

A Ground-Air Collaborative System Based on Digital Twin: Improving Urban Transportation Efficiency

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Received: October 22, 2025; Accepted: November 11, 2025; Published: November 12, 2025

Abstract

With the development of the low-altitude economy, it is essential to establish a coordinated urban transportation system integrating ground and air resources. Improving urban comprehensive transportation efficiency through technology has become an important topic of urban governance and sustainable development. The development of digital twin technology provides a new technical path for the solution of this problem. As a product of the deep integration of the new generation of information technology and urban governance, Digital twin technology shows great potential for application. This paper will focus on the key links in the ground-air coordination system, Explore the application path and technical support system of digital twin platform in the field of ground-air collaboration, and promote the transformation of transportation system from traditional empirical management to integrated, intelligent and refined direction.

Keywords: digital twin technology, ground-air collaborative system, urban transportation

1. Foreword Introduction

1.1 Research Background

With the rapid development of low-altitude economy, new business forms such as UAV logistics and air taxi are emerging rapidly, and urban airspace resources are increasingly becoming the core elements of the transportation system. However, the coordinated management of ground traffic network and low-altitude aircraft faces great challenges: the traditional airspace command system relies on manual scheduling and slow response speed; there is no dynamic interaction between ground traffic signals and UAV tracks, and the risk of conflict is high. According to statistics, in 2023, the global near-collision incidents between drones and ground facilities increased by 65% year on year, and there is an urgent need for technical means to solve this three-dimensional traffic management problem.

Digital twin technology provides important technical support for ground-air collaboration. By building a high-fidelity dynamic mirror of urban traffic, millimeter-level modeling of the airspace height layer and ground lane is realized, and the conflict scenario is pre-enacted and resource allocation is optimized with the help of reinforcement learning algorithm. For example, the Shenzhen pilot project shows that digital twins can reduce the response time of emergency drones by 70 percent while improving airspace utilization by 40 percent. This technology not only provides the core support for the safe and efficient operation of low-altitude economy, but also lays the technical foundation for the transformation of three-dimensional traffic governance paradigm in smart cities.

1.2 Purpose of Research

Under the background of accelerating urbanization and increasingly complex transportation system, how to improve the comprehensive transportation efficiency of cities and realize the coordinated development of land and air through advanced technology has become an important topic of urban governance and sustainable development. Improving the comprehensive transportation efficiency of the city by digital twin technology is not only helpful to optimize the allocation of transportation resources and improve the efficiency of urban operation, but also lays a solid foundation for exploring ground-air collaboration technology and realizing the goal of smart city construction. This paper will explore the application path and technical support system of digital twin platform in these fields around the key links in urban transportation system. Promote the transformation of the transportation system from traditional empirical management to integrated, intelligent and refined management. Promote the transformation

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1.3 Research Meaning

In terms of dispatching optimization of urban comprehensive transportation hubs, digital twin technology improves the operation efficiency of hubs and the travel experience of passengers by building a collaborative dispatching model of multiple modes of transportation and ground-air integration. At the same time, the closed-loop iteration mechanism between the digital twin model and the optimization algorithm enables the scheduling scheme to be adjusted and optimized continuously according to the real-time data, which enhances the adaptability and flexibility of the system. The application of digital twin technology in urban transportation field can not only promote the digital transformation of the traditional transportation system, but also has profound significance and value for promoting the development of ground-air integration.

2. Overview of Digital Twin Technology

Digital twin technology is an advanced technology based on the physical entity or system to build its digital mirror. Through real-time data collection, modeling, simulation, data analysis and feedback control, it realizes dynamic mapping of the physical world and intelligent decision support. Digital twin technology is widely used in industrial manufacturing, urban management, transportation dispatching, energy management and other fields, and has shown great potential in smart city and urban transportation management.

The working principle of digital twin technology mainly relies on three pillars: data acquisition, modeling and simulation, and intelligent analysis. First of all, through the deployment of sensors, cameras, GPS and other devices on physical entities, various operational data, including location, status, behavior, etc. , are collected in real time to form multi-source heterogeneous space-time big data. These data are cleaned, fused and structured as the input basis of the digital twin model. Secondly, based on the geometric structure, operation rules and interaction relationship of physical entities, a high-fidelity 3D digital model is constructed, and its operation state under different environments and conditions is simulated by the simulation engine. This process not only includes static modeling, but also emphasizes dynamic evolution, that is, the digital model can constantly update and adjust its state according to real-time data, to achieve a high degree of synchronization with the physical entity. Finally, with the help of artificial intelligence, big data analysis, knowledge graph and other technologies, the digital twin model is deeply mined to identify the operation rules, predict potential problems, and provide scientific basis for optimization decisions. For example, in urban transportation systems, digital twin platforms can simulate traffic flow changes, predict congestion trends, and compare the effects of different governance options through simulation, so as to assist managers in developing optimal strategies.

