# Low-Altitude Infrastructure for Large-Scale Operation: System Composition, Construction Paths, and Key Challenges<sup>*</sup>

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## Abstract

Low-altitude infrastructure is an important foundation supporting the organization, management, and safe operation of low-altitude flight activities, and its level of development directly affects the large-scale development of the low-altitude economy. However, the industry still lacks a clear and consensual definition of its system composition, which to some extent constrains a unified understanding and in-depth comprehension of its connotation. Based on the practical demands of low-altitude economic development for low-altitude infrastructure, this paper systematically reviews and analyzes it from three aspects: system composition, construction pathways, and key challenges. The study divides low-altitude infrastructure into two major categories: physical infrastructure and information infrastructure. The former is centered on takeoff and landing facilities and ground support facilities, providing physical conditions and basic support for low-altitude flight; the latter encompasses low-altitude communication and sensing facilities, a digital base, and a low-altitude traffic management system, providing key support for the safety and orderliness of flight activities through continuous perception and organizational management of the operating environment, flight status, and airspace resources. In response to the current situation in which the integrity of the infrastructure system is insufficient and its operational support capability is difficult to match the future demand for high-density and large-scale operations, this paper proposes that emphasis should be placed on strengthening refined airspace management, communication, navigation, and surveillance support, the construction of the digital base and traffic management system, and the improvement of multi-stakeholder collaborative governance mechanisms. Meanwhile, continuous verification and iterative optimization should be conducted in combination with typical scenarios such as logistics delivery, emergency rescue, and inspection operations, so as to promote the evolution of low-altitude infrastructure from point-based demonstrations toward systematic and networked operations, thereby providing solid support for the safe, orderly, and sustainable development of the low-altitude economy.


## Full Text

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**Abstract:** Low-altitude infrastructure is an important foundation supporting the organization, management, and safe operation of low-altitude flight activities, and its level of development directly affects the scaled development of the low-altitude economy. However, the current industry still lacks a clear and consensus-based definition of its system composition, which to a certain extent constrains unified cognition and in-depth understanding of its connotation. Based on the practical needs of low-altitude economic development for low-altitude infrastructure, this paper systematically reviews and analyzes it from three aspects: system composition, construction paths, and key challenges. The study divides low-altitude infrastructure into two major categories: physical infrastructure and information infrastructure. The former is centered on takeoff-and-landing facilities and ground support facilities, providing physical conditions and basic safeguards for low-altitude flight; the latter encompasses low-altitude communication and sensing facilities, digital foundations, and low-altitude traffic management systems, providing key support for the safety and orderliness of flight activities through continuous sensing and organizational management of the operating environment, flight status, and airspace resources. In view of the current deficiencies in the completeness of the infrastructure system and the difficulty of matching operational support capabilities with future high-density, large-scale demands, this paper proposes that emphasis should be placed on strengthening refined airspace management, communications-navigation-surveillance support, construction of digital foundations and traffic management systems, and improvement of multi-actor collaborative governance mechanisms. At the same time, typical scenarios such as logistics delivery, emergency rescue, and inspection operations should be used for continuous verification and iterative optimization, promoting the evolution of low-altitude infrastructure from point-based demonstrations toward systematic and networked operation, thereby providing solid support for the safe, orderly, and sustainable development of the low-altitude economy.

**Keywords:** low-altitude economy; low-altitude infrastructure; system architecture; physical infrastructure; information infrastructure

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**Abstract:** Low-altitude infrastructure serves as a crucial foundation for organizing, managing, and ensuring the safe operation of low-altitude flight activities. Its construction level directly impacts the large-scale development of the low-altitude economy. However, the current industry still lacks a clear and consensus definition of its system composition, which to some extent restricts unified cognition and in-depth understanding of its connotation. Based on the practical needs of low-altitude economic development for low-altitude infrastructure, this paper systematically analyzes the system composition, construction path, and key challenges. The research divides low-altitude infrastructure

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into two major categories: physical infrastructure and information infrastructure. The former primarily consists of takeoff and landing facilities and ground support facilities, providing physical conditions and basic support for low-altitude flight. The latter encompasses low-altitude communication and perception facilities, digital platforms, and low-altitude traffic management systems. Through continuous perception and organizational management of the operating environment, flight status, and airspace resources, it provides crucial support for the safety and orderliness of flight activities. In response to the current situation where the integrity of the infrastructure system is insufficient and operational support capabilities struggle to match future high-density large-scale demands, it is proposed to focus on strengthening the refinement of airspace management, communication, navigation, and surveillance support, the construction of digital platforms and traffic management systems, and improving multi-agent collaborative governance mechanisms. At the same

time, continuous verification and iterative optimization should be conducted in conjunction with typical scenarios such as logistics distribution, emergency rescue, and inspection operations, promoting the evolution of low-altitude infrastructure from point-like demonstration to systematic and networked operation, thus providing solid support for the safe, orderly, and sustainable development of the low-altitude economy.

