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https://ieeexplore.ieee.org/xpl/RecentIssue.jsp?punumber=11344065
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Available on IEEE Xplore®

Review

https://doi.org/10.1631/ENG.ITEE.2025.0173

Key technologies of vertical take-off and landing infrastructure for urban air mobility: a comprehensive review

Chenglong LI[1,6]✉, Runming WANG[2], Zhaoxuan ZHANG[2], Yuan ZHENG[3], Yang WANG[4], Rui YANG[5,6]

[1]*Flight Technology College, Civil Aviation Flight University of China, Chengdu 641419, China*
[2]*College of Air Traffic Management, Civil Aviation Flight University of China, Chengdu 641419, China*
[3]*School of Computer Science and Artificial Intelligence, Civil Aviation Flight University of China, Chengdu 641419, China*
[4]*Institute of Computing Innovation, Zhejiang University, Hangzhou 310058, China*
[5]*Discipline Construction Office, Civil Aviation Flight University of China, Chengdu 641419, China*
[6]*Low-Altitude Operations Flight Technology Research Center, Civil Aviation Flight University of China, Chengdu 641419, China*

Abstract: As the frontier of multidimensional transportation systems, urban air mobility (UAM) is receiving increasing attention from international organizations, governments, and stakeholders in industry and academia owing to its high efficiency, low carbon footprint, and operational flexibility. Vertical take-off and landing (VTOL) infrastructure is the core facility that enables UAM and is therefore essential for its safe, efficient, and large-scale commercial implementation. However, the key technologies for establishing low-altitude VTOL infrastructure are still nascent, and government, industry, and academia have yet to harmonize the corresponding construction, management, and operation standards. To address this gap, we herein systematically review the related progress and trends, comprehensively surveying the key technologies of establishing VTOL infrastructure serving unmanned aerial vehicles (UAVs) and electric VTOL aircraft from three complementary perspectives of ground-side, airspace-side, and communication, navigation, surveillance, and information services. In the light of future UAM operations characterized by diverse vehicle types and dense air traffic, we propose a conceptual design for a public multioperator VTOL site to provide constructive insights into the sustainable growth of the low-altitude economy.

Key words: Urban air mobility (UAM); Vertical take-off and landing (VTOL) infrastructures; Low-altitude operations; Communication, navigation, surveillance, and information (CNSI)

1 Introduction

The National Aeronautics and Space Administration (NASA) defines urban air mobility (UAM) as the safe and efficient operation of piloted or unpiloted aircraft within metropolitan areas (Thipphavong et al., 2018). At its core, UAM seeks to realize multidimensional utilization of low-altitude airspace by integrating novel aircraft. Recent advances in batteries, electric propulsion, flight control systems, and related technologies for unmanned aerial vehicles (UAVs) and electric vertical take-off and landing (eVTOL) vehicles have unlocked revolutionary opportunities for UAM use in air-taxi services, logistics delivery, medical transport, law enforcement patrols, and airport shuttle operations (Fig. 1) (Wang WZ, 2024; Markets and Markets, 2025). Governments worldwide have introduced dedicated regulatory frameworks for UAM (State Council of the People's Republic of China and Central Military Commission of the People's Republic of China, 2023; Ministry of Transport of the People's Republic of China, 2024; Federal Aviation Administration, 2025). In China, the Civil Aviation Law was revised in 2025 (Ministry of Transport of the People's Republic of China, 2025) to incorporate the low-altitude economy and codify provisions on airspace, infrastructure, and other enabling safeguards. In the United States of America (USA), the Federal Aviation Administration (FAA) issued low-altitude unmanned aircraft regulations in 2025, establishing tiered authorization and minimum separation requirements for the beyond-visual-line-of-sight operations of unmanned aircraft systems (Federal Aviation Administration and Transportation Security Administration, 2025). Japan (Ministry of Economy, Trade and Industry and Ministry of Land, Infrastructure, Transport and Tourism, 2021), the European Union (European Union Aviation Safety Agency, 2020), and other jurisdictions have also promulgated relevant policies, collectively providing an institutional foundation for UAM development. The rapid advances in unmanned aircraft and 5G/6G communication technologies, largely driven by China, are creating technological underpinnings

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✉ Chenglong LI, lcl@cafuc.edu.cn
Chenglong LI, https://orcid.org/0000-0001-7523-7502

CLC number: TP393

Received: Dec. 10, 2025; Revision accepted: Jan. 1, 2026;
Crosschecked: Jan. 13, 2026

for innovative UAM applications. However, commercial UAM operations are expected to involve multiple aircraft types and be characterized by high frequency, high density, and high operational complexity. Consequently, comprehensive deployment faces numerous obstacles, notably gaps in supporting infrastructure. A Massachusetts Institute of Technology report identified ground operations and the construction of urban low-altitude vertical take-off and landing (VTOL) sites as core challenges for future urban air-transport systems (Massachusetts Institute of Technology, 1970).

VTOL infrastructure is a core component of the UAM system, providing safe platforms for aircraft take-off, landing, and maintenance, while optimizing terminal-area airspace management and sequencing and thereby enabling safe, efficient, and large-scale commercial operations. To meet diverse operational demands, the VTOL infrastructure for UAM comprises several types of facilities, including Skyports' eVTOL vertishop (Skyports, 2024), Urban Air Port's eVTOL vertiport (Hyundai Motor Group, 2021), the Korea Airports Corporation's eVTOL vertihub (Ji, 2024), UAV VTOL stations operated by Google Wing (Croft, 2022) and XAG (Zhu and Xu, 2024), and UAV VTOL cabinets deployed by Meituan (Niu Y, 2023) and DJI (Li YL, 2023). Site infrastructure categories are defined by the performance of the aircraft they serve and the requirements of each application scenario, the overarching aim being the avoidance of resource wastage or performance shortfalls caused by design standards diverging from practical needs.

UAV VTOL stations and cabinets support small UAVs in parcel delivery and urban inspection missions (Fig. 1). A UAV VTOL cabinet typically handles a single UAV and is highly automated, making it suitable for end-node applications. By contrast, a UAV VTOL station can accommodate multiple UAVs simultaneously and provide charging and maintenance facilities, thus being appropriate for hub node operations. According to NASA's technical guidance (Northeast UAS Airspace Integration Research Alliance, 2020), vertistops, vertiports, and vertihubs are ground facilities designed to serve eVTOL aircraft and are typically deployed in UAM applications such as airport access services and air taxis. Vertistops and vertiports are structurally and functionally simple, generally comprising only one to three pads, and are therefore suited for terminal nodes within these service networks. By contrast, a vertihub aggregates numerous VTOL pads and parking stands, and supports a broader range of functions such as take-off and landing operations, charging, maintenance, and storage, thus being appropriate for deployment as a hub node.

Key technologies for VTOL site infrastructure—such as airspace clearance management, surface layout design, and operational scheduling—are being developed with the objectives of safety, low cost, and high operational efficiency to address the practical problems and challenges these facilities face and pave the way for their large-scale commercial deployment in complex urban environments (Fig. 2). Despite the multitude of available technical solutions and optimization methods, most of them remain at an early stage, and the academia and industry have yet to reach consensus on unified technical standards.

This review is structured as follows: Section 2 describes the employed literature search strategy, screening and inclusion criteria, and the final corpus used for analysis. Section 3 examines the

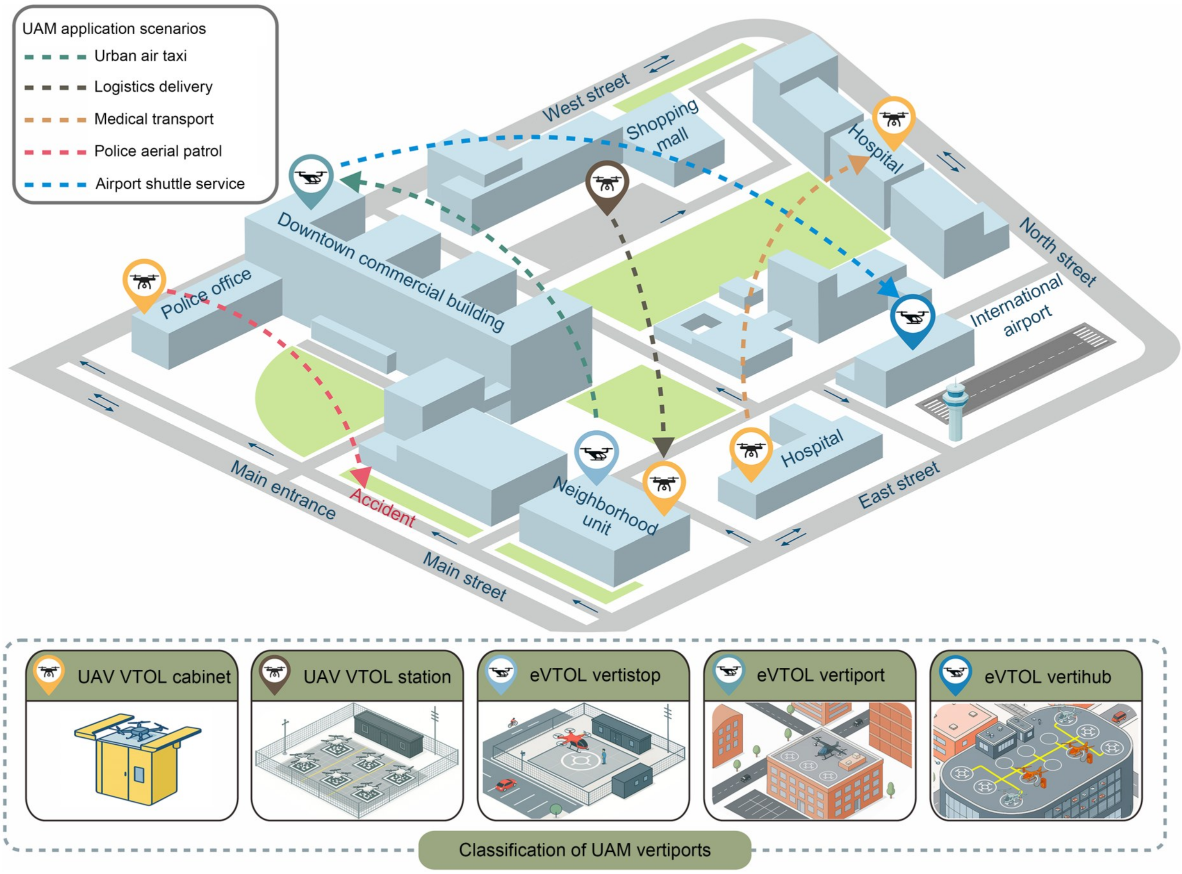


Fig. 1 Conceptual framework of the VTOL infrastructure for UAM

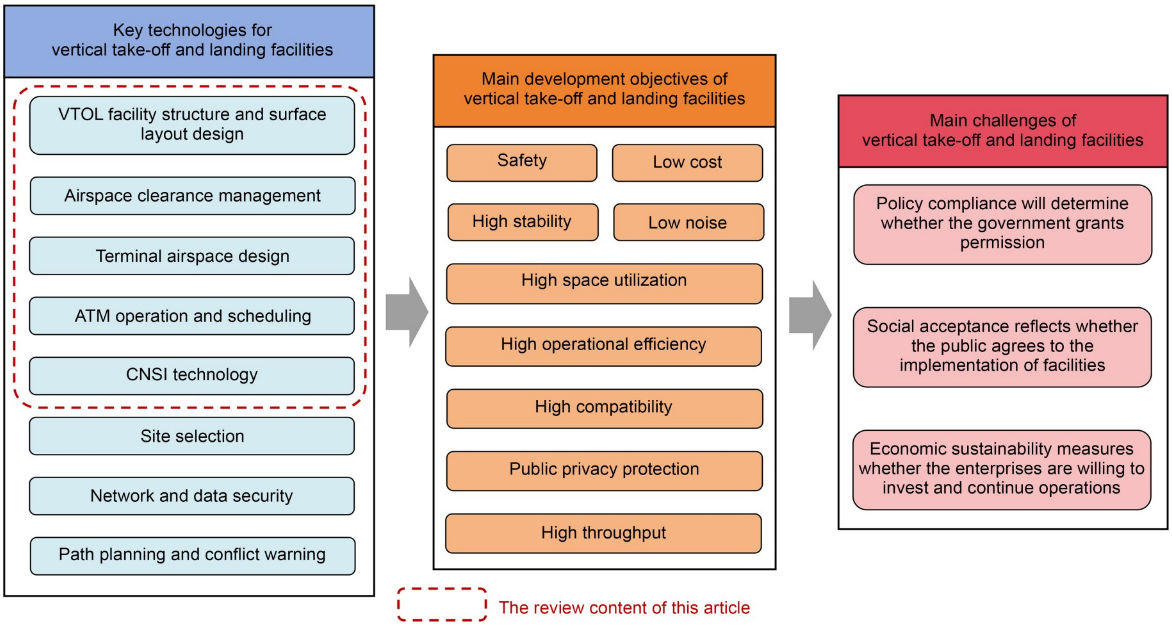


Fig. 2 Key technologies, development objectives, and current challenges for VTOL infrastructure in UAM

ground-side technologies for eVTOL aircraft and VTOL UAV infrastructure, concentrating on structural and layout design and recent regulatory and industrial developments. Section 4 discusses airspace-side technologies—obstacle clearance management, terminal-area airspace design, and air traffic sequencing—while highlighting commonalities and differences arising from the performance characteristics of eVTOL aircraft and UAVs. Section 5 focuses on communication, navigation, surveillance, and information (CNSI) services required for on-site operations, framed by piloting mode, operating environment, and airworthiness rules for each vehicle class. Section 6 proposes an innovative public multioperator UAV VTOL station concept tailored to UAM operations characterized by diverse vehicle types and dense air traffic expected in the near future, which aims to support the healthy growth of the low-altitude economy. Section 7 outlines future research directions, identifies promising topics and key challenges, and sketches probable trajectories for technological development. Finally, Section 8 presents the overall conclusions.

