Geographical Twin and Spatiotemporal Artificial Intelligence Technology Empowering High-Quality Urban Development

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Abstract: With the rapid advancement of urbanization, the complexity of urban systems has become increasingly prominent, and traditional governance models face severe challenges. As a concrete expression of digital twin technology in urban space, the geographical twin, when integrated with spatiotemporal artificial intelligence (AI) technology, is reshaping urban governance models. Based on this, this paper explores the technical applications of geographical twins and spatiotemporal AI in data integration, pattern mining, and predictive simulation, starting from the three-dimensional spatial modeling and dynamic sensing capabilities of geographical twins. It analyzes the application mechanisms of this technological system in urban planning, traffic governance, environmental monitoring, and public safety scenarios. The study shows that geographical twins and spatiotemporal AI, by constructing a "perception–cognition–decision–regulation–monitoring" closed loop, achieve precise mapping, intelligent diagnosis, and dynamic optimization of complex urban systems, providing technological support for high-quality urban development.
Keywords: geographical twin; spatiotemporal artificial intelligence technology; high-quality urban development

1. Introduction

As open and complex megasystems, cities exhibit highly nonlinear characteristics in the spatiotemporal dimension due to the aggregation and interaction of their elements. Traditional urban management methods based on static data cannot address systemic challenges such as population concentration, resource scarcity, and environmental degradation. Digital twin technology, by constructing real-time interactive channels between physical cities and virtual spaces, offers new approaches for urban governance. Geographical twins focus on the urban spatial dimension, integrating multi-source sensor data, geographic information systems, and building information models to establish three-dimensional digital mappings of cities. Spatiotemporal AI technology overcomes the limitations of traditional analytical methods, possessing the ability to extract complex patterns and predict evolutionary trends from massive spatiotemporal data. The integration of these two technologies forms a technical pathway of "spatial digitization–cognitive intelligence–precision decision-making," promoting the evolution of urban governance from experience-based control to data-driven management, and from static planning to dynamic regulation and optimization. Based on this, the main objective of this study is to systematically elucidate the technical connotations of geographical twins and spatiotemporal AI, deeply investigate their synergistic mechanisms, and analyze their empowering role in high-quality urban development.

2. Technical Connotations of Geographical Twins and Urban Spatial Reconstruction

Geographical twins go beyond traditional three-dimensional modeling, constructing urban virtual representations with full-element expression, real-time sensing, and dynamic simulation capabilities. Its technological system comprises three levels: the physical layer, where urban entities continuously collect data on building forms, infrastructure, human and vehicle flows, and environmental parameters through IoT sensors, remote sensing monitoring, and mobile sensing devices; the model layer, which, based on urban information models, comprehensively integrates geographic spatial data and socio-economic data to establish a semantically linked urban spatial database; and the functional layer, which, through spatial analysis and visualization engines, supports multi-dimensional presentation of urban states.

Urban spatial reconstruction is fully reflected in the deep integration of physical and virtual spaces. Geographical twins precisely reproduce the geometric features of urban buildings, road networks, and public spaces through centimeter-level real-scene modeling and indoor–outdoor integration technologies, further clarifying the topological relationships among different elements. Change detection based on temporal imagery enables dynamic monitoring of urban expansion and land use, supporting compliance review for territorial spatial planning. At the microscopic scale, visual management of internal building structures and equipment operation optimizes building energy consumption scientifically and strengthens emergency evacuation planning effectively. This not only extends the dimension of urban management but, through historical state backtracking, further expands the spatiotemporal boundaries of urban cognition.

3. Technological System of Spatiotemporal Artificial Intelligence

Spatiotemporal artificial intelligence (AI), as an interdisciplinary field combining AI and spatiotemporal data analysis, specializes in processing complex data with spatial autocorrelation and temporal dependency. Its technical framework comprises the data layer, algorithm layer, and application layer: the data layer integrates remote sensing imagery, GPS trajectories, geotagged social media, and other data, combining spatiotemporal indexing and data fusion techniques to construct a unified analytical foundation; the algorithm layer covers tasks such as spatiotemporal prediction, anomaly detection, and pattern mining, extracting knowledge through deep learning and spatiotemporal statistical methods; the application layer provides decision support for specific scenarios such as urban planning, traffic management, and environmental monitoring.