**Key words:** Low-altitude economy; low-altitude infrastructure; architecture; physical infrastructure; information infrastructure

# 1 Introduction

The low-altitude economy is a comprehensive economic form that relies on low-altitude airspace resources, is driven by low-altitude flight activities of various manned and unmanned aircraft, and promotes the coordinated and integrated development of related fields. Owing to its long industrial chain, broad coverage, strong growth potential and driving capacity, and green and environmentally friendly characteristics, the low-altitude economy has attracted extensive attention worldwide and is a typical representative of new-quality productive forces. In December 2023, the Central Economic Work Conference identified it as a national strategic emerging industry; in 2024, the low-altitude economy was written into the State Council Government Work Report for the first time[1].

To develop the low-altitude economy, infrastructure must come first. Low-altitude infrastructure connects the upstream and downstream of the low-altitude economy industrial chain and provides support services such as takeoff and landing, communications, navigation, and airspace monitoring for safe low-altitude flight; it is the key to the rapid scaled development of the low-altitude economy[2]. In the future, high-density flight involving a mixture of manned/unmanned low-altitude aircraft—including low-altitude unmanned aerial vehicles, electric vertical takeoff and landing aircraft (eVTOL), short-range takeoff and landing aircraft, and flying cars—will become an important development trend[3]. Because the low-altitude environment is complex and variable, densely populated, and subject to numerous flight constraints, the disorderly operation of large numbers of low-altitude aircraft will require low-altitude infrastructure—such as ground facilities and public safety systems that remain to be improved—to solve the safety problems of various low-altitude aircraft in low-altitude airspace, namely that they are "invisible, unreachable, and unmanageable," and to address the safety, efficiency, and cost problems in scaled low-altitude flight characterized by "heterogeneity, high density, high frequency, and high complexity."

**Figure 1. Text in the diagram:**

[1] Reference [1] as cited in the source page.
[2] Reference [2] as cited in the source page.
[3] References [3-4] as cited in the source page.

- **Key to the rapid scaled development of the low-altitude economy**
- **Upstream: production and manufacturing**
  - **Complete aircraft manufacturing**
    - Consumer-grade UAV
    - Industrial UAV
    - Military/police UAV
    - eVTOL
  - **Core components**
    - Avionics
    - Flight control
    - Chip module
    - Battery
    - Motor
    - Airframe materials
- **Midstream: infrastructure**
  - **Physical infrastructure**
    - Takeoff and landing station
    - Airport
    - Energy station
    - Traffic standard system
  - **Information infrastructure**
    - Communication network
    - Positioning network
    - High-precision map
    - Meteorological network
    - Route network
    - Supervision platform
- **Downstream: industry applications**
  - **Consumption**
    - Tourism
    - Film and television
    - Passenger transport
  - **Industry services**
    - Logistics distribution
    - Agriculture, forestry, and plant protection
    - Geographic surveying and mapping
    - Industrial inspection
  - **Public services**
    - Emergency rescue
    - Forest firefighting
    - Event security
    - Urban security
- **Low-altitude economy industrial chain**

**Figure 1 Industrial chain of the low-altitude economy**

Low-altitude infrastructure, and its supporting role in the development of the low-altitude economy, has attracted considerable attention from the central government and local governments at all levels. At the 16th collective study session of the Political Bureau of the CPC Central Committee on July 30, 2024, General Secretary Xi Jinping clearly stated that China should do a good job in national air traffic management and promote the healthy development of the low-altitude economy[5]. The *Statistical Classification of the Low-Altitude Economy and Its Core Industries (Trial)* issued by the National Development and Reform Commission has listed low-altitude infrastructure and information services as important components of the core industries of the low-altitude economy[6]. Current local action plans for promoting the development of the low-altitude economy have also proposed that low-altitude infrastructure systems should be planned, built, and improved ahead of demand. For example, the *Action Plan of Guangdong Province for Promoting the High-Quality Development of the Low-Altitude Economy* proposes moderately forward-looking deployment of low-altitude infrastructure[7]; Anhui Province' s *Implementation Plan and Several Measures for Accelerating the Cultivation and Development of the Low-Altitude Economy (2024–2027)* lists the coordinated co-construction of low-altitude intelligent connected infrastructure as the foremost key task[8]; Beijing' s *Action Plan for Promoting the High-Quality Development of the Low-Altitude Economy Industry (2024–2027)* calls for optimizing the layout of low-altitude infrastructure, strengthening the construction of takeoff-and-landing and service-support sites, building low-altitude air routes and flight paths, and enhancing communications, navigation, sensing, and low-altitude intelligent connectivity capabilities[9]; and Henan Province' s *Implementation Plan for Promoting the High-Quality Development of the Province-Wide Low-Altitude Economy (2024–2027)* likewise proposes balancing current and long-term needs, coordinating the requirements of manned and unmanned aircraft, scientifically laying out ground takeoff-and-landing, low-altitude communications, and service-support facilities, and improving the infrastructure network system[10].