2 Methods

To synthesize and critically examine the key technologies associated with VTOL facilities, we conducted a systematic literature search using the Web of Science and China National Knowledge Infrastructure (CNKI) databases on topics including the core technologies of low-altitude VTOL facilities. Keywords such as “vertical take-off and landing facility,” “structural design,” and “CNSI” were used to identify relevant studies published up to September 2025. In parallel, we reviewed market analyses, government reports, and other pertinent materials.

Given the emerging nature of the examined field of research and the large and rapidly growing body of planning, deployment, and industrial case studies, some examples may have been missed. As summarized in Fig. 3, we removed 195 duplicate records and then screened titles, excluding 355 publications not aligned with the research topic, including 34 items of gray literature. Finally, we carefully examined the abstracts of the remaining records and excluded 339 works that did not meet the inclusion criteria, among which 29 were gray literature. In total, 129 publications were retained for subsequent analysis.

3 Ground-side technologies for VTOL infrastructure

Herein, ground-side technologies for VTOL infrastructure are examined from the complementary perspectives of structural and layout design. Structural design addresses the composition, dimensions, and physical parameters of the take-off and landing infrastructure, whereas layout design focuses on the spatial distribution and separation requirements of site functional zones. As eVTOL aircraft and UAVs markedly differ in performance, their ground-side designs inevitably diverge. For instance, eVTOL aircraft generate stronger downwash, whereas UAVs produce lower thrust and therefore impose less environmental disturbance. Thus, UAV VTOL infrastructure can be more compact. The larger mass and size of the eVTOL aircraft typically require self-powered or tug-assisted ground movement and hence, dedicated taxiways, whereas lightweight UAVs can be handled manually and the corresponding sites need only provide passageways for personnel.

Given these distinctions, the remainder of this section outlines the specific ground-side requirements and design features of VTOL infrastructure for eVTOL aircraft and UAVs.

3.1 Structural design of VTOL infrastructure

3.1.1 Structural design of eVTOL infrastructure

To date, five jurisdictions—China (Civil Aviation Administration of China, 2024b), the USA (Federal Aviation Administration, 2022), the European Union (European Union Aviation Safety Agency,

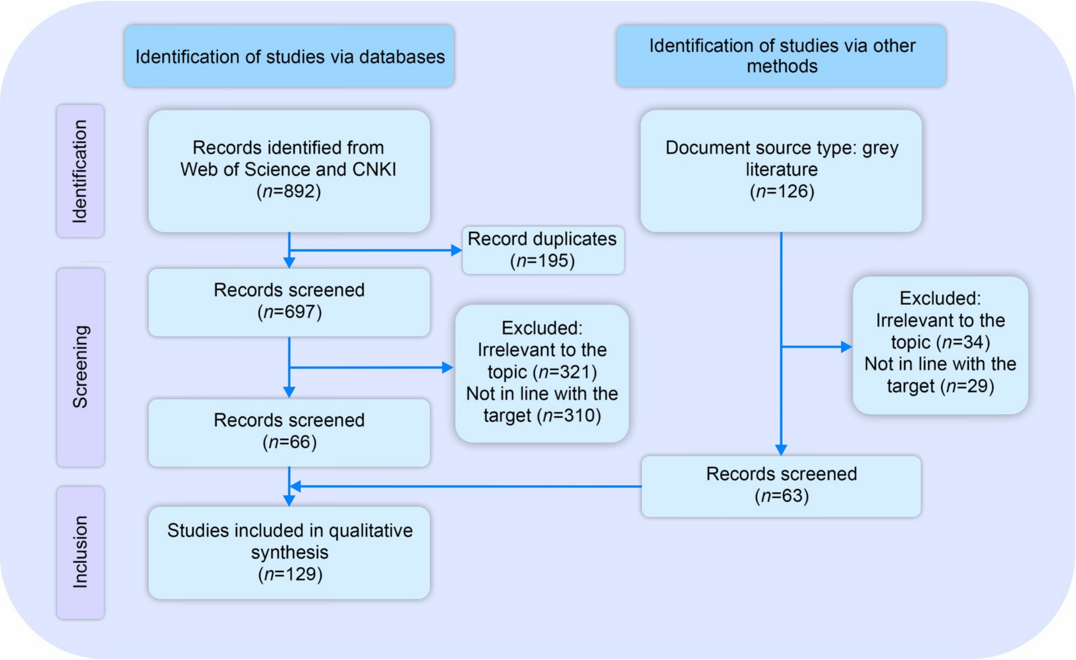


Fig. 3 Flowchart of the literature selection process

2022), Japan (Japan Civil Aviation Bureau, 2023), and Australia (Civil Aviation Safety Authority, 2022)—have issued structural design codes for eVTOL vertiports. As the operational procedures and flight mechanics of eVTOL aircraft closely resemble those of helicopters, most of these documents are adaptations of the International Civil Aviation Organization Annex 14, Volume II (heliports). Consequently, the physical structure of eVTOL vertiports largely mirrors that of heliports, and dual-use facilities are expected to become increasingly common (Federal Aviation Administration, 2023). In the cited codes, the term physical structure—derived from physical characteristics (European Union Aviation Safety Agency, 2022; Civil Aviation Administration of China, 2024b; Civil Aviation Safety Authority, 2022)—refers to the core structural components of a vertiport, each defined by specific attributes such as size, geometry, and bearing strength. Functionally, these components fall into three groups, namely, landing and take-off, taxi, and apron zones.

The landing and take-off zones comprise the final approach and take-off area (FATO, a defined area for VTOL aircraft transitioning from the final approach to touchdown/hovering and from ground/hovering to take-off (Japan Civil Aviation Bureau, 2023)), touchdown and lift-off area (TLOF, a defined area for VTOL aircraft undercarriage to touchdown/lift-off within the FATO or stand (Japan Civil Aviation Bureau, 2023)), and safety area (SA, a defined area surrounding the FATO to reduce the risk of damage during VTOL due to accidental deviation (Japan Civil Aviation Bureau, 2023)), which defines the landing and take-off areas, provides structural support, and furnishes a safety buffer. As these areas must withstand high loads generated during vertical operations, their pavements must satisfy strict criteria for bearing capacity, drainage, impact resistance, and surface friction. The FAA stipulates that both the FATO and TLOF should support a static load equal to the maximum take-off weight (MTOW, the maximum weight at which an aircraft is allowed to take off), distributed over the landing-gear contact area and a dynamic load of at least 150% of the MTOW (Federal Aviation Administration, 2022). The Japanese Civil Aviation Bureau (JCAB) requires static load capacity to exceed 150% of the MTOW (Japan Civil Aviation Bureau, 2023). To ensure obstacle-free operations, no objects other than essential lighting and markings are permitted: object heights may not exceed 5 cm within the FATO and 2.5 cm within the TLOF (European Union Aviation Safety Agency, 2022; Japan Civil Aviation Bureau, 2023; Civil Aviation Administration of China, 2024b; Civil Aviation Safety Authority, 2022). Within the SA, the object height must remain below a sloping plane originating 25 cm above the FATO perimeter and rising outward at a gradient of 5% (European Union Aviation Safety Agency, 2022; Japan Civil Aviation Bureau, 2023; Civil Aviation Administration of China, 2024b). The European Union Aviation Safety Agency (EASA) defines a rotor-downwash protection zone, lateral protection slope, and clearway to provide supplementary safeguards (European Union Aviation Safety Agency, 2022).

The taxi zone comprises taxiways and taxi routes linking the landing and take-off zones to the apron. Taxiway (a defined path at the vertiport for VTOL ground movement between areas (Civil Aviation Safety Authority, 2022)) pavements must bear the dynamic loads of ground maneuvering while resisting rotor downwash and providing effective drainage. Minimum separation standards differ across jurisdictions: the EASA and JCAB require the centerline spacing between adjacent taxiways to be at least 1.25 times the aircraft width (European Union Aviation Safety Agency, 2022; Japan Civil Aviation Bureau, 2023), whereas Australia's Civil Aviation Safety Authority mandates a minimum wing-tip clearance of 0.25 times the aircraft width between aircraft operating on adjacent taxiways (Civil Aviation Safety Authority, 2022). A taxi route, a defined path for VTOL movement between vertiport areas (Civil Aviation Safety Authority, 2022), is normally a virtual route; however, when physically marked and combined with a taxiway, it must meet the same bearing, drainage, and impact resistance requirements. Except for essential equipment, no obstacles are allowed within taxiways or taxi routes. Essential objects must be positioned outside the taxiway and at least 50 cm from the taxiway edge, and their height must remain below a plane that originates 25 cm above the taxiway edge, 50 cm laterally, and rises outward at 5% (Civil Aviation Safety Authority, 2022; European Union Aviation Safety Agency, 2022; Japan Civil Aviation Bureau, 2023).

The apron zone contains stands and associated protection areas (PAs). Stand surfaces must meet the same bearing, drainage, impact, and friction requirements as landing and take-off zones. Here, stand is a defined area intended to accommodate aircraft for loading or unloading passengers, mail, or cargo, fueling/charging, parking, or maintenance (Civil Aviation Safety Authority, 2022). Codes issued by the Civil Aviation Administration of China (CAAC) and JCAB additionally require mooring and lightning protection installations (Japan Civil Aviation Bureau, 2023; Civil Aviation Administration of China, 2024b). EASA and JCAB introduced a geometry-based stand design, in which the minimum clearance between a stand and any fixed object is 3 m; unlike traditional circular or rectangular stands, this approach scales the footprint to the aircraft platform and affords greater flexibility (European Union Aviation Safety Agency, 2022; Japan Civil Aviation Bureau, 2023). The PA, a defined area around a stand for turning or reducing damage from accidental deviation (Japan Civil Aviation Bureau, 2023), surrounding each stand mitigates risks arising from inadvertent aircraft deviation. The height limits for essential objects vary with radial distance: within $0.75D$ of the stand center, the object height may not exceed 5 cm above the stand surface; beyond $0.75D$, it must remain below a plane that originates 25 cm above the stand surface at a radius of $0.75D$ and rises outward at 5%, where D is the diameter of the smallest circle enclosing the aircraft–ground projection in the landing configuration (Civil Aviation Safety Authority, 2022; European Union Aviation Safety Agency, 2022; Japan Civil Aviation Bureau, 2023).

