Proceedings of CONF-SEML 2026 Symposium: Multimodal Data Acquisition: Applications in Physiological and Behavioral Research
DOI: 10.54254/2755-2721/2026.AD33921

Integration of Low-Altitude Economy and Smart City: A Review of Big Data Collaborative Governance, AI Scenario Applications, and Construction Effectiveness

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Abstract. With the acceleration of global urbanization, ground space resources are becoming increasingly saturated. The low-altitude economy, a new growth pole of the spatial economy, is strategically important for the sustainable development of smart cities. This study aims to illustrate the thematic importance of the integration between the low-altitude economy and smart cities, and to analyze how to resolve the contradiction between the fragmentation of urban airspace resources and the complexity of security governance through technological means. This paper systematically reviews the current development status of the low-altitude economy at home and abroad, outlines the dynamic allocation logic of airspace under big data collaborative governance, and the application paths of artificial intelligence in specific scenarios. The results indicate that the large-scale development of the low-altitude economy highly relies on cross-departmental data sharing mechanisms and the precise support of AI algorithms. The conclusion points out that the deep integration of the low-altitude economy and smart cities can significantly improve urban operational efficiency, and proposes optimization directions for future construction in response to current challenges such as inconsistent standards and weak infrastructure.

Keywords: Low-altitude economy, Smart city, Big data collaborative governance, Artificial intelligence, Scenario application

1. Introduction

As a typical representative of new quality productive forces, the strategic value of the low-altitude economy has been clearly reflected in the national development blueprint [1]. Currently, the industrialization process in this field is showing obvious digital and intelligent characteristics. Especially under the deep empowerment of artificial intelligence technology, smart logistics and emergency response application scenarios based on the "perception-decision-execution" chain are accelerating from theoretical exploration to practical implementation [2]. This deep integration of technology and industry is not only an inevitable choice for the three-dimensional extension of smart city space, but also a key path to improving the comprehensive operational efficiency of the city. However, despite active breakthroughs in single-point technologies, the process of translating low-altitude technologies into practical industries still faces systemic obstacles such as lagging regulatory environments and fragmented governance models [1]. At present, the deepening development of this field is mainly constrained by the following bottlenecks: firstly, the lagging regulatory environment leads to obvious fragmentation characteristics in the spatial governance model; secondly, existing research mostly focuses on the performance optimization of single aircraft, leaving a research gap in the big data collaborative governance of the "air-ground integration" of smart cities; most prominently, there is a significant mismatch between current governance mechanisms and the actual efficacy of AI algorithms [2].

This study combines literature review and empirical case analysis, aiming to sort out the driving logic of low-altitude technology on urban industrial development and propose policy recommendations for potential management overlaps. This study provides a theoretical reference for future urban management departments to formulate three-dimensional transportation plans, striving to provide a predictive perspective for the intelligent evolution of the low-altitude economy under the constraints of the "dual carbon" goals.

2. Spatial digital intelligence

As a fundamental resource for the development of the low-altitude economy, the fragmented, heterogeneous, and dynamic characteristics of low-altitude geographic information have become the core bottleneck restricting the efficient utilization of airspace resources. Through a big data collaborative governance mechanism, decentralized geographic information can be transformed into computable, schedulable, and predictable digital assets, providing a solid foundation for the refined management and intelligent operation of low-altitude airspace [3].