However, low-altitude infrastructure, which is positioned in the middle reaches of the low-altitude economy industrial chain, is still at an early stage of development. Its system composition has not yet been clearly and consensually defined, which constrains a unified understanding and in-depth comprehension of its connotations across the industry. In the *White Paper on the Development of the Low-Altitude Economy (2.0)—A Fully Digital Solution*, the Guangdong–Hong Kong–Macao Greater Bay Area Digital Economy Research Institute proposes the concept of "low-altitude intelligent integrated infrastructure" and divides it into a facility network, an air-connected network, an air-route network, and a service network[11]. The facility network refers to various physical infrastructures that support low-altitude flight operations, such as takeoff-and-landing stations and energy stations; the air-connected network refers to information infrastructures such as communications, navigation, and sensing; the air-route network refers to the core platform that provides digital management and service capabilities for airspace and flights; and the service network refers to applications constructed by combining digital management and service capabilities to empower various management and business entities in the low-altitude economy. China Mobile' s *White Paper on the Technical System of the Low-Altitude Intelligent Internet* proposes the concept of the low-altitude intelligent Internet, defining it as a networked, digital, and intelligent system built on an integrated space–air–ground network and incorporating information and communications, artificial intelligence, and big-data technologies, thereby realizing integrated services for low-altitude communications, navigation, and supervision[2]. The Low-Altitude Industry Alliance' s *Reference Architecture for the Low-Altitude Intelligent Connected System* divides the low-altitude intelligent connected system into an onboard terminal and infrastructure layer, a data and service support layer, and an application system layer[12]. The onboard terminal and infrastructure layer covers low-altitude vehicles, avionics systems, and information-physical infrastructures such as communications, navigation, surveillance, meteorology, and takeoff-and-landing facilities; the data and service support layer realizes unified data access and distribution through access networks, switching networks, and service networks; and the application system layer includes operation management systems, low-altitude traffic management and service systems, and infrastructure support systems. In its *White Paper on Integrated Communications-and-Sensing Low-Altitude Networks*, China Telecom proposes that low-altitude networks are intelligent, interconnected, digital service systems that integrate communications, sensing, and computing by relying on infrastructures such as cellular mobile communications, the Internet of Things, and cloud computing; their functional architecture is divided into an application layer (serving industry users in emergency rescue, agriculture and forestry plant protection, logistics distribution, and other sectors) and a functional layer (providing communications, sensing, intelligent computing, and other capabilities)[13]. The *Research Report on the Development of Low-Altitude Infrastructure (2025)* by the Low-Altitude Economy Branch of the China Information Association points out that low-altitude infrastructure mainly includes ground support facilities and information infrastructure[14]. Among these, ground support facilities cover five major categories: general aviation airports, aviation flight camps, vertical takeoff-and-landing sites, flight service stations, and fixed-base operations; information infrastructure mainly includes low-altitude communications systems, low-altitude navigation systems, low-altitude surveillance systems, low-altitude meteorological systems, low-altitude security systems, and low-altitude digital bases. The *Framework Guidelines for Low-Altitude Economy Infrastructure (2025)*, researched and compiled by the China Civil Airports Association, proposes that the infrastructure of the low-altitude economy includes low-altitude air traffic management infrastructure, low-altitude takeoff-and-landing infrastructure, supporting infrastructure for low-altitude industries, and supporting infrastructure for low-altitude application scenarios, thereby extending the scope of infrastructure to various facilities in industrial support and application scenarios[15].

Based on existing literature and industry reports, this paper systematically reviews the core constituent elements and functional positioning of low-altitude infrastructure, clarifies its system architecture, and, on this basis, explores feasible future construction pathways and the key challenges it faces. This paper aims to deepen understanding of low-altitude infrastructure across different sectors, provide a reference basis for the planning and construction of low-altitude infrastructure, and help China' s low-altitude economy enter a new stage of high-quality development.

## 2 System Composition of Low-Altitude Infrastructure

As low-altitude flight activities evolve from applications in a single scenario toward operation in multiple scenarios at scale and on a routine basis, low-altitude infrastructure is no longer confined to takeoff and landing sites or flight-support facilities; rather, it is gradually developing into an integrated system collaboratively supported by multiple types of elements. As shown in Figure 2, from the perspective of system architecture, this paper divides the core constituent elements of low-altitude infrastructure into two major categories: physical infrastructure and information infrastructure. The former is mainly responsible for the physical carrying capacity required for aircraft operation and for ground-support functions, while the latter provides the information sensing, computing, and exchange capabilities necessary for low-altitude operations. On this basis, the low-altitude infrastructure system can be further divided into five interrelated components: takeoff and landing facilities, ground-support facilities, low-altitude communication and sensing facilities, a low-altitude digital base, and a low-altitude traffic management system. Together, these components constitute the foundational architecture that supports safe, orderly, and efficient development of low-altitude operations.