Table 1 compares the publication timelines and parameter specifications of the major national and regional standards, revealing that structural design work on eVTOL infrastructure has evolved into a pattern of US–Europe leadership with regional followers, with design parameters exhibiting clearly differentiated regional schools of practice. The USA and Europe were the earliest entrants in this field. The FAA guidance adopts a relatively conservative stance, relying largely on legacy heliport design standards and only partially adapting them to the specific characteristics of eVTOL aircraft. By contrast, EASA specifications are more detailed and forward-looking in their technical prescriptions. The standards issued by JCAB and CASA draw heavily on the European framework and converge with those of EASA in terms of structural requirements and technical parameters. The more recently issued CAAC guidance primarily references FAA material and currently concentrates on key dimensional and load-bearing requirements. Some detailed provisions, e.g., those on slope limits, stand PAs, and rooftop applications, are still in an early development stage and are expected to be refined as the domestic UAM demonstration project progresses and operational experience accumulates.

The abovementioned results show that multiple countries and regions have achieved initial progress in the structural design of eVTOL infrastructure, although important limitations remain. First, the existing standards are fragmented, often explicitly interim in nature, and lack international harmonization, resulting in inconsistent global operating requirements and high design and certification costs for manufacturers and operators. Second, in dense urban environments where spatial resources are severely constrained, repurposing existing building rooftops as vertiports is a practically feasible solution; however, no related research or regulatory guidance is currently available. Third, current regional frameworks do not provide technical specifications or guidelines for charging infrastructure, which undermines the coherence and feasibility of integrated infrastructure planning and deployment.

3.1.2 Structural design of UAV VTOL infrastructure

Compared with eVTOL aircraft, UAVs are lighter, generate weaker downwash, and are more maneuverable, thus requiring simpler and more compact infrastructure. Given adequate positioning and control redundancy, a UAV landing pad needs a diagonal of only 2.5–3 times the UAV wheelbase to ensure safe take-off and

Table 1 Dimensional and slope parameters for the physical components of electric vertical take-off and landing (eVTOL) infrastructure in current standards (Civil Aviation Safety Authority, 2022; European Union Aviation Safety Agency, 2022; Federal Aviation Administration, 2022; Japan Civil Aviation Bureau, 2023; Civil Aviation Administration of China, 2024a)

Physical structure	Parameter	China (CAAC) 2024 Edition	USA (FAA) 2022 Edition	Europe (EASA) 2022 Edition	Japan (JCAB) 2023 Edition	Australia (CASA) 2022 Edition
FATO	Size	⩾2.0D	⩾2.0D	⩾1.5D	⩾1.5D	⩾1.5D
	Slope	N/A	−5.0%~−1.5%	⩽2%	⩽2%	⩽2%
TLOF	Size	⩾1.0D	⩾1.0D	⩾0.83D	⩾0.83D	⩾0.83D
	Slope	N/A	−1.0%~−0.5%	N/A	⩽2%	⩽2%
SA	Size	⩾0.5D/5 m	⩾0.5D	⩾0.25D/3 m	⩾0.25D/3 m	⩾0.25D/3 m
	Slope	N/A	⩽2:1	⩽4%	⩽4%	N/A
Taxiway	Size	N/A	N/A	⩾2.0UCW	⩾2.0UCW	⩾2.0UCW
	Slope	N/A	N/A	⩽2%/3%	⩽2%/3%	⩽2%/3%
Taxi route	Size	N/A	N/A	⩾1.5W	⩾1.5W	⩾1.5W
	Slope	N/A	N/A	⩽7%/10%	⩽4%	⩽7%/10%
Stand	Size	⩾1.5D	N/A	⩾1.2D	⩾1.2D	⩾1.2D
	Slope	N/A	N/A	⩽2%	⩽2%	⩽2%
PA	Size	N/A	N/A	⩾0.4D	⩾0.4D	⩾0.4D
	Slope	N/A	N/A	⩽4%	⩽4%	⩽4%

W and UCW denote the maximum overall and undercarriage (landing gear) track widths of the aircraft served, respectively. N/A: not available landing (Song CH and Cheng, 2022). In current practice, UAV VTOL infrastructure falls into two main categories (stations and cabinets) based on the mission profile and sortie frequency.

UAV VTOL stations are used at high-frequency logistics hub nodes. Companies such as Google Wing (Croft, 2022), Flytrex (DroneLife, 2024), Drone Delivery Canada (Sousa, 2024), and Meituan (Meituan, 2024) have begun exploring UAV-based delivery models. These logistics hubs are typically staffed, require a low level of automation, and have relatively simple structures. UAV movement, battery replacement, and cargo loading rely mainly on manual operations. A typical station comprises only a landing mat, vision-based positioning markers, such as AprilTag or ArUco, a micrometeorological station, a UAV storage area, and personnel walkways. Most enterprises currently favor this manually assisted, low-complexity design because it offers better cost control and equipment reliability than fully automated systems.

Beyond conventional planar configurations, Amazon has proposed a tower-shaped multilevel UAV VTOL hub infrastructure called the drone hive (Fig. 4) (Curlander et al., 2017). The facade is populated with hundreds of hexagonal cells, each serving as an independent UAV VTOL interface for take-off and landing, while the base integrates truck loading bays and vertical logistics elevators to enable stratified air–ground operations. This concept combines a minimal ground footprint with high throughput; however, concerns regarding noise, privacy, and safety arising from high-density UAV operations prevent the real-world deployment.

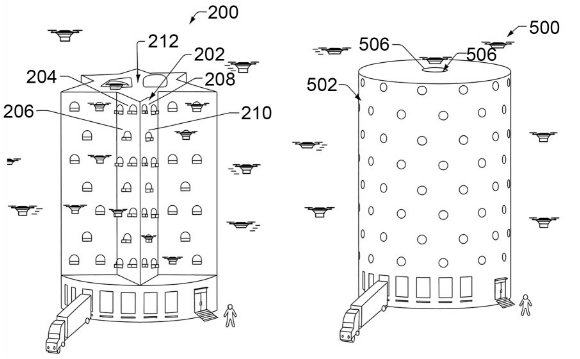


Fig. 4 Schematic structural design of the drone hive (Curlander et al., 2017)

UAV VTOL cabinets are employed at low-frequency end nodes in inspection or delivery networks and usually provide a single landing platform for one UAV. As these sites are unattended, complex mechanical structures are required to achieve a high level of automation. A UAV VTOL cabinet is a multifunctional system comprising subsystems such as landing, positioning alignment, vision-assisted landing, power supply and energy replenishment, and UAV storage systems (Grlj et al., 2022), which are closely tied to UAV operational needs. For example, equipping the landing pad with an energy replenishment module is one of the most promising ways of extending mission endurance with minimal modifications to the UAV, thereby enlarging flight range and reducing operating costs (Galimov et al., 2020).

The positioning alignment system can be categorized as active or passive ones and serves to realign a UAV that has landed on the pad to an exact position for subsequent energy replenishment or storage operations. In an active system, mechanical devices push the UAV into the designated location after touchdown. The Beijing Institute of Technology designed a parallel pushrod structure (Fig. 5a), in which pushrods (6) and (8) move simultaneously under actuator drive to center the aircraft (Beijing Institute of Technology, 2017). Yunxi Intelligent Systems (Shanghai Yunxi Intelligent Systems Co., Ltd., 2017) and Shandong University (Shandong University, 2017) proposed W- and V-shaped push structures (Figs. 5b and 5c), respectively. Compared with the parallel pushrod design, the W- and V-shaped layouts feature fewer actuators and thus lower the risk of mechanical failure, but they are less adaptable to UAVs of varied geometry.

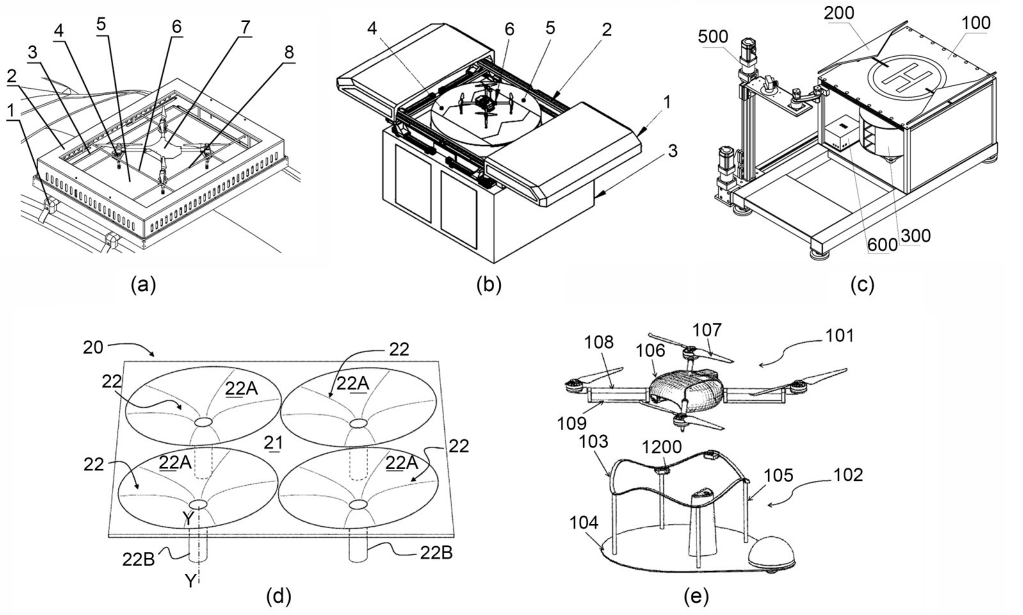


Fig. 5 Structural designs of positioning alignment systems for unmanned aerial vehicle (UAV) VTOL pads/cabinets. (a)–(c) illustrate the designs of three active positioning systems. (d) and (e) illustrate the designs of two passive positioning systems (Beijing Institute of Technology, 2017; Shandong University, 2017; Shanghai Yunxi Intelligent Systems Co., Ltd., 2017; Kespry Inc, 2018; Antonini et al., 2019)

A passive positioning system contains no powered mechanisms that contact the UAV; instead, pad geometry guides the aircraft to the target position. Telecom Italia (Antonini et al., 2019) and Kespry USA (Kespry Inc, 2018) designed funnel-shaped and wavy elastic support structures (Figs. 5d and 5e), respectively, allowing the landed UAV to slide to the desired spot under the action of gravity. Passive systems do not rely on complex electromechanical devices and therefore tolerate harsh outdoor environments better than active systems, thus having a wider practical application scope (Galimov et al., 2020).

Energy replenishment systems are classified into charging-based or battery-swap types. Charging-based replenishment typically uses wireless power transfer via magnetic resonance coupling. Bin Junaid et al. (2017) mounted three pairs of series-connected XKT-510 coils on the pad and UAV (Fig. 6a) to transfer energy between the two systems. However, fitting coils to the airframe adds weight and bulk and imposes stricter landing precision requirements. To address this issue, some researchers have transformed the entire pad into a conductive plane and equipped the landing gear with spring-loaded conductive pins, enabling any touchdown point to complete the circuit. Following this idea, Xiamen Dnake IoT Smart Technology Co., Ltd. (2016) and Al-Obaidi et al. (2020) designed direct-contact charging systems (Figs. 6b and 6c), with the chessboard-style pad of 16 copper plates in the latter case achieving an efficiency of 86%.

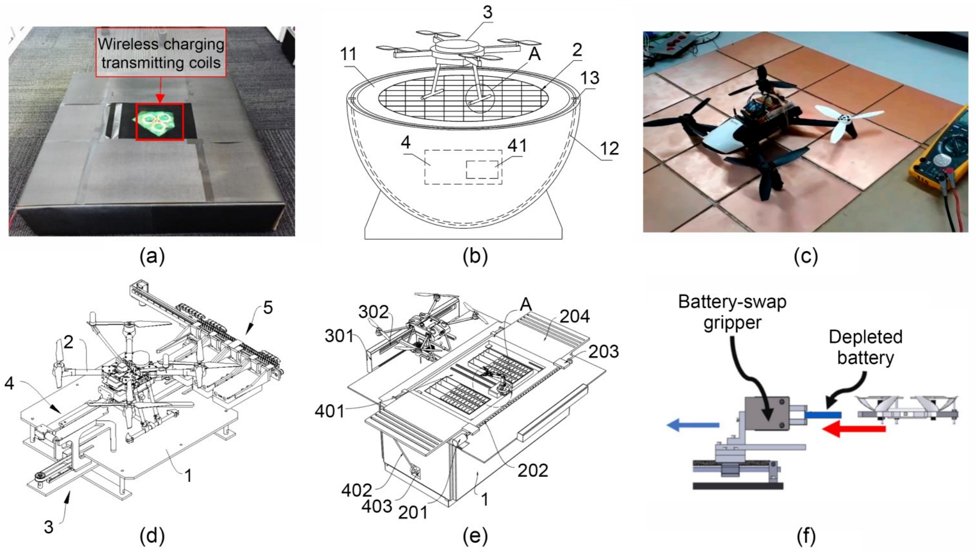
Despite their flexibility, charging-based systems suffer from low charging rates and average efficiencies (~46.4% for Bin Junaid et al. (2017)). Consequently, the development of more efficient battery-swap systems has drawn considerable attention. Qingdao Tongchan Intelligent Technology Co., Ltd. (2025) developed an automated UAV battery-swap system incorporating a compact robotic arm (Fig. 6d). Henan Agricultural University (2025) proposed an automatic swapping device equipped with a cleaning module to help prevent battery contamination by rainwater and debris (Fig. 6e). To address the difficulty of swapping batteries for UAVs carrying parcels suspended beneath the fuselage, De Silva et al. (2022) introduced an inverted swapping mechanism allowing battery replacement without payload unloading (Fig. 6f).

