction and semantic enrichment of DT shop floor models. The study validates the method through a case study on shop floor resource scheduling, demonstrating improved efficiency in model generation and industrial applicability.

The fourth article[A4] investigates the integration of DTs with IoT networks to optimize location-based services in smart buildings. The authors propose a novel framework that enhances IoT deployment strategies through genetic algorithms and a multitier architecture, improving coverage and extending service availability. A use case on indoor guidance services demonstrates the system's potential to enhance operational efficiency and user experience in smart environments.

The fifth article[A5] presents a cognitive DT for microgrid optimization developed for a real-world deployment in Singapore. The DT framework includes a

client for real-time control and a cloud-based server for computationally intensive energy management algorithms. The system is validated through operational scenarios, demonstrating significant improvements in microgrid resilience, efficiency, and cost reduction, with only a 0.24% difference from the theoretical optimal energy cost.

The sixth article[A6] explores the use of DT technology for cultural heritage conservation, focusing on the Beichakou section of the Great Wall in China. The authors propose the "Beichakou Method," which integrates real-time monitoring, risk assessment, and conservation planning through a multitier DT framework. The study highlights the benefits of DTs in optimizing conservation efforts while identifying challenges in data acquisition, multiparty coordination, and system scalability.

The seventh[A7] article explores the concept of HDTs and their role in enhancing interactions within digital ecosystems. The authors propose a multicontext distributed HDT architecture that integrates human-specific data with smart systems, addressing challenges in privacy, interoperability, and real-time adaptation. The study outlines key application areas, including Industry 5.0 and intelligent transportation, and highlights the potential for HDTs to improve human–system collaboration.

The eighth article[A8] introduces the Internet of Twins concept, proposing a DT as a platform architecture for scalable and interoperable DT deployments. By leveraging a knowledge graph-based orchestration approach, the framework enhances data integration and system automation. A pilot study in wind energy management demonstrates the system's ability to optimize fault detection, reduce data preprocessing overhead, and improve operational efficiency.

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