Text in Figure 2:

- Aircraft
- Third-party systems
- Airspace management personnel
- Information infrastructure
    - Low-altitude traffic management system
        - Low-altitude traffic services
            - Low-altitude traffic control
            - Flight information
            - Alerting services
        - Low-altitude traffic flow management
            - Flow analysis and prediction
            - Flow control
        - Low-altitude airspace management
            - Airspace classification
            - Route planning
            - Dynamic airspace allocation

  - Low-altitude digital base
    - Data pool
      - Basic geographic data
      - Obstacle data
      - Flight-facility data
      - Airspace-structure data
      - Route-network data
      - Dynamic operational data
    - Computing-power pool
      - Heterogeneous computing resources
      - Cross-domain computing-power integration
      - Computing-power on-demand scheduling
      - Elastic load balancing
      - Communication-fusion processing
      - Safe operation and maintenance assurance
    - Intelligence pool
      - Dynamic route planning
      - Airspace capacity assessment
      - Meteorological risk prediction
      - Airspace grid partitioning
      - Multi-source data fusion
      - Three-dimensional visualization
  - Low-altitude communication and sensing facilities
    - Communication facilities
    - Navigation facilities
    - Surveillance and countermeasure facilities
    - Meteorological facilities

- Physical infrastructure
  - Takeoff and landing facilities
    - eVTOL takeoff and landing airport
    - Helicopter airport
    - UAV takeoff and landing site
    - Emergency alternate landing site
  - Ground-support facilities
    - Hangar
    - Maintenance and upkeep facilities
    - Charging and battery-swapping facilities
    - Emergency rescue facilities

**Figure 2. System architecture of low-altitude infrastructure**

### 2.1 Physical Infrastructure

Low-altitude physical infrastructure refers to the various carriers that objectively exist in the physical environment and support low-altitude flight activities.

It mainly includes two major parts: takeoff and landing facilities and ground-support facilities, as shown in Table 1. They constitute the material foundation for ensuring the safe, efficient, and sustainable operation of low-altitude aircraft.

**(1) Takeoff and landing facilities** Takeoff and landing facilities are the physical sites that support low-altitude aircraft such as UAVs, helicopters, and eVTOLs in completing takeoff, landing, and temporary parking, and they are nodes in the low-altitude flight network. Depending on differences in service objects and operating modes, takeoff and landing facilities mainly include the following three categories: 1) general airports and general-aviation takeoff and landing bases, which are usually equipped with facilities such as runways, taxiways, and terminal buildings, mainly serve small fixed-wing aircraft and helicopters, and undertake takeoff, parking, and dispatching functions at the regional hub level; 2) vertical takeoff and landing sites, covering helicopter pads and emerging eVTOL pads, whose core components include final approach and takeoff areas, safety areas, and approach lighting systems, and which are key nodes for meeting the demand for vertical takeoff and landing in urban air transportation; 3) UAV take-

landing sites and automated drone nests. They typically integrate automatic charging, battery-swapping modules, and edge-computing units, support fully automated operations by drones for logistics delivery and inspection, and constitute the basic units for achieving high-density coverage of low-altitude logistics networks.

(2) Ground support facilities

Ground support facilities are built in conjunction with takeoff and landing facilities, and provide various services for aircraft, including parking, energy replenishment, maintenance, cargo/passenger transfer, and emergency support. As shown in Table 1, ground support facilities specifically include: parking and storage facilities, such as hangars and aprons, used for aircraft parking and protection; energy replenishment facilities, covering charging/battery-swapping stations for electric aircraft, fuel-refueling stations for conventional fuel-powered aircraft, and hydrogen-refueling stations; maintenance facilities, providing regular inspection, troubleshooting, and aviation-material storage services; and passenger/cargo transfer and safety emergency facilities, used to realize seamless transfer of personnel and goods as well as safety support such as firefighting and rescue.

Table 1: Composition and Functional Description of Low-Altitude Physical Infrastructure

| Facility category | Subtype | Main constituent elements | Core functions and uses |
|---|---|---|---|
| Takeoff and landing facilities | General aviation airport / takeoff and landing base | Runways, taxiways, aprons, simple terminal buildings, control towers | Serve fixed-wing aircraft and helicopters, providing regional-hub-level takeoff and landing, parking, and passenger-service functions. |
| Takeoff and landing facilities | Vertical takeoff and landing site | Landing pads, safety zones, navigation aid lighting, wind vanes | Designed specifically for helicopters and eVTOLs, addressing the need for vertical takeoff and landing in urban air transport; they can be built on rooftops or on the ground. |
| Takeoff and landing facilities | UAV takeoff and landing site / drone nest | Hardened platforms, automatic hatch covers, charging/battery-swapping modules, edge-computing units | Support automatic takeoff, landing, and return-to-nest operations for multirotor UAVs, and serve as basic units for building logistics and inspection networks. |
| Ground support facilities | Parking and storage facilities | Aprons, hangars, etc. | Provide aircraft parking space, protect equipment from environmental impacts, and prevent unauthorized access. |