Staffed operation with relatively simple structural layouts has become the dominant paradigm for UAV VTOL stations, whereas demand for fully unattended operation in UAV VTOL cabinets has stimulated technological innovation. Among the enabling technologies, passive positioning systems are the least complex but depend on UAV navigation capabilities, providing the most cost-effective solution when combined with mature vision-based localization algorithms. Charging-based systems are relatively inefficient and therefore suitable mainly for UAV VTOL cabinets dedicated to inspection-type missions. Battery-swap systems achieve substantially higher energy turnaround efficiencies than charging-based solutions but require complex mechanical systems, which increases the physical footprint of the cabinet and the risk of mechanical failure. Both approaches share a fundamental limitation: UAVs must be specially modified to support automated energy replenishment. In the absence of unified standards for charging and battery swapping, proprietary designs developed by different manufacturers are mutually incompatible, which leads to considerable wastage and underutilization of infrastructure resources.

In summary, unlike the standards-first trajectory followed in the development of eVTOL infrastructure, the structural design of UAV VTOL infrastructure has not yet been codified into formalized standards, with its evolution characterized by a commercial practice-first pattern and driven primarily by the demands of commercial operations and iterative technological innovation. As UAV VTOL infrastructure transitions toward high-frequency high-density operations, aviation authorities and professional bodies will need to absorb the emerging industry consensus and establish more comprehensive regulatory frameworks.

3.2 Layout design of VTOL infrastructure

Layout design concerns the spacing and distribution of functional zones within VTOL infrastructure. Separation is a mandatory safety requirement: minimum separations between zones must



(a) (b) (c)
(d) (e) (f)

Fig. 6 Structural designs of energy replenishment systems for UAV VTOL pads/cabinets. (a)–(c) show the designs of three charging-based energy replenishment systems. (d)–(f) show the designs of three battery-swap energy replenishment systems (Beijing Institute of Technology, 2017; Shandong University, 2017; Shanghai Yunxi Intelligent Systems Co., Ltd., 2017; Kespry Inc, 2018; Antonini et al., 2019)

account for potential adverse effects on interaircraft operations and aircraft–ground-crew interactions arising from aerodynamic interference, wind field influences, and navigation control errors. Distribution is a multiobjective optimization task that targets spatial utilization, aerodrome capacity, and operational efficiency. By employing various optimization models and simulation methods, designers adjust the quantity ratios and positional relationships of the functional zones to create high-capacity, high-efficiency topologies within the space-constrained urban environment.

As the functional layout of UAV VTOL infrastructure is simple and lacks optimizable node–edge variables, the current research on zone distribution optimization is mainly centered on the eVTOL vertiports.

3.2.1 Layout design of eVTOL infrastructure

The current research on the minimum separation between functional zones within eVTOL vertiports mainly focuses on the aerodynamic interference generated by eVTOL aircraft and urban wind-induced turbulence. Meyer-Oehme et al. (2023) employed a bow-tie risk model combined with nonlinear dynamic inversion simulations to evaluate the influence of urban gusts on landing trajectories, thereby specifying detailed requirements for safe eVTOL landings in city wind fields. Starting from an analytical relationship between disk loading and downwash, Ison (2024) proposed a concentric safety zone method that partitions an inner safety zone, an outer safety zone, and a buffer zone using multiples of the aircraft's maximum overall diameter *D*; the exact factors should be refined for each aircraft type and operating environment. A wind-tunnel/CFD (CFD is a discipline that uses numerical methods and computer simulations to model and analyze fluid flows and associated heat and mass transfer processes) coupled study by RWDI Canada introduced a turbulence index and recommended verifying pad-to-pad and pad-to-building spacings during early design by CFD analysis and on-site anemometry, using gust acceleration and energy margin rather than fixed distances as criteria (Larose et al., 2024). Overall, most studies treat $1D$–$1.5D$ as an initial reference for parallel eVTOL operations and emphasize the need for refined evaluation that accounts for complex urban winds, aircraft characteristics, and control performance.

Looking ahead, airport air shuttle service scenarios are expected to make coordinated operations between airports and eVTOL infrastructure an important trend. A core issue for the commercial deployment of UAM vertiports is the estimation of the minimum separation between eVTOL infrastructure and the air-side movement area of conventional airports to ensure operational safety while enabling rapid terminal access. The FAA specifies the minimum horizontal separation between the FATO of eVTOL infrastructure and the centerline of an airport runway; this distance is a function of the eVTOL MTOW and aerodrome reference code (Fig. 7 and Table 2) (Federal Aviation Administration, 2022).

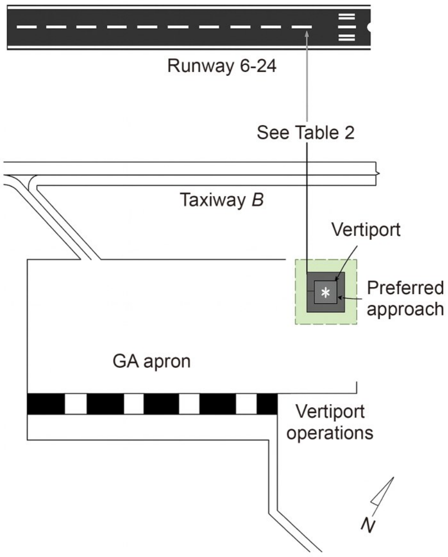


Fig. 7 Example of an eVTOL vertiport situated within an airport (Federal Aviation Administration, 2022). "GA apron" denotes the general aviation apron used for parking/servicing conventional (primarily fixed-wing) aircraft, in contrast to the eVTOL vertiport area

The similarity between eVTOL aircraft and helicopter flight mechanics enables the cross-referencing of optimization studies on functional zone distribution. Drawing on heliport design principles, Vascik and Hansman (2019) classified the layout of low-altitude VTOL infrastructure into landing pads, stands, and preparation areas and identified four topological surface design topologies (linear, satellite, pier, and remote-stand). Aiming to maximize total departure and arrival efficiency, the authors used integer programming to analyze departure/arrival capacity envelopes, examined capacity changes by adjusting the number and layout of the three areas, and evaluated the impacts of factors such as taxi and turnaround time on capacity. The results showed that facility throughput can be maximized by balancing the configuration and number of landing pads.

Building on the work of Vascik and Hansman (2019), Ahn and Hwang (2022) applied linear, satellite, and pier topologies to the VTOL infrastructure at Gimpo Airport (Republic of Korea) and performed the corresponding capacity evaluations. Under FAA standards, a pier layout with two TLOFs and 12 stands was optimal; under EASA standards, a satellite layout with four TLOFs and 18 stands was optimal. Preis (2023) calculated land area requirements and found that a linear topology with nine stands had the smallest footprint.

Zelinski (2020) proposed three more complex topologies (disconnected, ring, and hub-and-spoke) and used integer programming for capacity and efficiency assessment. Li JF (2023) refined this work and introduced boundary-, central-, and separated-type layouts,

Table 2 Recommended minimum horizontal separation between the center of an eVTOL final approach and take-off area and runway centerline (Federal Aviation Administration, 2022)

Reference VTOL aircraft MTOW	Airplane size	Distance from the vertiport FATO center to the runway centerline
≤5670 kg (12 500 lb)	Small (≤5670 kg (12 500 lb))	91 m (300 ft)
≤5670 kg (12 500 lb)	Large (5670–136 079 kg (12 500–300 000 lb))	152 m (500 ft)
≤5670 kg (12 500 lb)	Heavy (>136 079 kg (300 000 lb))	213 m (700 ft)

lb is the abbreviation for pound

evaluating surface area utilization, average taxi distance, and throughput. Preis (2021) presented a rapid-design method that selects vertiport sites from street maps, determines optimal component composition, and produces a detailed layout within minutes. Hack Vázquez (2021) developed an integer programming approach for automatic layout generation and throughput estimation, analyzing more than 25 million combinations and finding that the best throughput is obtained at one to seven stands per TLOF.

The above studies on intrasite layout rationality did not consider the effect of internal traffic flows on capacity. Rimjha and Trani (2021) therefore examined the influence of on-site charging, number of prepositioned aircraft, and service time at each stage on capacity, revealing low sensitivity to the first two factors and high sensitivity to stage-service time. Preis and Hornung (2022) introduced an agent-based simulation that models internal flows by incorporating peak demand, arrival–departure imbalance, pad operations, and service zone operations, demonstrating that delays can be kept within limits by controlling these factors. This model also validates layout choices by adjusting pad and stand counts and arrival–departure timings. Zhang et al. (2023a) proposed a connected and compact topology and, using queuing theory under UAV delay scenarios, evaluated vertiport capacity.

Current research on the minimum separation between the functional zones of eVTOL infrastructure primarily relies on control simulation and computational fluid dynamics, with most studies still confined to the numerical simulation stage and exhibiting limited technological maturity and demonstrable feasibility. For future airport shuttle applications, the FAA has begun to investigate the minimum separation between the eVTOL site infrastructure and the air-side movement areas of civil airports. Given the substantial differences between fixed-wing aircraft and eVTOL aircraft in terms of size and taxi speed, mixed operations within the same airport environment face considerable challenges, including collision risk, wake turbulence effects, and constraints imposed by surveillance technologies. In the authors' opinion, spatially segregating eVTOL infrastructure from existing civil airport facilities remains the optimal near-term strategy. Regarding the internal layout of functional zones within VTOL infrastructure, Table 3 compares the advantages, disadvantages, and typical application scenarios of representative topological configurations.

3.2.2 Layout design of UAV VTOL infrastructure

Research on the minimum placement distance between UAV landing pads has evolved through three stages, namely, single-aircraft flow-field characterization, dual-aircraft interference quantification, and environment/obstacle-coupled extension. Shen A et al. (2018) visualized the hovering flow field of a representative quad-rotor using CFD, demonstrated the presence of a narrow high-velocity downwash core directly beneath the airframe, and showed that the velocity rapidly decays with increasing distance from the rotor disk and that a recirculating ring forms at the periphery. Thus, this work provides qualitative evidence for an intense downwash core that landing pads must avoid. Building on this, Liu C et al. (2022) performed a parametric numerical/experimental comparison for two hovering drones and quantified the thrust and moment responses induced by vortex–airframe coupling. When the longitudinal spacing Z was equal to or greater than $5D$, the trailing aircraft thrust recovered to the baseline; reducing the lateral spacing to $X=1D$ lowered the total thrust by ~18% and amplified the pitching moment eightfold, whereas interference markedly weakened at $X\geqslant 2D$. Thus, the safety threshold was determined as $X\geqslant 2D$ and $Z\geqslant 5D$.