The successful breakthroughs of this technology are reflected in the deep cognition of urban complexity. Graph neural networks effectively capture spatial dependencies among urban elements, while spatiotemporal Transformer models identify long-range spatiotemporal correlations through self-attention mechanisms. Multi-agent urban simulations reproduce the generation mechanisms of macro phenomena such as population flows and land-use evolution, enhancing the accuracy of urban state perception. Furthermore, generative models enable precise prediction of urban system responses under policy interventions and external shocks, providing forward-looking decision-making support for urban governance.

4. Transformation of Urban Governance Driven by Technological Integration

By integrating geographical twin and spatiotemporal AI technologies, a "data–model–decision–monitoring" closed loop is formed, promoting the development of urban governance from fragmentation to systematization. In practical applications, the integrated technical framework uses the geographical twin as the spatial carrier to host multi-dimensional urban data; employs spatiotemporal AI as the analytical engine to further extract data value; and utilizes a collaborative platform as the interaction interface to support joint decision-making across multiple departments, successfully addressing issues of data silos and business fragmentation in traditional smart city construction.

In the field of urban safety, with real-time access to video surveillance and social media data, the geographical twin platform dynamically presents crowd density in key areas, while spatiotemporal AI algorithms identify abnormal gathering patterns, predict the evolution path of stampede risks, and generate graded warning plans. In environmental governance, the integration of high-precision atmospheric pollution diffusion simulations with real-time monitoring data enables accurate tracing of pollution sources and assessment of emission reduction measures. The essence of this governance paradigm transformation lies in the reconstruction of urban cognition—from experience-based judgment to data-driven analysis, from static analysis to dynamic simulation, and from passive response to proactive intervention[1].

5. Analysis of Empowerment Mechanisms in Typical Application Scenarios

5.1 Urban Spatial Planning and Land Management

Geographical twin technology, by integrating high-precision real-scene three-dimensional models, BIM/CIM data, and dynamic sensing information, constructs a digital mirror space covering the entire urban area, providing a simulatable decision-making environment for urban territorial spatial planning. On this basis, multiple planning scenarios can be visualized and compared simultaneously, significantly enhancing the scientific validity of plan evaluation and strengthening the intuitiveness of public participation. Spatial planning outcomes are no longer limited to two-dimensional drawings but are presented in dynamic forms showing the coupling relationships among spatial morphology, development intensity, industrial growth, and ecological constraints, effectively reinforcing the unity of planning rigidity control and adaptive flexibility.

Spatiotemporal artificial intelligence, from a dynamic evolution perspective, analyzes urban operational logic by utilizing data such as mobile signaling, points of interest (POI), and remote sensing imagery to construct spatiotemporal coupling models of population, employment, and facilities, accurately identifying structural issues such as residential–workplace imbalance, service blind spots, and inefficient commuting. Combined with machine learning algorithms, it evaluates the development potential of land parcels from multiple dimensions, integrating location conditions, infrastructure capacity, and ecological sensitivity, autonomously generating priority maps for land supply, and optimizing the timing and spatial allocation of land release. During the implementation phase of territorial spatial planning, the geographical twin platform automatically compares historical urban morphological changes, quantitatively assesses deviations between actual construction and planning intentions, triggers early warning mechanisms, and promotes the evolution of planning from a “static blueprint” to “dynamic governance,” comprehensively enhancing the precision of urban spatial management[2].