| Facility category | Subtype | Main constituent elements | Core functions and uses |
|---|---|---|---|
| Ground support facilities | Energy replenishment facilities | Charging piles / battery-swapping stations, aviation-fuel refueling equipment, hydrogen-refueling stations, etc. | Provide aircraft with replenishment of power sources, and constitute core support for ensuring flight frequency and endurance. |
| Ground support facilities | Maintenance facilities | Maintenance hangars, aviation-material spare-parts warehouses, testing-tool rooms | Carry out routine inspections, scheduled maintenance, and overhauls to ensure that aircraft continuously meet airworthiness standards. |
| Ground support facilities | Passenger and cargo transfer facilities | Cargo sorting areas, loading and unloading platforms, waiting areas, security-check areas | Enable efficient connection between low-altitude transport and ground transport/warehousing, improving logistics efficiency and passenger experience. |
| Ground support facilities | Safety and emergency facilities | Firefighting equipment, emergency alternate-landing signs, perimeter security, etc. | Respond to emergencies such as fires and forced landings, safeguard personnel and property, and meet air-defense security requirements. |

## 2.2 Information Infrastructure

Compared with physical infrastructure such as takeoff and landing facilities and ground support facilities, information infrastructure undertakes the sensing, computing, and exchange of various types of information in the low-altitude operation system, and is a key foundation for realizing safe, orderly, and efficient operation of low-altitude flight activities. As the scale of low-altitude flight activities continues to expand and operating scenarios become increasingly complex, relying solely on traditional physical facilities can no longer meet the needs of refined management and dynamic operations. It is therefore necessary to build a low-altitude operation support system centered on information systems. In terms of system composition, low-altitude information infrastructure is not a single system, but is instead collaboratively composed of multilevel and multifunctional information systems, mainly including three core components: low-altitude communication and sensing facilities, a low-altitude digital base, and a low-altitude traffic management system. These three components respectively undertake sensing of the low-altitude environment, information on various low-altitude elements

the aggregation and processing of information, as well as functions such as the organization of flight activities and operational management and control, together constitute the basic information architecture that supports low-altitude operations.

(1) Low-altitude communications and sensing facilities

Low-altitude communications and sensing facilities are a core component of low-altitude information infrastructure. Their principal function is to achieve comprehensive, real-time, and precise control over low-altitude flight activities and their operating environment through multi-source sensing and information interaction. As shown in Figure 3, from the perspective of system composition, low-altitude communications and sensing facilities mainly consist of communications facilities, navigation facilities, surveillance and countermeasure facilities, and meteorological facilities. Their functions include multiple aspects such as obtaining aircraft status, determining position and trajectory, identifying operational risks, and sensing environmental conditions. Communications facilities ensure stable information interaction between aircraft and ground systems through methods such as 5G-A, low-orbit satellites, and high-frequency communications[16–17]; navigation facilities rely on satellite navigation, ground-based augmentation, and visual navigation technologies to provide continuous and reliable position and attitude information for low-altitude flight; surveillance facilities use methods such as ADS-B, Remote ID, and low-altitude radar to identify, track, and supervise cooperative and non-cooperative targets in low-altitude airspace[18]; meteorological facilities obtain key meteorological elements affecting low-altitude flight safety through equipment such as weather radar, wind-profiler radar, and meteorological stations.

**Low-altitude communications and sensing facilities**

- **Communications facilities**
  - 5G-A
  - Low-orbit satellites
  - VHF communications
- **Navigation facilities**
  - Satellite navigation
  - Ground-based augmentation
  - Visual navigation
- **Surveillance and countermeasure facilities**
  - ADS-B
  - Remote-ID
  - Low-altitude radar
  - Radio interference
  - High-energy laser
- **Meteorological facilities**
  - Weather radar
  - Meteorological stations
  - Wind-profiler radar

*Figure 3. Composition of low-altitude communications and sensing facilities*

(2) Low-altitude digital foundation

On the basis of the data acquired by low-altitude communications and sensing facilities, the low-altitude digital foundation undertakes the core functions of data integration, spatial representation, and operational simulation, and serves as the basic operating platform for the entire low-altitude information infrastructure. Unlike a single business system, the low-altitude digital foundation is oriented toward the overall environment of low-altitude operations. Its objective is to aggregate, fuse, store, and model basic geographic data as well as raw data from sensing facilities such as communications, navigation, surveillance, and meteorology, thereby constructing a computable low-altitude digital space that closely corresponds to real-world low-altitude airspace.