2.1. Spatio-temporal coupling mechanism of multi-source heterogeneous data

Low-altitude airspace involves multi-source heterogeneous data such as meteorological conditions, geographic topography, aircraft trajectories, and environmental perception. In a three-dimensional dynamic environment, these data exhibit significant spatio-temporal asynchrony and semantic differences [4]. Under the traditional governance model, the phenomenon of data silos is prominent, leading to insufficient situational awareness capabilities and making it difficult to support real-time decision-making [2]. The spatio-temporal coupling mechanism aims to achieve the deep integration of multi-source data through a unified spatio-temporal representation framework. Specifically, firstly, standardized preprocessing is performed on meteorological data, geographic information, and trajectory data to establish a unified spatio-temporal coordinate system; secondly, feature alignment and dynamic mapping technologies are used to achieve synchronous integration of heterogeneous data in time series and spatial grids; finally, a high-performance computing platform is utilized to conduct real-time updates and feature extraction on the fused datasets [4]. The deployment of national supercomputing provides critical computational power support for this mechanism, improving the processing efficiency and accuracy of massive heterogeneous data through parallel computing and distributed processing algorithms [1]. This mechanism can effectively break the deadlock of fragmented governance. In smart logistics scenarios, real-time fusion of meteorological disturbances and trajectory data can optimize path planning; in emergency rescue scenarios, spatio-temporal coupling supports rapid environmental perception and obstacle avoidance decisions [2]. The above process enhances data availability and lays a computable foundation for subsequent conflict prediction and resource optimization, providing an important guarantee for the stable operation of the low-altitude economy under complex weather conditions.

2.2. Digital twin architecture for cross-domain collaborative governance

Digital twin technology provides a systematic architectural solution for cross-domain collaborative governance. This architecture generally adopts a four-layer structural design: the physical layer is responsible for real-time data collection, the data layer builds an integration base for multi-source heterogeneous data, the model layer realizes dynamic evolution modeling, and the application layer supports decision interaction and closed-loop feedback. On this basis, government regulatory departments, enterprise operating entities, and regulatory platforms can achieve cross-domain collaboration through standardized data sharing protocols. Specific protocols include data interface specifications, security authorization mechanisms, and privacy protection strategies, ensuring the trusted circulation and real-time synchronization of information among multiple entities [2]. The deployment of national supercomputing further strengthens the resilience of this architecture, supporting high-speed data integration and complex simulation computation through the computing power network, realizing the refined and real-time scheduling of airspace resources [1]. For example, in the physical-virtual bidirectional mapping, the digital twin model can synchronously update the physical airspace state and optimize management decisions through a feedback mechanism [4]. Under the constraint of the "dual carbon" goals, this architecture can also embed an energy efficiency optimization module to support green route planning and low-energy consumption scheduling [2]. Overall, the digital twin architecture not only solves the fragmentation problem of airspace governance but also provides a scalable and evolvable technical foundation for the high-quality development of the low-altitude economy, laying a unified data foundation for subsequent multi-mode coordination and intelligent scheduling.

3. Intelligence chain driven: AI scenario evolution based on "perception-decision-execution"

As the core driving force of the low-altitude economy, artificial intelligence injects an intelligent "soul" into low-altitude operations through the closed-loop technical chain of "perception-decision-execution," realizing a fundamental transformation from passive response to active optimization [3].

3.1. Ubiquitous perception and autonomous obstacle avoidance empowered by edge intelligence

Low-altitude airspace is characterized by high dynamics, strong uncertainty, and multi-dimensional constraints, making it difficult for traditional cloud-based AI to meet the low-latency requirements of real-time perception and decision-making. Edge intelligence significantly improves ubiquitous perception and autonomous obstacle avoidance capabilities by deploying AI models locally on UAVs or adjacent edge servers. The edge computing architecture migrates computing tasks to the network edge, effectively reducing data transmission latency and energy overhead, which is particularly suitable for low-latency responses in highly dynamic environments [5, 6]. Specifically, edge nodes can fuse multi-source sensor data (vision, LiDAR, environmental perception, etc.) in real time, build an adaptive spatio-temporal graph model, and dynamically focus on critical risk nodes through the attention mechanism to achieve precise obstacle detection and obstacle avoidance decision-making [5]. The low-altitude emergency event grade prediction model further deeply integrates the attention mechanism with the spatio-temporal graph neural network. Through adaptive spatial domain graph construction and gated spatio-temporal attention mechanisms, it achieves accurate representation and efficient prediction of dynamic risk modes, significantly outperforming mainstream spatio-temporal prediction models on low-altitude safety datasets, providing high-precision, interpretable algorithmic support for low-altitude safety early warning [7]. In low-altitude intelligent transportation systems, this mechanism can control perception latency to the millisecond level, supporting UAV autonomous obstacle avoidance in urban canyons and dynamic obstacle scenarios [6]. Edge intelligence also supports lightweight model inference, maintaining high-precision perception performance on resource-constrained UAV platforms, while providing reliable environmental semantic representations for the subsequent decision-making layer [5]. The processes not only enhance the safety of low-altitude operations but also lay a technical foundation for the smooth connection of the "perception-decision-execution" chain, effectively addressing the real-time challenges in the large-scale application of the low-altitude economy.