Table 3 Comparison of topological layout designs for VTOL infrastructure

Layout topology	Reference	Core advantage	Core limitation	Applicability
Linear	Vascik and Hansman, 2019; Ahn and Hwang, 2022; Preis, 2023	eVTOL operation is simple and efficient	eVTOL directions are limited	Highway/Railway scenarios, short eVTOL turnaround, and narrow spaces
Satellite	Vascik and Hansman, 2019; Ahn and Hwang, 2022; Preis, 2023	Compact layout and high apron utilization rate	Small capacity and limited eVTOL directions	Small roof vertihubs in square/circular shapes
Pier	Vascik and Hansman, 2019; Ahn and Hwang, 2022; Preis, 2023	Large capacity, accommodates more stands	eVTOL aircraft have long ground turnaround time	Medium-to-large vertihubs and large open spaces
Remote stand	Vascik and Hansman, 2019	Large capacity	Large space requirement	eVTOL vertiports cobuilt with civil aviation airports
Boundary (ring)	Zelinski, 2020; Li JF, 2023	Complete passenger waiting area, facilitation of passenger flow, luggage transfer, and facility support	Large space requirement, the longest eVTOL taxi distance	Suburban passenger transport vertihubs
Central	Zelinski, 2020; Li JF, 2023; Zhang et al., 2023a	Optimal surface area utilization rate and high operational efficiency	Scattered passenger areas, conflict-prone taxiways	Freight-focused vertihubs
Separated (disconnected)	Zelinski, 2020; Li JF, 2023	Taxiways are not prone to congestion	Vulnerable operations under wind constraints, a very large footprint due to numerous stands	Scenic area transfer vertiports and low take-off/landing demand
Connected	Zhang et al., 2023a	Little congestion on taxiways and high layout flexibility	Low capacity and the longest eVTOL taxi distance	Space-constrained vertiports requiring moderate flexibility
Compact	Zhang et al., 2023a	Optimal surface area utilization rate	Small capacity and limited eVTOL directions	Urban central areas or areas with an extremely limited space

Site and meteorological factors exacerbate the above interference. Wang BH et al. (2019) compared Lamb–Oseen and Burnham–Hallock vortex models, noting that gusts and shear winds can notably increase the peak vortex velocity and prolong the decay distance. Therefore, the authors recommended wind-coupled corrections to pad spacing in urban low-altitude environments rather than the direct adoption of calm-air baselines. Caprace et al. (2023) employed high-/medium-fidelity CFD to study the asymmetric ground effect during the rooftop hovering of multirotors and found that wall-induced recirculation can raise rotor-load imbalance by ~20% and induce tipping toward the roof edge. Thus, additional margins were found to be needed for both pad–pad and pad–edge distances when pads are placed near roof edges or narrow platforms.

Overall, existing studies on the minimum spacing between landing pads in UAV VTOL infrastructure have converged on an evaluation framework that starts from rotorcraft aerodynamic characteristics and progressively incorporates multivehicle interactions and external disturbances. For small multirotor UAVs with rotor diameters on the order of 0.2–0.3 m, an initial baseline spacing of $X \geqslant 2D$ and $Z \geqslant 5D$ between pads can be adopted in open environments with the mean wind speeds of $\leqslant 5\ \mathrm{m \cdot s^{-1}}$ and without pronounced wall-bounded flows. In sites subject to frequent gusts or located near roof edges and complex building geometries, this baseline should be augmented using the results of CFD or in situ wind measurements with an additional safety margin of up to 20%–30%, calibrated to local turbulence intensity and load imbalance, to preserve adequate thrust stability and attitude control authority.

4 Airspace-side technologies for VTOL infrastructure

Marked differences in size, noise, energy consumption, and avionics between eVTOL aircraft and UAVs lead to distinct requirements for terminal airspace architecture. However, their shared VTOL modes result in certain commonalities in arrival–departure trajectory planning, air-side obstacle restrictions, and operational sequencing.

Accordingly, this section analyses the common and differing aspects of eVTOL and UAV airspace-side technologies in light of their performance characteristics and discusses the technical requirements and optimization strategies for obstacle clearance management, terminal airspace design, and air traffic control scheduling.

4.1 Obstacle clearance management at VTOL infrastructure

Obstacle clearance management involves the delineation of a set of air-side obstacle limitation surfaces based on aircraft take-off and landing trajectories, followed by the restriction of any objects whose relative positions to these surfaces could endanger flight safety. The aim is to prevent collisions between aircraft and tall obstacles near the vertiport that might occur under adverse conditions, such as poor weather or navigation errors. For eVTOL infrastructure, the requirements for air-side obstacle limitation are well developed, as reflected by clear standards in national regulations (Civil Aviation Safety Authority, 2022; European Union Aviation Safety Agency, 2022; Federal Aviation Administration, 2022; Japan Civil Aviation Bureau, 2023; Civil Aviation Administration of China, 2024b). In contrast, a systematic, mature scheme for UAV VTOL infrastructure is lacking.

The geometry of an obstacle limitation volume is closely tied to take-off and landing modes. Vertically operating aircraft equipped with skid-type landing gear mainly use the two modes illustrated in Figs. 8a and 8b, which differ in whether the departure/arrival profile includes a vertical segment that rises above the ground effect height. Mode (b), which can clear nearby obstacles, is widely adopted for UAM vehicles. The two modes define their protection volumes using obstacle-limitation surfaces (OLSs) and obstacle-free volumes (OFVs).

An OLS generally comprises an approach surface, a take-off climb surface, and a transitional surface. The approach and take-off climb surfaces are planes aligned with the aircraft's flight path and

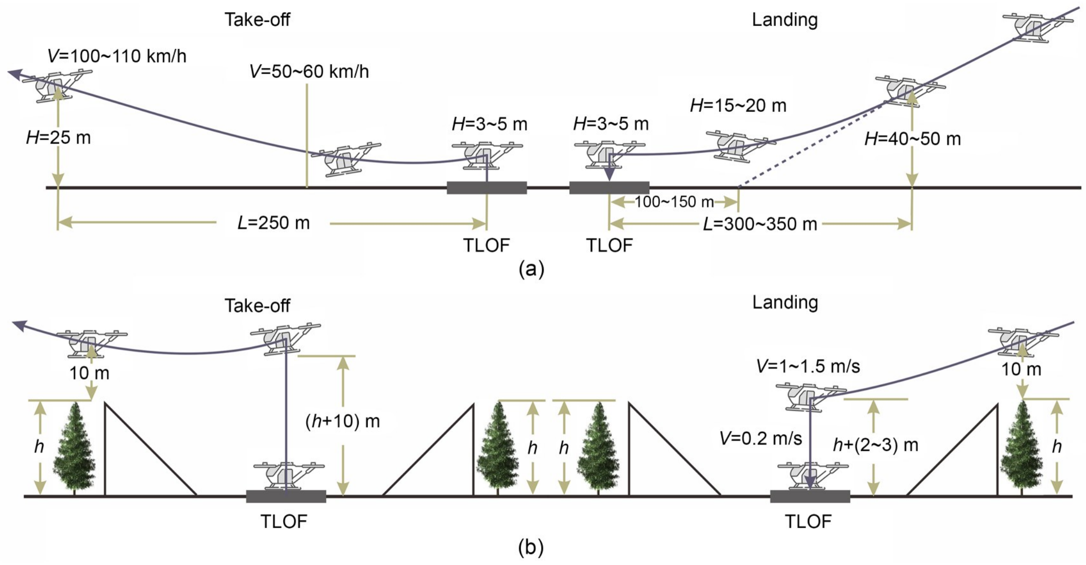


Fig. 8 Flight profiles for the two take-off and landing modes. (a) illustrates the flight mode of "tilted take-off and landing," while (b) illustrates the flight mode of "vertical take-off and landing"

form a minimum angle of 135°. Transitional surfaces lie on either side and protect lateral movements or overshoots within the vertiport area.

The FAA prescribes a simpler OLS (Fig. 9). The approach/take-off climb surface extends outward and upward from the SA outer edge to a point 1219 m away and 152 m high; its outer edge is 152 m wide and slopes at 1:8. The transitional surface extends outward and upward from the SA side boundary at a 2:1 slope to 76 m and then joins the outer edge of the approach/take-off climb surface (Federal Aviation Administration, 2022).

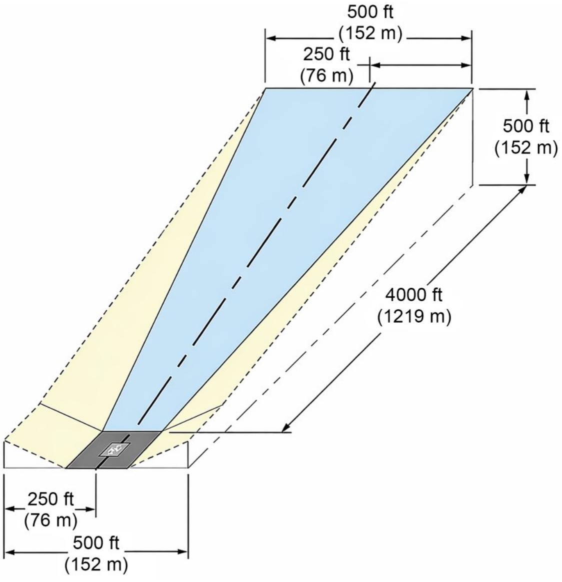


Fig. 9 Cross-sections of OLS in the Federal Aviation Administration (2022) standard

Building on this framework, the EASA and JCAB specified a more detailed OLS delineation method. The inner edge of the approach/take-off climb surface coincides with the outer edge of the SA and shares its width and height. From that inner edge, the side edges expand laterally at 10% by day or 15% by night and rise at a 1:8 slope until they reach an outer edge $7D$ (day) or $10D$ (night) wide; this outer edge is 152.5 m above and 1220 m horizontally away from the inner edge. If the prescribed width is reached before the 1220 m distance, the edge continues parallel until the height of 152.5 m and the distance of 1220 m are attained. Each transitional surface is bounded above by a horizontal line 45 m high that intersects the side edge of the approach/take-off climb surface; its lower edge starts at this intersection and follows the side edge down to the SA boundary, with the slope equaling 50% (European Union Aviation Safety Agency, 2022; Japan Civil Aviation Bureau, 2023).

The EASA introduced the concept of OFV, which is created by adding a safety buffer to the VTOL procedure volume. As shown in Fig. 10, the procedure volume is a conical space that extends upward and outward from the FATO edge, with its dimensions listed in Table 4. Expanding the procedure volume laterally by $0.25D$ and $0.5D$ yields the OFV. After expansion, the OFV has a length and a width of $\text{FATO}_{\text{back}}+\text{FATO}_{\text{front}}+0.5D$ and $\text{FATO}_{\text{width}}+0.5D$ at height h_1, respectively, and $\text{FATO}_{\text{back}}+\text{FATO}_{\text{front}}+1D$ and $\text{FATO}_{\text{width}}+1D$ at height h_2, respectively (see Table 4 for variable definitions) (European Union Aviation Safety Agency, 2022).

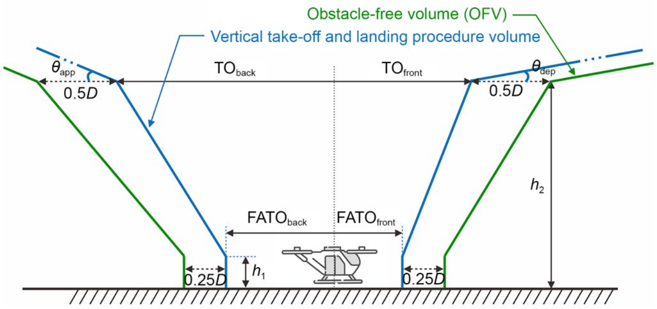


Fig. 10 Design method for the obstacle-free volume in the EASA standard (European Union Aviation Safety Agency, 2022)

Table 4 Dimensional requirements for the VTOL procedure volume (European Union Aviation Safety Agency, 2022)

Parameter	Short description	Minimum/Maximum
h_1	Low hover height	
h_2	High hover height	$\geqslant h_1$
TO_{width}	Width at h_2	$\leqslant 5D$
TO_{front}	Front distance at h_2	$\leqslant 5D$
TO_{back}	Back distance at h_2	$\leqslant 5D$
$\text{FATO}_{\text{width}}$	FATO width	$\geqslant 1.5D$
$\text{FATO}_{\text{front}}$	Front distance on the FATO	$\geqslant 0.75D$
$\text{FATO}_{\text{back}}$	Back distance on the FATO	$\geqslant 0.75D$
θ_{app}	Slope of the approach surface	$\geqslant 4.5\%$
θ_{dep}	Slope of the departure surface	$\geqslant 4.5\%$

The CASA and CAAC propose another OFV model. Here, the OFV is a truncated cone space whose lower base coincides with the SA. The difference between the diameters of the lower and upper bases grows with height: for every 100 ft (30.4 m) of height, the upper-base diameter increases by $1D$. In addition, the CASA and CAAC attach a set of transitional surfaces whose lower edge starts at the circumscribed square around the upper base of the cone and rises outward at the same gradient as the approach/take-off climb surface until the maximum width of this surface is reached (Civil Aviation Safety Authority, 2022; Civil Aviation Administration of China, 2024b).