As shown in Figure 2, the low-altitude digital foundation is mainly composed of three core elements: a data pool, a computing-power pool, and an intelligence pool. The data pool accesses and aggregates full-element spatiotemporal data, including basic geographic data such as road networks and terrain/landforms, obstacle data, flight-facility data, airspace-structure data such as suitable-flight areas and no-fly zones, route-network data, and dynamic operational data such as meteorological conditions and route traffic conditions, thereby providing accurate and trustworthy spatial information support for low-altitude flight. The computing-power pool is the heart and power source of the low-altitude digital foundation, providing a powerful computing engine. By managing heterogeneous computing resources in the cloud, at the edge, and on the aircraft side, and by relying on cloud–edge–terminal collaborative scheduling and elastic computing capabilities, it enables real-time parsing of massive low-altitude data and rapid response, providing underlying computing support for the inference of various AI models. The intelligence pool is the intelligent center of the low-altitude digital foundation. By integrating core algorithmic models such as multi-source data fusion, meteorological risk prediction, dynamic route planning, route capacity assessment, airspace grid partitioning, trajectory prediction and conflict resolution, and digital-twin simulation, it provides various intelligent analysis and decision-making capabilities for the safe operation of low-altitude airspace.

### (3) Low-Altitude Traffic Management System

The low-altitude traffic management system relies on a low-altitude digital foundation and low-altitude communications and sensing facilities, and undertakes the operational organization and management functions for low-altitude flight activities. As the types and operating scale of low-altitude flight activities continue to expand, low-altitude operations have placed higher demands on flight-plan management, operational coordination, and airspace resource allocation. The role of the low-altitude traffic management system in the low-altitude operation system has become increasingly prominent; it is the core platform supporting the safe, orderly, and efficient operation of low-altitude flights.

As shown in Figure 4, similar to existing civil aviation air traffic management systems[^19], the low-altitude traffic management system should include three core modules: low-altitude traffic services, low-altitude traffic flow management, and low-altitude airspace management. In terms of low-altitude traffic services, the system assumes responsibility for comprehensive information services and safety assurance for aircraft and flight crews. Its specific functions include: providing key operational information such as weather, traffic flow, traffic control, takeoff-and-landing site status, and flight status; issuing control instructions such as avoidance and speed reduction; and providing emergency rescue services to ensure timely response to unexpected situations during flight. In terms of low-altitude traffic flow management, the system focuses on the planning and monitoring of the full life cycle of flight activities. Its main functions cover: accepting and approving flight-plan applications; planning flight routes; monitoring flight status in real time; and predicting potential flight conflicts, thereby effectively regulating the traffic load within the airspace and preventing congestion and collision risks. In terms of low-altitude airspace management, the system emphasizes the dynamic allocation and operational monitoring of airspace resources. Its specific tasks include: conducting airspace planning; implementing airspace allocation and release; carrying out airspace control and the designation of no-fly zones; monitoring airspace status in real time; designing and adjusting routes according to operational needs; and executing route allocation and release, thereby ensuring the optimal use of airspace resources.

**Figure 4. Functional structure of the low-altitude traffic management system**

- **Low-Altitude Traffic Management System**
  - **Low-Altitude Traffic Services**

    - Provide information on weather, traffic flow, traffic control, takeoff-and-landing site status, flight status, etc.
    - Issue control instructions such as avoidance and speed reduction
    - Emergency rescue services
- **Low-Altitude Traffic Flow Management**
    - Flight-plan application
    - Flight-plan approval
    - Flight-route planning
    - Takeoff and landing management
    - Flight-status monitoring
    - Flight-conflict prediction
- **Low-Altitude Airspace Management**
    - Airspace planning
    - Airspace allocation and release
    - Airspace control and no-fly-zone designation
    - Airspace-status monitoring
    - Route designation and adjustment
    - Route allocation and release

## 3 Pathways and Challenges for Building Low-Altitude Infrastructure for Scaled Operations

As the low-altitude economy moves gradually from the exploratory demonstration stage toward exploration of normalized and scaled applications, low-altitude infrastructure—serving as an important physical and information-technology carrier that supports the development of low-altitude flight activities—has become an important foundational condition for the development of the low-altitude industry. The construction of low-altitude infrastructure not only involves the coordinated allocation of low-altitude airspace resources, but also includes multiple aspects such as the layout of takeoff-and-landing facilities, organization of routes and flight paths, communications surveillance support, meteorological services, and the construction of operational service systems. It is characterized by strong systematicity, numerous stakeholders, and high requirements for coordination. In the process of expanding the low-altitude economy from localized pilots to broader applications, it is necessary, under the guidance of overall planning and driven by application-scenario requirements, to build in stages and optimize continuously, gradually forming a low-altitude infrastructure system with a relatively clear structure, increasingly complete functions, and continuously improving operational support capabilities. At the same time, low-altitude infrastructure construction also faces practical challenges in areas such as technical complexity, standards alignment, operational safety, and collaborative management. Therefore, it is necessary to analyze the development approach and technical challenges faced by low-altitude infrastructure from two dimensions: the system construction pathway and key constraining factors.