In recent years, digital twin technology has been expanding to the field of urban governance, promoting the arrival of the "digital twin city 2.0" era. At this stage, digital twin not only realizes the digital expression of urban static space, but also enhances the ability to describe dynamic "flow" and "field", so that the urban operation state can be perceived and precisely controlled in real time. For example, the introduction of traffic simulation platform makes urban traffic management shift from traditional empirical judgment to data-driven scientific decision-making, realizes the comprehensive monitoring of traffic operation situation, accurate identification of congestion causes and virtual simulation of governance plans, and significantly improves the intelligent level of urban traffic management. With the continuous maturity and deepening of the application of digital twin technology, its role in promoting the sustainable development of cities and improving the quality of public services will become increasingly prominent.

3. Overview of the Ground-to-air Coordination System

Ground-air coordination system is a highly integrated intelligent system, whose design goal is to realize the efficient coordination and information interaction between ground equipment and aerial vehicles. The system consists of multiple hardware and software modules that support its ability to operate in complex environments. In terms of hardware, the system mainly includes ground control terminal, communication relay equipment, aircraft platform and various sensors. In terms of software, the ground-air coordination system relies on the collaboration of multiple levels of software modules. The bottom layer is the embedded operating system and flight control software, which is responsible for the stable flight and basic control logic of the aircraft. The middle layer includes task planning and path optimization algorithm, communication protocol stack and data fusion module, which can automatically generate the optimal flight path according to the task goal, and ensure the efficient transmission and processing of data between different devices. The upper layer software includes human-machine interface, situational awareness system and intelligent decision support system, which clearly presents

flight status, mission progress and environmental information to operators through visual interface, and supports intelligent analysis and decision-making suggestions based on AI.

As an important part of modern urban transportation system, ground-air coordination system is becoming one of the key ways to improve urban transportation efficiency. With the acceleration of urbanization, the traditional two-dimensional transportation network has been unable to meet the increasing travel demand, and the problems of traffic congestion, resource waste and inefficient space utilization have become more and more prominent. In this context, the rise of low-altitude economy provides a new development dimension for urban transportation system.

By building a three-dimensional collaborative infrastructure system of "surface-low-altitude-underground", the urban transportation space can be expanded in three dimensions, which not only improves the efficiency of transportation resource allocation, but also provides a new idea for the optimal utilization of urban space. The continuous expansion of "low-altitude +" application scenarios such as UAV logistics, aerial emergency rescue and low-altitude freight has enabled the urban transportation system to realize more efficient resource allocation and dynamic scheduling in both time and space.

4. Application of Digital Twin Technology in Ground-Air Collaborative System

4.1 Data Modeling

In the context of increasingly complex urban transportation system, digital twin technology provides a new way of thinking and method for the construction of virtual model of urban transportation system. Digital twin technology can realize dynamic perception and simulation analysis of traffic system operation state by modeling and mapping information of traffic facilities, operation status and passenger behavior in the virtual space with high precision. First of all, the construction of digital twin model of urban transportation system requires three-dimensional modeling of physical elements such as transportation hub, road network, public transportation lines and various kinds of transportation vehicles, and the combination of geographic information system (GIS) to realize accurate positioning and visualization of spatial information. At the same time, by integrating sensor network, video surveillance, card swiping records, GPS positioning and other multi-source data, the digital twin system can obtain dynamic information such as traffic flow, vehicle running status and passenger transfer behavior in real time, providing continuous data support for the model.

4.2 Real Time Protection, Real Time Monitoring

As an important support for the development of smart cities, digital twin technology is showing great potential in the field of traffic management, especially in the real-time monitoring of urban traffic conditions. By building a virtual model highly synchronized with the real urban traffic system and an integrated ground-air monitoring model, the digital twin technology can realize the real-time collection and analysis of multi-dimensional data such as traffic flow, road status, vehicle operation, air route planning and aerial aircraft, providing scientific decision support for urban traffic management. In this process, the Internet of Things sensing devices, including cameras, radars, sensors, etc. , play a key role. They are deployed at key nodes of the road to continuously collect traffic operation data, such as vehicle speed, vehicle distance, vehicle flow, airspace route conditions and traffic light status, to provide data basis for the digital twin system. At the same time, digital twin technology can also integrate environmental factors such as weather, wind speed and visibility, and even consider the impact of non-motor vehicles such as pedestrians and pets on traffic, so as to build a more comprehensive and accurate picture of urban traffic operation. With the help of big data and artificial intelligence technology, the digital twin system can carry out in-depth mining and intelligent analysis of the massive traffic data collected, which can not only reflect the current traffic situation in real time, but also predict the future traffic trend.

4.3 Forecast and Optimize

Digital twin technology is playing an increasingly important role in traffic flow prediction and optimal scheduling. By building a virtual model highly synchronized with the real traffic system, it realizes real-time perception, dynamic simulation and intelligent decision-making of traffic operation state. In terms of traffic flow prediction, digital twin technology relies on the fusion and analysis of multi-source heterogeneous data, combined with artificial intelligence, big data mining and deep learning, and can accurately identify and predict the spatial and temporal distribution characteristics, periodic laws and sudden abnormal behaviors of traffic flow. For example, by building a three-dimensional intelligent computing engine integrating "time-space-semantic-entity", the digital twin system can model and predict key indicators such as traffic flow density, traffic speed and congestion trend in the urban road network in real time, so as to provide scientific prediction basis for traffic management departments. Compared with traditional static prediction models, digital twins have stronger dynamic adaptability

and can constantly adjust the prediction results according to real-time traffic data to improve the accuracy and timeliness of prediction.