3.2. Task-oriented path planning and swarm intelligent scheduling

Taking smart logistics and emergency response as typical cases, the AI decision-making system achieves a synchronous improvement in energy efficiency optimization and task execution accuracy through task-oriented path planning and swarm intelligent scheduling under the constraint of the "dual carbon" goals [3]. Task-oriented path planning transforms multi-constraint optimization problems into a multi-objective decision-making framework, comprehensively considering range, energy consumption, time windows, and safety constraints. Two typical algorithms exhibit complementary advantages within this framework. Targeting multi-task environments, the improved Hunter-Prey Optimization (HPO) algorithm enhances population initialization randomness through chaotic mapping, and uses the golden sine strategy to optimize the population update mechanism, significantly enhancing global exploration capability and convergence speed. In 3D complex maps, this algorithm effectively solves the robustness and real-time issues of multi-UAV cooperative path planning [8]. In contrast, the joint trajectory planning and semantic communication design further deeply couples path optimization with communication resource allocation, proposing an attention-enhanced CNN proximal policy optimization (ACPPO) algorithm. By reconstructing the efficiency index (REI) to simultaneously quantify transmission power reduction and trajectory length maintenance, this algorithm achieves an optimal trade-off between power and trajectory. In urban low-altitude scenarios, it can reduce transmission power by up to 90.90% while trajectory length increases by only 3.80% [9]. The combined analysis of the two algorithms shows: the HPO algorithm excels in discrete multi-task global search and robust optimization, suitable for initial path generation under high-dimensional constraints; whereas the ACPPO algorithm performs exceptionally well in continuous trajectory fine-tuning and semantic communication constraints, making it particularly suitable for real-time, resource-constrained urban environments. The two complement each other to form a "global search + local refinement" mixed strategy, effectively addressing the synergistic optimization demand for energy consumption intensity and task accuracy under the "dual carbon" goals [3]. Swarm intelligent scheduling relies on a cross-modal cooperative control architecture to achieve task allocation and dynamic reconfiguration for multiple UAVs and multiple ground/surface platforms. In emergency response scenarios, distributed scheduling strategies can realize event-driven task reallocation based on real-time task demands and resource status; in smart logistics, swarm scheduling avoids resource conflicts and optimizes overall energy efficiency through hierarchical games and spatio-temporal resource prediction [10]. Under the premise of meeting the "dual carbon" goals, the AI decision-making systems significantly improve task execution accuracy and achieve the synergistic optimization of energy consumption intensity and emission factors, providing an operable technical path for the high-quality and sustainable development of the low-altitude economy [3].

4. Value transformation: construction effectiveness and resilience evaluation of low-altitude new quality productive forces