### 3.1 Pathway for Building the Low-Altitude Infrastructure System

From the perspective of the development concept, the construction of low-altitude infrastructure should aim to support normalized and scaled operations, promoting its evolution from single-point demonstrations toward systematization and networking. Its core lies in building an integrated support system covering the entire process of low-altitude flight through planning guidance, optimization of facility layout, and coordinated capacity development.

First, the construction of a low-altitude infrastructure system should adhere to the combination of planning first and systematic coordination. In top-level design, the allocation of low-altitude airspace resources and the layout of infrastructure should be incorporated into the framework of territorial spatial planning and the integrated transportation system. The functional positioning, applicable scenarios, and operational boundaries of low-altitude flight activities should be clarified, so as to promote coordinated linkage with urban spatial structure, industrial layout, and the ground transportation system. On this basis, overall design is needed for the designation of low-altitude airspace, the siting of takeoff and landing facilities, and the organization of air routes and flight paths, thereby reserving conditions for subsequent expansion of operational scale and extension of application scenarios.

Second, under the constraints of overall planning, moderately forward-looking construction of foundational capabilities should be advanced, with priority given to consolidating key support capabilities such as takeoff and landing facilities, communication and surveillance nodes, meteorological sensing points, and key air routes and flight paths. Around key areas and typical application scenarios, foundational infrastructure such as takeoff and landing sites, low-altitude communication, surveillance, and meteorological sensing may be laid out in advance, forming a basic network with preliminary operational support capability. This construction model, which takes demonstration areas and key air routes and flight paths as entry points, helps to gradually verify technical solutions, facility configurations, and operational models under conditions in which risks and costs are relatively controllable, thereby accumulating experience for subsequent promotion and application.

As the density of low-altitude flight activities increases and operational scenarios become more complex, the construction of low-altitude infrastructure also needs to shift from a simple emphasis on facility construction toward greater attention to the development of operational support capabilities. Among these, promoting the platform-based development of a low-altitude operation service system is an important direction. By building a digital foundation for low altitude and a low-altitude traffic management system platform that integrates flight plan management, dynamic airspace management, operation monitoring, and information services, the digitalized and refined management capacity for low-altitude flight activities can be improved, providing unified support for parallel operations involving multiple actors and multiple tasks.

Finally, the improvement of the low-altitude infrastructure system should be based on the needs of actual application scenarios and be continuously fed back and optimized during operation. Scenarios such as logistics distribution, emergency rescue, and inspection operations usually feature relatively clear demand, relatively high operating frequency, and relatively clear application boundaries, making them important scenarios for testing the rationality of infrastructure layout and technical adaptability. By forming a cyclical mechanism of "operation—feedback—optimization," low-altitude infrastructure can be promoted from being basically usable toward stable usability and continuous optimization, and its development can be further advanced from point-based demonstrations toward regional networked operations.

### 3.2 Key Challenges Facing the Development of Low-Altitude Infrastructure

In the process by which low-altitude infrastructure gradually moves from development concepts to engineering implementation, and from demonstration operations to scaled applications, issues related to technical adaptation, operational management, and multi-actor collaboration have gradually emerged, as shown in Table 2, and to a certain extent affect its high-quality development.

**Table 2: Key Challenges in the Development of Low-Altitude Infrastructure and Priorities for Future Construction**

| Challenge dimension | Problem orientation | Priorities for future construction |
|---|---|---|
| Airspace management | Insufficient capability for refined delineation and dynamic regulation | Airspace classification and layering, and dynamic allocation |
| Technical support | Insufficient adaptation of communication, navigation, surveillance, and meteorology | Improvement of low-altitude sensing coverage and support capabilities |
| Platform operation | Increasing pressure from multi-source data fusion, real-time processing, and safety | Data fusion, collaborative scheduling, and safety protection |
| Institutional coordination | Insufficient alignment of standards; unclear boundaries of responsibilities and rights among multiple actors | Unified standards, responsibility allocation, and collaborative supervision |

The construction of refined low-altitude airspace management and dynamic regulation capabilities is a fundamental challenge in low-altitude infrastructure development. The flight altitude in low-altitude operations is relatively low, and the activity range is close to the ground, making it susceptible to factors such as terrain and surface features, the built environment, and urban operating conditions. At the same time, the types of low-altitude flight actors are diverse, and mission requirements vary greatly, placing demands on the refinement of airspace delineation

⋯the degree, the flexibility of airspace use, and the capacity for dynamic adjustment during operations. Therefore, under the premise of ensuring operational safety, how to achieve the rational allocation, efficient use, and dynamic management of low-altitude airspace resources is one of the issues that currently requires focused attention in the development of the low-altitude infrastructure system.