In summary, the OFV concept provides a more economical and practicable obstacle protection scheme for the operation mode illustrated in Fig. 8b. Although this take-off and landing configuration can also be evaluated using OLS surfaces, the low starting height of the OLS often brings obstacles in the vicinity of the VTOL infrastructure into the restricted zone even when they do not, in practice, compromise operational safety. This, in turn, complicates site selection for urban VTOL infrastructure. By contrast, OFV-based protection can be more effectively tailored to dense urban environments, facilitating the deployment of UAM-oriented VTOL infrastructure.

Owing to the fundamentally different safety baselines required for manned versus unmanned operations, current research on obstacle clearance management for VTOL infrastructure has focused primarily on eVTOL, whereas studies and practical implementations targeting UAV VTOL are scarce. As large-scale commercial UAV operations continue to expand, the absence of dedicated obstacle clearance management frameworks will directly constrain operation safety and efficiency; addressing this gap is therefore an urgent research priority.

4.2 Terminal airspace design

Terminal airspace serves as the interface between en route flight segments and arrival/departure procedures, enabling effective sequencing and holding of multiple aircraft during peak demand periods, thus being a critical enabler of safe, efficient, and large-scale commercial UAM operations.

From a structural perspective, terminal airspace layouts are classified as ring and route network structures. Kleinbekman et al. (2018, 2020) proposed a ring-structured terminal airspace for eVTOL infrastructure, laying the groundwork for subsequent studies. Bertram and Wei (2020) introduced the concepts of an approach ring and arrival gate, redefining the ring as a flyable circular track rather than a mere boundary. With automation emerging as a key goal for urban VTOL infrastructure, later studies made ring tracks more plentiful and functional. Zeng YX et al. (2021) designed a dual-ring terminal airspace for UAV VTOL infrastructure; Chen et al. (2023) proposed a four-ring configuration comprising an outer ring, an operation ring, a holding ring, and an inner ring; Joby Aviation and NASA subsequently adopted this layout in the first eVTOL terminal-area instrument-flight procedures (Zahn et al., 2023). As identical radii or altitudes would demand extensive clear airspace, many researchers have introduced an inverted-frustum design, in which concentric rings expand radius with height (Shao Q et al., 2021; Shao MX, 2021; Song K et al., 2021; Song K and Yeo, 2021; Lei et al., 2023; Lei, 2023; Song K, 2023; Yang et al., 2024; Zhao and Yuan, 2024). Based on this geometry, Lei (2023) and Lei et al. (2023) devised a method for merging two landing pads into a single terminal airspace.

By contrast, few route network structures have been proposed. Zeng GQ et al. (2019) developed a single-entry single-exit network with intersecting routes and multiple pads for UAV VTOL infrastructure. As this layout lacked provisions for emergency landings, Cui et al. (2020) introduced additional emergency nodes above the entry gate and each pad.

From the standpoint of approach-holding procedures, terminal airspace designs are classified as continuous-flight holding or hover-holding. In the layout of Kleinbekman et al. (2018, 2020), eVTOL aircraft perform speed and glide path adjustments while flying continuously; however, this design suffers from a low airspace capacity and limited flexibility available to controllers. To enlarge capacity, Chen et al. (2023) added a discrete holding ring divided into segments: when demand exceeds the vertiport capacity, the automated air traffic management (ATM) system directs aircraft to circle the ring and assigns the required number of segments. While effective, this approach accommodates only arrivals. Shao et al. split the holding ring into approach and departure halves, enabling the simultaneous sequencing of inbound and outbound traffic without enlarging the airspace footprint (Shao Q et al., 2021; Shao MX, 2021).

Hover-holding designs distribute fixed waiting points evenly around a ring; aircraft hover at these points and move between inner and outer rings according to the prescribed rules. Song et al. proposed such a layout, defined four eVTOL strategies (SBA, BQA, SBAM, and BBQA), and examined their efficiency and safety via simulations (Song K et al., 2021; Song K and Yeo, 2021; Song K, 2023). Zhao and Yuan (2024) devised a UAV terminal airspace with hover-holding that accounts for drone noise and navigation errors. Both designs serve arriving traffic only. To support mixed arrivals and departures, Yang et al. (2024) separated inbound and outbound drones into two altitude layers within a hover-holding structure, maximizing safety margins.

Research on the terminal airspace design for VTOL infrastructure remains at an early stage, and neither academia nor industry has yet reached a broad consensus on how terminal airspace requirements should differ between eVTOL and UAV VTOL infrastructure. Against this backdrop, this section provides a systematic review of domestic and international research from the perspectives of terminal airspace structure and arrival holding procedures. Table 5 compares the (dis)advantages of the principal terminal airspace designs discussed above.

Terminal airspace concepts based on route network structures combined with hover-based holding procedures offer the benefits of simple operational scheduling and low risk of in-air conflicts within the controlled volume. However, these concepts suffer from high noise exposure and elevated energy consumption and are therefore more suitable for unmanned aircraft with simple avionics, small acoustic and energy footprints, and short interarrival time, particularly in the case of hub-type logistics UAV VTOL infrastructure. By contrast, eVTOL aircraft are larger and exhibit higher noise and energy use, thus being poorly suited for such designs. Owing to their more advanced avionics, these aircraft are better aligned with terminal airspace architectures based on ring-shaped structures and continuous-flight holding procedures, which can provide greater airspace capacity and more relaxed obstacle clearance requirements around eVTOL infrastructure.

4.3 ATM and operational scheduling

In conventional civil aviation, arrival–departure sequencing is typically handled by algorithms such as first-come first-served

Table 5 Advantages and disadvantages of the four terminal airspace design types

Classification dimension	Terminal airspace category	Advantages	Disadvantages
Airspace structure	Circular (ring) pattern	1. Omnidirectional arrivals/departures 2. Large airspace capacity 3. Low obstacle clearance requirements	1. Complex arrival/departure sequencing 2. High risk of collision within the airspace
	Route network pattern	1. Simple arrival/departure sequencing 2. Low collision risk	1. High noise 2. Limited adaptability to different aircraft types
Arrival-holding procedure	Continuous-flight holding	1. Large airspace capacity 2. Low energy consumption	1. Complex arrival/departure sequencing 2. High risk of collision within the airspace
	Hover-holding	1. Simple arrival/departure sequencing 2. Low collision risk	1. High noise 2. High energy consumption

(FCFS), constrained-position shifting, time-advance, and optimal-window sequencing (Erzberger and Itoh, 2014). However, low-altitude vehicles in UAM operate under much tighter battery endurance constraints, and their on-demand mission profiles preclude reliable flight planning. Consequently, a highly automated scheduling and resource allocation system is required.

4.3.1 ATM at eVTOL infrastructure

NASA has proposed the Vertiport Automation System for high-density eVTOL operations. This system responds to aircraft resource requests in real time and strategically allocates vertiport assets, thereby supporting resource management and operational sequencing (Northeast UAS Airspace Integration Research Alliance, 2021).

Pradeep and Wei (2019) introduced a heuristic that combines insertion local search with a time-advancing algorithm and mixed-integer linear programming (MILP) to optimize approach sequencing for heterogeneous eVTOL fleets, demonstrating real-time performance. This method was later extended by coupling insertion local search with MILP or a time-advance heuristic to shorten landing time under aircraft heterogeneity (Pradeep and Wei, 2020).

Earlier studies optimized sequences in free airspace without reference to a structured terminal layout. Kleinbekman et al. (2018) incorporated a ring-structured terminal airspace, formulated an MILP that minimized operational delay subject to vertiport capacity and battery constraints, and provided the first optimal solution for such an environment. Building on this concept, Kleinbekman et al. (2020) proposed a rolling horizon sequencing algorithm that minimizes deviations from scheduled take-off and landing time, with simulations showing average peak-period delays of ~50 s and off-peak delays of <10 s. Bertram and Wei (2020) refined the airspace structure and developed a self-organizing arrival–departure sequencing algorithm based on a Markov decision process, demonstrating its ability to maintain separation and mitigate collision risk. Shao et al. devised an adaptive control system for multipad vertiports that integrates path planning with distributed sequencing via a back-pressure strategy (Shao Q et al., 2021; Shao MX, 2021). Chen et al. (2023) built on Pradeep's work to produce an optimization algorithm that manages terminal airspace and ground operations in an integrated manner.

4.3.2 ATM at UAV VTOL infrastructure

Research on sequencing at UAV VTOL infrastructure is scarce. Zeng GQ et al. (2019) and Cui et al. (2020) applied graph-theoretic methods to arrival–departure sequencing at multipad UAV VTOL infrastructure. Zhang et al. (2023b) addressed flight plan allocation for logistics UAVs in urban environments, formulating a pre-tactical planning model that minimizes transport and delay costs under multiple constraints. Shen Z (2024) proposed a sequencing model based on the Hungarian algorithm that achieved operation costs lower than those obtained using FCFS. Chang et al. (2024) introduced a dynamic priority take-off time scheduling method: mission priority was determined via entropy-weight and fuzzy clustering approaches, a cost-minimization model was formulated, and a genetic algorithm provided the solution.

Existing research on ATM and operational scheduling for VTOL infrastructure typically formulates terminal-area sequencing models with objective functions that minimize total delay or total energy consumption while incorporating constraints such as minimum landing separation and thresholds on the remaining battery state-of-charge. These models are then solved using commercial optimizers and intelligent metaheuristics, such as genetic and ant colony algorithms, to determine the aircraft landing sequence (Table 6).

The corresponding limitations are as follows: first, dynamic uncertainties such as weather variability and knock-on flight delays are generally not modeled, and system robustness has not been rigorously validated, which limits applicability in complex airspace environments. Second, most studies focus exclusively on arrival sequence optimization for UAVs, neglecting departure procedures and thus precluding integrated arrival–departure management while overlooking emerging scenarios such as air–ground intermodal operations. Third, the prevailing use of static optimization frameworks complicates the accommodation of the highly time-varying traffic patterns induced by on-demand UAM services, and real-time scheduling capabilities are largely absent.

Table 6 Comparison of different scheduling algorithms

Scheduling algorithm	Reference	Core advantage	Core limitation
Commercial solvers (Gurobi, CPLEX, and IPOPT)	Kleinbekman et al., 2018, 2020; Pradeep and Wei, 2019; Chen et al., 2023	Can ensure optimal scheduling solutions and, by supporting various optimization formulations, accurately capture UAV/eVTOL aircraft operational constraints	For large-scale traffic, the solution time notably increases, and disturbances such as weather or temporary restrictions require re-solving, which limits real-time adaptability
Genetic algorithm	Song K and Yeo, 2021; Chang et al., 2024	Can handle multiobjective scheduling problems, including the total delay and the total energy consumption	Owing to the stochastic nature of this algorithm, solution reproducibility and determinism are weak, which renders it unsuitable as the sole decision-making core in safety-critical contexts
Hungarian algorithm	Shen Z, 2024	For scheduling problems that can be formulated as a flight-time-slot assignment, this algorithm can rapidly compute and guarantee a globally optimal solution	Mainly used for local allocation subproblems in scheduling and has difficulty covering the complete arrival–departure scheduling on its own
Ant colony algorithm	Shao Q et al., 2021; Shao MX, 2021	Well-suited for scheduling in complex route networks and offers good robustness	Requires many parameters and converges slowly, which complicates convergence in high-frequency rolling scheduling
Insertion local search algorithm	Pradeep and Wei, 2020	Performs well for handling real-time disruptions by locally adjusting an existing arrival–departure schedule	Relies on the initial schedule and exhibits a weak global exploration ability

5 Communication, navigation, surveillance, and information technologies for VTOL infrastructure

5.1 Comparative CNSI requirements for eVTOL and UAV VTOL infrastructure

CNSI technology refers to the integrated suite of capabilities tailored for both manned eVTOL aircraft and UAVs and extends this framework by superimposing an information service layer upon the foundational communication, navigation, and surveillance infrastructure. This layer is dedicated to the aggregation and processing of operational data, including micrometeorological conditions and electromagnetic environments. The CNSI requirements of eVTOL and UAV VTOL infrastructure fundamentally differ because the two aircraft classes employ distinct operational modes. Table 7 compares the CNSI capabilities of eVTOL and UAV VTOL infrastructure.