4.1. Digitalization effectiveness of three-dimensional transportation infrastructure

Digital transformation has significantly improved the utilization rate of physical facilities such as takeoff/landing pads and perception networks, providing a solid foundation for the large-scale release of low-altitude new quality productive forces [3, 6]. Through the integration of digital twins and edge intelligence, three-dimensional transportation infrastructure achieves real-time state mapping and intelligent scheduling, increasing the utilization rate of takeoff/landing pads by over 30%, while simultaneously improving the coverage density of perception networks and the accuracy of data fusion [6]. In the low-altitude intelligent transportation system, digitally transformed infrastructure can effectively divert ground traffic flow, alleviate urban congestion pressure, and simultaneously optimize energy structures and emission factors under the constraints of the "dual carbon" goals [3]. The deployment of large AI models further strengthens the intelligent level of infrastructure, significantly enhancing the overall operational efficiency of the system through the deep integration of environmental perception and resource perception [11, 12]. Quantitative evaluations show that this digitalization effectiveness improves the efficiency of the overall transportation system by 25%-40% and provides a highly reliable physical base for scenarios such as emergency response and smart logistics [12]. These achievements not only verify the substantial alleviating effect of infrastructure digitalization on ground traffic pressure but also highlight its strategic value as a core carrier of low-altitude new quality productive forces, laying a solid foundation for the extension and upgrading of the low-altitude economy industry chain.

4.2. Resilience measurement and bottleneck analysis of the industrial ecosystem

The current process of translating technology into industry is still at the low end of the technology maturity curve, and a lagging regulatory environment has become a key bottleneck restricting the release of "new quality productive forces" [1]. Employing a digital intelligent innovation ecosystem resilience evaluation system comprising five dimensions, including genetic reproduction, structural redundancy, and functional upgrading, empirical analysis shows that the national supercomputing layout can significantly enhance the quantity and quality of technological innovation in regional low-altitude economies, but some mechanistic paths are not yet scalable [1]. The deployment of large AI models further exposes systemic challenges such as resource constraints, environmental adaptability, and data security [11, 12]. The lack of standards and the fragmentation of airspace governance caused by lagging regulations directly limit the resilience and scalability of the industrial ecosystem [10]. Although cutting-edge technologies have made progress, the transition from the laboratory to practical deployment still faces bottlenecks, including computing resources, model generalization, and security guarantees [7]. Facing the above bottlenecks, it is necessary to accelerate the upward movement of the technology maturity curve through policy coordination, technological breakthroughs, and ecological construction, realize the value transformation of the low-altitude economy from "factor-driven" to "innovation-driven," and provide scientific guidance for building a sustainable and highly resilient low-altitude industrial ecosystem.

5. Conclusion

Through the deep deconstruction of the integration path of the low-altitude economy and smart cities, this paper demonstrates the inherent logic of three-dimensional spatial governance evolving from a physical form to a "computable entity." Research shows that constructing a big data collaborative governance system centered on low-altitude geographic information is the key foundation to overcome urban airspace fragmentation and governance failures; through the spatio-temporal coupling mechanism of multi-source heterogeneous data, it realizes the refined scheduling and dynamic allocation of airspace resources at the underlying logic level. At the technical application level, the AI-driven "perception-decision-execution" integrated architecture constitutes the core support for the large-scale implementation of low-altitude operations. The deep coupling of edge intelligence and digital twin technologies significantly enhances the autonomous obstacle avoidance accuracy and conflict prediction efficacy of aircraft in complex urban habitats, providing a quantified technical paradigm for the green transportation transition under the constraints of the "dual carbon" goals. However, the value transformation of low-altitude new quality productive forces is subject to the dual constraints of "technology maturity" and "institutional lag." The improvement of current industrial ecosystem resilience is still limited by the lack of cross-departmental data sharing protocols and the fragmentation of the regulatory framework, resulting in overall construction effectiveness remaining in the transition stage from point-based trials to full-domain collaboration. Future research should deeply focus on the standardized layout of integrated sensing and communication infrastructure, and prioritize the development of multi-agent cooperative algorithms with strong robustness, driving a fundamental transformation of governance models through technological iteration.

Significant limitations remain in this study. The penetrative analysis of proprietary algorithms and closed-source empirical data that have not yet been publicly disclosed within cutting-edge industries is still insufficient. It also leans towards qualitative review and logical deduction, lacking quantitative verification based on ultra-large-scale real-world urban operational datasets. Subsequent research should be optimized by conducting large-scale, multi-variable discrete event simulations and deep reinforcement learning experiments. From these dimensions, the evolutionary laws of low-altitude traffic flows can be accurately characterized, thereby providing more scientific quantitative evidence for three-dimensional urban governance decision-making.

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