In addition to airspace management, the adaptability of communications, navigation, surveillance, and meteorological support technologies in complex low-altitude environments is also a prominent issue. The *Implementation Opinions on Strengthening the Capacity Building of the Information and Communications Industry to Support the Development of Low-Altitude Infrastructure*, issued by the Ministry of Industry and Information Technology and other departments, also proposes supporting the development of information infrastructure such as low-altitude communications, surveillance, navigation, and low-altitude intelligent connected systems [20]. Compared with traditional flight scenarios, factors such as building obstruction, terrain undulation, multipath effects, and electromagnetic interference are more complex in low-altitude environments, and may affect the continuity of communication and navigation links as well as the stability of surveillance coverage. At the same time, low-altitude meteorological conditions are characterized by strong locality, rapid change, and small spatial scales, placing higher demands on the accuracy, timeliness, and service capability of meteorological sensing. Therefore, improving the adaptability of communications, navigation, surveillance, and meteorological support systems in complex low-altitude scenarios is an important technical issue facing low-altitude infrastructure development.

At the platform operation level, operational service platforms such as the low-altitude digital base and traffic management systems also face pressures from increasing system complexity and information security assurance. As the number of operating entities grows and mission types become increasingly diverse, platforms must access and process multi-source heterogeneous data from aircraft, takeoff-and-landing facilities, communication and surveillance systems, meteorological service systems, and management authorities, while supporting multiple functions such as flight plan management, operation monitoring, information services, and collaborative scheduling. This places higher requirements on platform system architecture, data fusion capability, real-time processing capability, and network and information security assurance. Meanwhile, differences may still exist among different regions and different platforms in terms of data interfaces, operating rules, and technical standards; issues of interconnection and standard unification will also affect the overall efficiency of low-altitude operation networks.

In addition, under conditions of multi-actor participation, operational rules and the definition of responsibilities still require further improvement. The construction and operation of low-altitude infrastructure involve multiple types of actors, including government management departments, platform operators, aircraft operating entities, infrastructure construction units, and relevant service providers. The boundaries of responsibility among these actors in planning and construction, operational management, safety assurance, data sharing, and emergency response need to be further clarified. If the relationship between authority and responsibility is unclear, it may affect the collaborative efficiency and safety management effectiveness of the low-altitude operation service system. Therefore, while advancing low-altitude infrastructure construction, it is also necessary to improve operational rules, regulatory mechanisms, and responsibility allocation at the institutional and management levels, thereby providing support for the long-term stable operation of low-altitude infrastructure.

## 4 Summary

This paper, focusing on the needs of low-altitude infrastructure arising from the development of the low-altitude economy, has reviewed and analyzed the system composition, construction pathways, and key challenges of low-altitude infrastructure. Low-altitude infrastructure is not a simple combination of several takeoff-and-landing sites and ground support facilities, but rather an important foundational system that supports the organization, management, and safe operation of low-altitude flight activities. As low-altitude flight activities gradually expand from pilot applications toward normalized and large-scale operations, low-altitude infrastructure needs to form a composite system jointly composed of physical infrastructure and information infrastructure. Among these, physical infrastructure such as takeoff-and-landing facilities and ground support facilities provides the necessary physical conditions and basic guarantees for low-altitude flight; information infrastructure such as low-altitude communication and sensing facilities, the low-altitude digital base, and the low-altitude traffic management system provides important support for the safety and orderliness of low-altitude flight activities through continuous sensing and organized management of the operating environment, flight status, and airspace resources.

At present, low-altitude infrastructure is still in a process of continuous exploration and improvement, and there remains a considerable gap between its system completeness and operational support capability and the future demand for high-density, large-scale low-altitude flight. Going forward, efforts should be made to strengthen refined airspace management, communications-navigation-surveillance support, construction of the low-altitude digital base and traffic management system, and multi-actor collaborative governance capabilities. In addition, typical scenarios such as logistics delivery, emergency rescue, and inspection operations should be used to continuously verify and optimize the infrastructure support capability, promoting the transformation of low-altitude infrastructure from point-based demonstrations to systematic and networked operation, and providing support for the safe, orderly, and sustainable development of the low-altitude economy.

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## Author Contributions Statement:

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Liu Zheng: Participated in the design of the research plan; was responsible for collecting and organizing literature, policy documents, and industry reports; participated in the analysis of the composition, construction pathways, and key challenges of the low-altitude infrastructure system; participated in drafting the main content of the paper, organizing figures and tables, and revising the paper.

Xu Tao: Guided the overall research ideas and technical route; reviewed and ensured the quality of the research framework, core viewpoints, and key content of the paper; participated in revising the paper and approving the final version.

Wang Lijun: Participated in discussions on the research plan; proposed revisions regarding the policy background of the low-altitude economy, content related to physical infrastructure, and the structure of the paper; participated in revising the paper.

Han Zhigang: Participated in discussions on the research plan; proposed revisions regarding the low-altitude digital foundation, the low-altitude traffic management system, and related technical content; participated in revising the paper.

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*Note: Figure translations are in progress. See original paper for figures.*