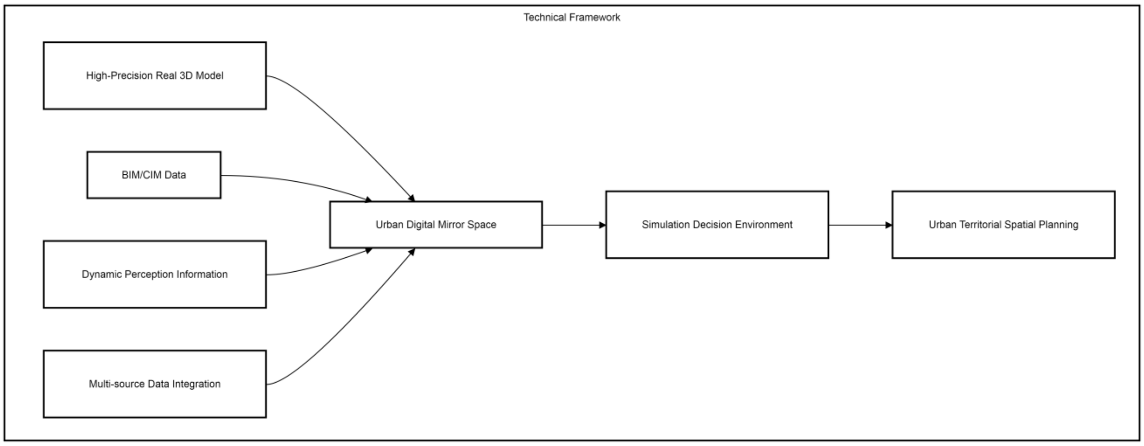

Figure 1. Digital Twin Visualization Platform

5.2 Traffic System Optimization and Travel Services

The geographical twin platform, by integrating dynamic data such as vehicle GPS trajectories, public transit IC card records, geomagnetic coils, and structured video detection, constructs a high-fidelity, real-time updated digital mirror of urban traffic, accurately reproducing the operational status of the road network and further clarifying travel behavior characteristics. This mirror not only supports retrospective analysis of historical traffic conditions but also serves as a simulation environment to anticipate and evaluate the road network response under traffic incidents, large-scale events, and extreme weather, providing visual support for management decision-making[3].

On this basis, the ST-ResNet spatiotemporal deep learning model utilizes historical and real-time traffic flow data to predict short-term traffic with high accuracy, effectively identifying frequently congested nodes and propagation paths. Combined with reinforcement learning algorithms, the signal control system can dynamically optimize phase durations based on real-time traffic conditions, enhancing intersection throughput[4]. For the public, the “Mobility as a Service” (MaaS) system fully integrates transportation resources including buses, subways, shared bicycles, and ride-hailing services, comprehensively considering individual travel preferences and real-time traffic conditions to autonomously generate personalized route recommendations. This promotes the evolution of urban transportation services from traditional supply-oriented to demand-responsive models, significantly improving travel efficiency and facilitating the development of intelligent urban traffic systems[5].

5.3 Environmental Monitoring and Ecological Protection Geographical Twin Technology

Geographical twin technology, by deeply integrating ground-based air quality monitoring stations, high-resolution remote sensing inversion data, and atmospheric diffusion numerical models, constructs a comprehensive “air–sky–ground” integrated environmental sensing system (see Figure 2). This system overcomes the limitations of traditional point-based monitoring, and, relying on advanced algorithms such as spatiotemporal kriging interpolation and Bayesian maximum entropy, reconstructs high-precision data in monitoring blind spots, generating hourly, 100-meter-resolution concentration fields for pollutants such as $PM_{2.5}$, NO_2, and O_3, achieving continuous representation of pollution distribution. On this basis, combined with meteorological fields and emission source inventories, it dynamically simulates the generation, accumulation, and diffusion processes of pollutants, providing a full-element digital foundation for environmental management[6].

Meanwhile, relevant organizations should actively introduce graph convolutional networks (GCN) to model urban road networks, wind fields, and pollution concentration fields, effectively identifying key channels and sensitive nodes of cross-regional pollutant transmission, accurately locating priority areas for collaborative governance, and supporting the development of air pollution prevention from “territorial control” to “regional joint prevention and control.” In the ecological protection dimension, based on landscape pattern indices on the geographical twin platform and combined with the minimum cumulative resistance model, the connectivity among ecological patches such as green spaces, water bodies, and mountains is quantitatively assessed, precisely identifying ecological fracture zones and scientifically guiding the construction of ecological networks[7]. This approach not only serves biodiversity conservation but also assists in delineating the core, buffer, and corridor management system of urban ecological security patterns, promoting the transition of ecological space from “fragmented protection” to “systematic restoration,” thereby consolidating the ecological foundation for high-quality urban development[8].