In terms of scheduling optimization, the digital twin technology realizes the efficient linkage between the physical traffic system and the virtual model through the virtual and real interactive feedback mechanism. Based on the digital twin platform, the traffic dispatching system can simulate the operation effect of various dispatching strategies, evaluate the comprehensive performance of different schemes in terms of capacity matching, passenger transfer time, traffic efficiency, etc. , so as to provide data support for the formulation of the optimal dispatching scheme. For example, for the problem of coordinated dispatch of multiple modes of transportation in urban integrated transportation hubs, the digital twin model can integrate passenger flow prediction results, passenger walking path simulation data and infrastructure operation status, build a transport capacity coordination and optimization model and a departure time interval optimization model, and realize the dynamic allocation of transport capacity resources and the closed-loop iteration of dispatching scheme. In addition, the digital twin technology also supports multi-dimensional simulation testing and risk rehearsal, which helps to identify potential problems before actual scheduling and reduce the risk and cost of scheduling decisions.

5. Challenges and Countermeasures

In the future development of digital twin transportation system, although it shows great potential in transportation governance and urban operation optimization, there are still many challenges between technological evolution and social application. From a technical point of view, the system relies on high-precision modeling, multi-source data fusion, real-time simulation and prediction capabilities, which are still faced with problems such as uneven data quality, insufficient model generalization ability and high consumption of computing resources. For example, the collection of traffic data is often limited by the coverage density and accuracy of sensors, especially in complex road networks and multi-mode traffic scenarios. How to achieve data integrity and consistency is still a technical bottleneck.

In addition, the simulation capability of digital twin system needs to take into account both accuracy and real-time performance, which puts forward higher requirements for algorithm optimization and computing power support. To address these challenges, we should strengthen the governance of basic data, promote the construction of urban-level transportation data platforms, and realize the standardized access and sharing of data across departments and systems. At the same time, we should increase the integration and application of emerging technologies such as artificial intelligence, edge computing and cloud computing to improve the intelligence and responsiveness of the system.

From a social perspective, the widespread use of digital twin systems may lead to social issues such as privacy protection, ethical responsibility, and public trust. Traffic data contains a large number of sensitive information such as individual travel trajectory and vehicle behavior. How to protect user privacy in the process of data collection, processing and application is the key to the sustainable development of the system. In addition, although the decision-making suggestions of the digital twin system are based on data analysis, their final impact is on the traffic operation in the real world and the travel experience of residents. Therefore, transparent mechanisms should be introduced in the system design and application to ensure that the decision-making process is interpretable and supervised. To this end, a sound data security and privacy protection system should be established, the development of traffic data anonymization, encryption and access control technology should be promoted, and public education and participation should be strengthened to improve the social awareness and acceptance of digital twin technology.

In addition, the development of digital twin transportation system needs to face the resistance of the transformation of traditional transportation management mode. For a long time, traffic management has relied on empirical judgment and single indicator analysis, while digital twin system emphasizes data-driven, multi-dimensional evaluation and dynamic optimization. This change of concept and method may encounter institutional inertia and implementation resistance. Therefore, promoting collaborative innovation between traffic management agencies and technicians, and establishing organizational structure and workflow adapted to the digital twin system, are important guarantees for realizing the system value. At the same time, through pilot demonstration and policy guidance, the in-depth application of digital twin technology in traffic governance should be gradually promoted, and a new paradigm of urban traffic operation with data as the core should be constructed.

6. Future Expectations, Vision of the Future, Future Tendency, Future Prospects

With the continuous breakthrough of cutting-edge technologies such as artificial intelligence, big data and metaverse, the application of digital twin technology in transportation system will move to a higher level of intelligence and collaboration. Through deep learning and reinforcement learning technology, the system will be

able to simulate the changing trend of traffic flow more accurately, predict congestion hot spots in advance, and automatically recommend the best management plan, so as to realize the transformation from "passive response" to "active intervention". The development of metaverse technology will provide a new way of interaction for traffic simulation and public participation. With the help of immersive virtual reality environment, traffic managers and the public will be able to experience the implementation effect of traffic management solutions from the first perspective, enhance the transparency of decision-making and public participation, and promote the evolution of traffic management from closed management to open collaboration. In this process, the traffic simulation platform will not only serve as a technical tool, but also become the core of urban traffic management, supporting the whole life cycle management from planning, construction to operation, and injecting strong impetus for the construction of smart city.

The further research direction and suggestions should focus on the deepening application of digital twin technology in the coordinated dispatch of multiple transportation modes in urban comprehensive transportation hubs. In terms of application scenario expansion, digital twin technology can be extended from transportation hub scheduling to urban transportation network optimization, public transportation service improvement, emergency response system construction and other fields, explore its comprehensive value in the construction of smart city, and promote the urban transportation system to a more intelligent, efficient and green direction.

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