Designed for passenger transport, eVTOL infrastructure must address stringent safety demands, dynamic obstacles, and dense airspace coordination, thus requiring multimodal navigation, low-latency antijamming communications, and real-time wide-area surveillance.

Table 7 Communication, navigation, surveillance, and information (CNSI) capabilities of eVTOL and UAV VTOL infrastructure

Capability category	Parameter/Requirement	eVTOL infrastructure	UAV VTOL infrastructure
Communication	Technical standard	Must support high-reliability, low-latency aviation-grade links (e.g., 5G-A/6G, satellite links, and dedicated aviation bands)	Ordinary wireless links (e.g., Wi-Fi, 4G/5G in civilian bands) and lightweight telemetry links
	Data bandwidth	High-bandwidth demand (real-time flight control, environmental sensing, and multivehicle coordination data)	Low-to-medium bandwidth demand (mainly control commands and basic status data)
	Antijamming capability	Must meet stringent anti-interference standards (e.g., electromagnetic compatibility certification)	Basic antijamming, relies on environmental separation or simple dual-band switching
	Multilink redundancy	Dual or multilink redundancy is required (e.g., satellite+ground station)	Primarily single-link, redundancy only in certain scenarios
Navigation	Precision requirement	Centimeter-level accuracy (RTK/PPP-augmented GNSS+INS, vision/LiDAR SLAM fusion)	Meter-level accuracy (standard GNSS, differential GPS in some cases)
	Dynamic update rate	High-rate updates, supports complex airspace dynamic obstacle avoidance	Medium-to-low rate updates, suitable for simpler environments
	Terrain-aided navigation	Requires integrated DEM, 3D maps, and real-time obstacle databases	Relies on preset geofences or basic obstacle avoidance logic
	Backup navigation system	Independent backup navigation needed	No independent backup normally available
Surveillance	Surveillance technologies	Integrated surveillance (ADS-B, radar, optical sensing, and UTM system fusion)	Basic surveillance (remote ID, GPS tracking, and simple optical monitoring)
	Coverage scope	Wide-area surveillance	Local-area surveillance
	Data-processing capability	Real-time fusion of multisource heterogeneous data (air traffic awareness, conflict prediction, etc.)	Lightweight processing (trajectory logging, basic status monitoring)
	Cooperative surveillance is needed	Must interconnect with ATC systems and UAM networks	Operates independently, only links to the local regulatory platform
Information	Data precision requirements	Given that eVTOL aircraft involve passenger transport and are predominantly deployed in dense urban airspaces, high-precision real-time local micrometeorological data are needed	Operations dominated by lightweight commercial and industrial UAVs typically require only fundamental local meteorological data
	Data coverage dimension	Systems must cover comprehensive information on both dynamic and static obstacles across all dimensions to facilitate collision avoidance via real-time sensing	Dynamic obstacle monitoring generally focuses on low-altitude small aircraft, and the requirements for information coverage scope and real-time performance are notably more relaxed than those for eVTOL vertiports
	Data standards and compliance	Operations must comply with civil aviation airworthiness certification standards, which necessitates robust capabilities for data redundancy and fault-tolerant backup	UAVs must adhere to local and industry-specific management regulations, but their requirements for data redundancy and compliance are considerably less stringent than those of the civil aviation-grade standards mandated for eVTOL aircraft
	Interference detection and mitigation	A system for eVTOL infrastructure is required to support multiband links and conduct full-spectrum electromagnetic environment monitoring and should be capable of real-time electromagnetic interference detection and frequency conflict warning	UAVs use relatively singular communication bands, requiring only basic electromagnetic environment monitoring and employing more simplified interference mitigation strategies

RTK: real-time kinematic; PPP: precise point positioning; 5G-A: 5G-advanced; LiDAR: light detection and ranging; SLAM: simultaneous localization and mapping; DEM: digital elevation model; UTM: unified threat management; ATC: air traffic control; GPS: global positioning system; Wi-Fi: wireless fidelity

Seamless integration with the current aviation system mandates bidirectional dynamic airspace negotiation, four-dimensional trajectory prediction, and automated conflict resolution. To meet aviation-grade CNSI standards and crewed-aircraft certification, eVTOL CNSI systems must feature full redundancy, high-integrity positioning, and continuous monitoring.

UAV operations focus on mission-specific tasks and have lower redundancy requirements. These flights are typically confined to segregated airspace with limited interaction with crewed aviation, and the corresponding airworthiness standards are less stringent. Accordingly, UAV CNSI systems can be simplified, rely predominantly on one-way data flows, and employ modular selectively installed components.

Communication, navigation, and surveillance are indispensable for scheduling eVTOL aircraft and UAVs. Incorporating digital information services for the airspace surrounding a vertiport, this study proposes a CNSI architecture suited for low-altitude vertiport environments (Fig. 11). The architecture illustrates the technical layering of a CNSI system and delineates differentiated adaptation schemes for UAVs and eVTOL aircraft through clearly defined functional modules.

5.2 Communication facilities

5.2.1 Communication facilities for eVTOL infrastructure

eVTOL aircraft typically undertake manned missions, and their communications must provide very low latency, high reliability, and long-range connectivity. Currently, most manned eVTOL aircraft adopt a single-pilot simplified vehicle operation (SVO) philosophy, which uses advanced automation, e.g., automatic obstacle avoidance and trajectory planning, to reduce pilot workload and enhance safety. SVO represents a transitional stage from piloted flight to full autonomy; by progressively increasing automation, it will ultimately enable uncrewed operations, lower costs, and broaden use cases. For beyond-line-of-sight environments where terrestrial links are unavailable, Huaxun Chuangtong (2024) developed a Tiantong satellite data-link terminal that supports small embedded platforms such as UAVs and eVTOL aircraft, providing adaptive control and real-time telemetry via satellite when ground networks are absent.

During dense urban operations, at the vertiport, eVTOL traffic must meet UAM minimum-separation standards, which impose latency requirements (on the order of 10 ms) stricter than those in conventional aviation, so that remote pilot-out and autonomous functions can be activated (Baltaci et al., 2021). Researchers including Zaid et al. (2023) have examined technologies that endow eVTOL aircraft with powerful computational capabilities, such as cloud/fog computing, multiaccess edge computing, and digital twins. 6G cellular networks are expected to deliver true three-dimensional (3D) connectivity for aerial platforms. Liu GH et al. (2025) noted that low-altitude missions, up to 120 m above ground level (AGL), can leverage the existing 5G infrastructure. By distinguishing between active-antenna units and single-beam 5G remote radio units (RRUs), the authors proposed differentiated coverage schemes for low-altitude communications.

The communication systems for eVTOL infrastructure are evolving toward multilink redundancy. This evolution aims to support the end-to-end ultralow latency, high reliability, and wide-area continuous coverage required for the transition of SVO to higher levels of automation. However, notable challenges remain. The low-altitude operational environment is characterized by 3D occlusions and

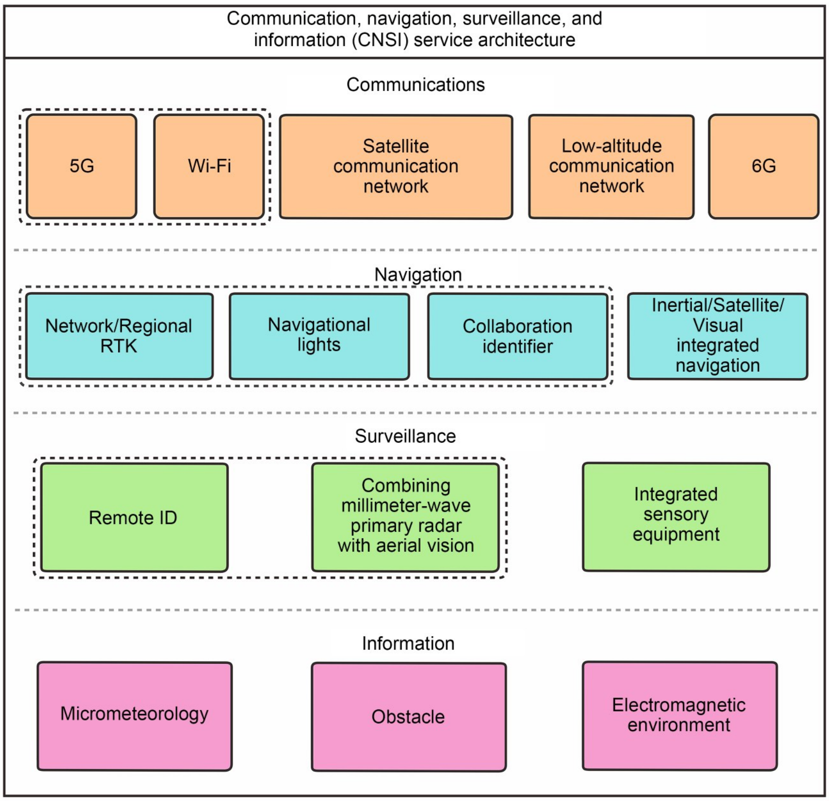


Fig. 11 Architecture of the CNSI services (dashed modules apply to UAVs; remaining modules apply to eVTOL aircraft)

complex electromagnetic conditions, leading to multipath effects and frequent handovers. Furthermore, issues regarding cochannel coexistence and the management of interference between public networks and private avionics links persist. Given the immaturity of 6G standards, the high cost of dedicated low-altitude networks, and the latency and the occlusion susceptibility of satellite communications, the current infrastructure struggles to stably meet the millisecond-level latency and high-availability targets required for advanced SVO in complex urban environments.

5.2.2 Communication facilities for UAV VTOL infrastructure

Given that UAVs are typically assigned short-range missions, their communications emphasize low power consumption, low cost, and short-distance links. In areas lacking 4G/5G coverage, Wi-Fi is recommended for UAV-to-VTOL infrastructure communications (Hou and Gao, 2011; Civil Aviation Administration of China, 2023). DJI's OcuSync system, for example, enables low-latency control during take-off and landing, ensuring precise maneuvering (DJI, 2021).

As UAV communication demands continue to grow, a single communication mode is unlikely to suffice because each technology has inherent limitations (He et al., 2021). In the future, 5G-A or 6G base stations that integrate communication, sensing, and computing functions are expected to supply real-time airspace status and obstacle data to UAVs, enabling dynamic path adjustments.

Conversely, the development of communication facilities for UAV VTOL infrastructure is driven by the requirements of the low power consumption, cost-effectiveness, and short-range reliability. Near-field communications typically employ Wi-Fi or proprietary vendor links for command and control and video backhaul, with multilink redundancy added as necessary. However, constrained by the limited energy budget of terminal devices, the stability of end-to-end latency, connection retention, and handover performance often fails to consistently meet the reliability targets required for varying mission assurance levels.

5.3 Navigation facilities

5.3.1 Navigation facilities for eVTOL infrastructure

Helicopters rely on conventional mechanical control and visual-flight rules, whereas eVTOL aircraft employ SVO or full autonomy, and medium-to-large UAVs usually follow preset routes with remote control intervention. System-level design in terms of navigation equipment compatibility and integrated technical standards is required to enable the collaborative operation of these three vehicle classes in shared vertiport space. The successful maiden flight of EHang EH216-S at Shanghai Longhua Heliport demonstrated the interoperability of eVTOL and helicopter navigation equipment. A BeiDou/GPS ground-based augmentation system provided unified high-accuracy positioning services; an automatic dependent surveillance-broadcast (ADS-B) receiver station deployed at the vertiport, together with a secondary radar, enabled target tracking in hybrid airspace; an inertial/satellite/vision integrated navigation technology delivered continuous high-reliability positioning information under complex urban conditions (Jiang, 2021). By combining LiDAR, visual SLAM, and an inertial measurement unit, a unified environmental perception model accommodating the take-off and landing guidance needs of different aircraft types was established.