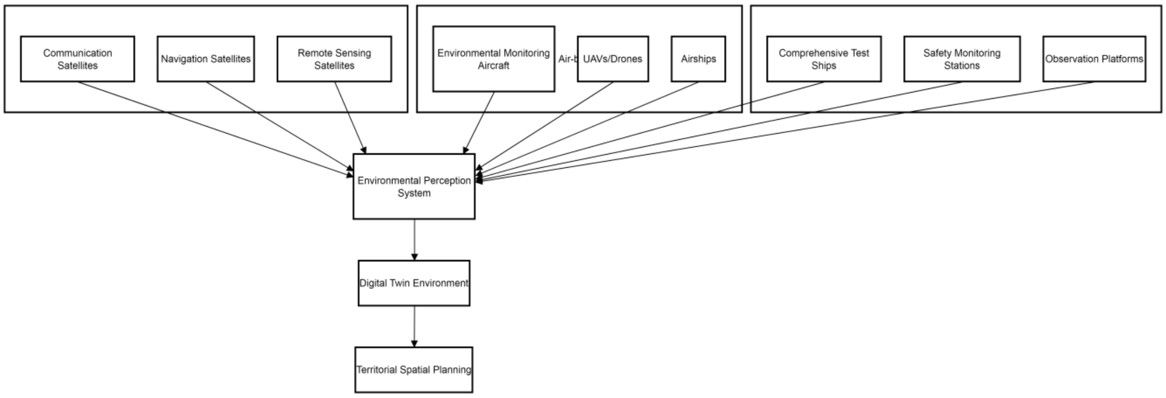

Figure 2. Construction of a "Air–Sky–Ground" Integrated Environmental Sensing System Covering the Entire Area

6. Conclusion

The technological synergy of geographical twins and spatiotemporal artificial intelligence provides a novel pathway for addressing governance issues in complex urban systems. By constructing digital representations of urban space, integrating multi-source sensing data, and employing intelligent algorithms to mine spatiotemporal patterns, it enables real-time perception of urban operational states, deep cognition of development laws, and accurate foresight of future trends. This technological integration drives a transformation in urban governance from experience-based judgment to data-driven approaches, from static planning to dynamic regulation, and from fragmented management to collaborative governance. With continued development of these technologies, geographical twins and spatiotemporal AI will exert greater value in urban assessment, spatial optimization, and risk prevention, providing robust technological support for building smart cities and contributing to the achievement of high-quality urban development goals.

References

[1] Duan, Y., & Dong, X. The Intrinsic Logic and Implementation Path of New-Quality Productivity in Promoting High-Quality Urban Development [J]. Journal of Xi'an Jiaotong University (Social Sciences Edition), 2025, 45(2):41-52.

[2] Ye, T. Implementing the Spirit of the Central Urban Work Conference to Promote High-Quality Urban Development [J]. Tianfu Review, 2025(5):1-7.

[3] Chen, Y., Liu, Y., & Cui, L. Research on Promoting High-Quality Urban Development through the "Internet Celebrity" Effect [J]. Learning Theory, 2025(1):76-82.

[4] Liu, H., & Wang, Q. Reflections on Empowering Resource-Based Cities for High-Quality Development through New-Quality Productivity [J]. Northern Economy, 2025(8):52-56.

[5] Zang, T., Fu, T., Zhang, L., et al. Research on High-Quality Development Path of Mega Cities Based on Park City Construction [J]. Landscape Architecture, 2025, 42(4):4-9.

[6] Shang, J. Construction and Measurement of Evaluation Index System for Trillion-Level Urban High-Quality Development [J]. China Economic and Trade Guide, 2025(8):64-66.

[7] Wei, W., & Tang, X. Research on the Path of Yellow River Wetland Ecological Protection and High-Quality Urban Development [J]. International Public Relations, 2025(7):137-139.

[8] Zhao, Y., & Fang, W. Impact of Innovative Urban Pilot Policies on High-Quality Urban Development [J]. Statistics and Decision, 2023, 39(22):178-182.