As most eVTOL aircraft operate with a single pilot, many manufacturers are strengthening the use of performance- and vision-based navigation technologies. Dream Aerospace equips its crewed eVTOL aircraft with multispectral cameras and millimeter-wave radars to recognize obstacles and perform autonomous avoidance in complex environments, with vision algorithms parsing runway markings and weather conditions in real time. Industry prototypes already demonstrate capabilities for automated take-off and landing for piloted eVTOL aircraft: EH216-S completed the world's first uncrewed eVTOL test integrated with an airport in China, with its automatic take-off and landing system exchanging real-time data with ATC via a 5G link throughout taxi, lift-off, and touchdown.

Gao et al. (2025) reviewed the progress in the development of vision navigation methods based on deep reinforcement learning (RL) over the past five years and concluded that future work must further enhance the navigation performance and practical value in complex open environments. Integrating image-based navigation, cooperative navigation techniques, and supplementary ground infrastructure can greatly improve accuracy. The fusion of GPS and cellular networks can reduce positioning errors to 15 cm (Shibasaki, 2019) and even 2 cm under favorable conditions (Niu Z et al., 2019). To mitigate interference in dense urban settings, Lu YJ et al. (2023) proposed an inertial/satellite/vision fusion algorithm based on improved graph optimization that effectively suppresses sensor errors caused by environmental changes.

Looking ahead, the convergence of airworthiness standards, multisource navigation integration, multimodal sensor fusion, and redundant architectures will allow helicopters, eVTOL aircraft, and medium-to-large UAVs to coexist safely at the same VTOL infrastructure.

Navigation facilities for eVTOL infrastructure are shifting from visual references and single Global Navigation Satellite System (GNSS) reliance typical of the helicopter era to multisource fusion schemes integrating GNSS, inertial navigation systems (INSs), visual navigation, and ground-based auxiliary equipment. Although existing research and trials indicate that integrated navigation provides notably higher positioning accuracy than traditional equipment and that automated guidance functionalities for single-pilot and SVO modes are advancing from validation to application, notable gaps remain, as exemplified by a lack of reproducible empirical evidence regarding navigation integrity, continuity, and availability under urban multipath and electromagnetic interference conditions. Furthermore, unified methodologies for assessing the impact of low visibility, strong reflections, and occlusion on visual and millimeter-wave sensors have yet to be established.

5.3.2 Navigation facilities for UAV VTOL infrastructure

As lightweight small UAVs are highly cost-sensitive, their navigation systems must balance affordability with functionality; to enable autonomous flight, they also need onboard processing and decision-making. Bauranov and Rakas (2021) and Liao et al. (2022) showed that RTK can greatly improve accuracy. In the vicinity of a vertiport, network-RTK corrections can be delivered via 4G/5G/Wi-Fi links; if the network fails, a Wi-Fi connection to a local RTK rover can still provide centimeter-level positioning. RTK, however, ultimately depends on GNSS, and the accuracy therefore sharply decreases in regions where signals are weak or disturbed (e.g., because of ionospheric activity). Lu YC et al. (2018) and Quan et al. (2020) reported that advances in vision navigation effectively overcome such limitations.

Vision-based methods maintain drift-free performance in GPS-denied environments, offer rich environmental information, work passively, and are cost-effective. Grlj et al. (2022) partitioned the landing phase into approach, precision positioning, and touchdown; the last step can achieve centimeter accuracy by combining visual guidance with docking station markers, while infrared light-emitting diodes (IR LEDs) or radio frequency (RF) beacons provide precision cues under low- or zero-visibility conditions. Zhong et al. (2023) showed that marker-based visual guidance enables centimeter-level autonomous landings for VTOL drones on static sites and summarized the progress in the development of markers and detection methods over the last decade. Beyond planar fiducials, Gui et al. (2013) devised a method that derives aircraft attitude from fixed IR lights on both sides of a runway.

In future practical mission execution, UAVs will often face the challenge of dynamic targets. Compared with static scenarios, dynamic ones are considerably more complex, placing higher demands on UAV navigation and control systems. Keller and Ben-Moshe (2022) designed a precise autonomous landing framework for dynamic targets, which ensures rotorcraft stability during landing under complex conditions, such as wind direction changes, dynamic obstacles, and moving landing platforms. Meng et al. (2019) proposed a vision/inertial integrated shipborne landing method for UAVs, expanding the application range of UAVs in dynamic environments. In future urban air traffic environments, UAVs will face issues such as unstable satellite positioning, signal interference, and high onboard computing power requirements from existing supplementary positioning systems. To address these challenges, Qu et al. (2025) proposed a lightweight UAV visual positioning system, providing a feasible visual solution for UAV positioning in urban air traffic environments.

In complex urban wind environments, autonomous UAVs must balance speed, safety, and energy efficiency under highly variable conditions. Traditional single-strategy RL controllers often underperform in scenarios outside their training distribution. To address this problem, Wu JH et al. (2025) fine-tuned a large language model (LLM) on simulation-derived environmental performance tuples to automate mode selection and enable the prediction of optimal strategies based on variables such as building density and wind speed. Although the results were promising, the mode space remained a discrete set, limiting the ability of the model to express continuous trade-offs.

Navigation for small-UAV VTOL infrastructure is evolving from single-satellite positioning to a multisource fusion architecture incorporating real-time kinetics, visual–inertial navigation integration, cooperative markers, and near-field reference guidance. Although RTK supported by cellular networks achieves high precision, its overall performance is constrained by satellite availability and interference. Similarly, visual and inertial methods perform well in static, well-lit environments, but lack systematic evidence of robustness and long-term calibration maintenance in complex urban scenarios featuring low visibility, glare, occlusions, and dynamic platforms. The absence of unified standards for the size, encoding, and deployment of cooperative markers and near-field references, coupled with inconsistent interoperability and evaluation benchmarks, currently hinders the scalable operation and validation of automated drone nests.

5.4 Surveillance facilities

5.4.1 Surveillance facilities for eVTOL infrastructure

Effective eVTOL traffic monitoring can be achieved using ADS-B, 5G-A integrated sensing and communication technology, or low-altitude airspace surveillance networks. Although some operators recommend ADS-B, its dedicated spectrum may face oversaturation in very high density environments (NASA, 2002); advanced surveillance systems that overcome these limitations are therefore urgently required (Templin et al., 2017). ISAC, one of the major innovations envisioned for 5G-A/6G, enables large-scale low-altitude regulatory networks that unify terrestrial and airspace coverage. Starting from application scenario requirements, Wang LL et al. (2025) analyzed key millimeter-wave ISAC techniques, driving communication technology toward higher efficiency and intelligence. By fusing BeiDou satellite communications, ADS-B, 5G, and other technologies, China completed its first province-wide low-altitude surveillance network in 2023, greatly enhancing the monitoring and communication capabilities of general aviation and unmanned aircraft below 500 m AGL (Hunan General Aviation Development Co., Ltd., 2023; Wu M and Wan, 2023).

This section proposes surveillance systems for eVTOL infrastructure centered on ADS-B and augmented by low-altitude airspace surveillance networks and ISAC technologies. However, the risk of ADS-B frequency saturation in high-density operations lacks sufficient validation. Furthermore, there is a lack of systematic evaluation regarding the detection performance, false alarm control, and coverage continuity of ISAC and millimeter-wave technologies under urban and near-ground clutter conditions.

5.4.2 Surveillance facilities for UAV VTOL infrastructure

Small and very small UAVs can be monitored through Wi-Fi, remote network monitoring, or remote identification (remote ID) broadcasts over Bluetooth. Regulations issued by the State Administration for Market Regulation in 2023 (State Administration for Market Regulation and National Standardization Administration, 2023) require such UAVs to broadcast identification data via Wi-Fi or Bluetooth during flight and upload remote ID information to regulatory platforms. The Civil Aviation Administration of China (2024a) further stipulated that broadcast identification must be receivable by ground stations within a 100-m radius of the UAV ground projection. Accordingly, UAVs operating below G-class airspace and within 100 m of the vertiport can be actively monitored via remote ID—data that may be captured over the Internet, Wi-Fi, or Bluetooth—whereas those beyond 100 m must be tracked via Internet-based services.

Medium UAVs can be monitored by combining Internet links with millimeter-wave primary radar and upward-looking vision sensors. The Airworthiness Certification Department of CAAC (2024) stipulated that medium UAVs must be capable of being monitored in the airspace and connected to the authority's regulatory system or its equivalent. Although Internet-based monitoring fulfills this requirement, access to regulatory data streams is necessary. Active surveillance works only for cooperative targets and is ineffective against noncooperative or rogue drones when cooperative drones lose navigation. Traditional civil-aviation radars are generally unsuitable for low-altitude UAV monitoring owing to cost and technical constraints. Drawing on the runway foreign-object-debris detection technology, Li PW (2012) recommended a hybrid solution that integrates millimeter-wave primary radar with upward-looking vision to facilitate the surveillance of medium UAVs.

Small and microscale UAVs can use Bluetooth remote ID broadcasts and network remote identification for active surveillance. For medium UAVs, noncooperative targets, unauthorized operations, and cooperative targets with navigation failures, surveillance can be achieved via Internet-based tracking or primary millimeter-wave radar combined with air-to-air visual technologies. However, current systems heavily rely on cooperative surveillance. The capabilities for identifying and managing noncooperative targets, rogue flights, and abnormal states of cooperative targets during navigation degradation are insufficient. Additionally, the detection range of remote ID is limited, and minimum compliance surveillance capabilities distinguished by aircraft type and mission level have not yet been solidified into actionable configuration tables or validation processes, which hinders consistent engineering inspection and delivery.

5.5 Information services

Low-altitude weather is highly variable: sudden strong winds, low visibility, rain, or snow can directly affect the stability and trajectories of eVTOL aircraft and UAVs. Current low-altitude meteorological sensing technologies are insufficiently mature to predict microweather in real time, which may impair flight and dispatch decisions. Dense urban obstacles—buildings, power lines, and billboards—may block flight paths and increase collision risk; inadequate obstacle clearance management around VTOL infrastructure can prevent safe VTOL or emergency avoidance. In addition, electromagnetic interference can disrupt command-and-control links or degrade navigation signals and thus cause control loss or route deviation.

The digital processing of micrometeorology, obstacles, and electromagnetic data for VTOL infrastructure and its surroundings and delivering these data to operators and aircraft in real time are therefore of practical importance. Aldao Pensado et al. (2024) proposed an approach that combines automated 3D modeling with computational fluid dynamics to enhance weather-sensing capability but omits fine details such as buildings and vegetation and is computationally intensive, which limits its applicability in dense urban areas. Liao et al. (2022) emphasized that high-precision meteorological data—meter-level spatial resolution with updates at hourly or even minute intervals—are key to UAV operations. The authors also noted that UAV CNSI systems are vulnerable to electromagnetic and terrain interference, calling for high-quality obstacle and terrain databases. Meeting these requirements entails equipping VTOL infrastructure with microscale meteorological sensors, digital terrain-and-obstacle databases for the vertiport and its vicinity, and electromagnetic environment monitors to comprehensively upgrade operational assurance.

The core of information services lies in the high-frequency granular digital representation of the micrometeorology, obstacles, and the electromagnetic environment surrounding the vertiport, which provides verifiable real-time or quasi-real-time support data to operators and aircraft. Despite progress in automated 3D modeling, microweather sensing, and high-precision data requirement definition, services in high-density urban scenarios remain limited by building occlusion, lack of vegetation detail, high computational overhead, and the trade-off between high resolution and timeliness. Mechanisms for dynamic updating, change detection, and version control of 3D obstacle databases remain immature.

6 Design framework for public UAV VTOL infrastructure

In future low-altitude operations, VTOL infrastructure will need to support multiple operators and diverse procedures, accommodate various types of uncrewed aircraft, and balance the safety, cost-effectiveness, and public service obligations. Building on the preceding review and recognizing that forthcoming UAM traffic will involve diverse vehicle types and dense high-frequency operations, this section proposes an innovative conceptual framework for shared public UAV VTOL infrastructure. This framework is particularly well-suited for future deployment in public logistics hubs serving commercial districts, where it can allow multiple logistics providers to share VTOL infrastructure, avoid redundant construction, and thus offer a UAM solution that combines equitable access to low-altitude airspace with economic efficiency.

1. Structural and layout design. Existing studies are largely tailored to a single aircraft type and seldom address the need for contingency landings that may arise when endurance is exhausted or the command-and-control link fails (DJI, 2024). To fill this gap, we outline a layout that includes a dedicated emergency landing zone and supports both very small and medium UAVs. The field comprises one medium-UAV pad, several very-small-UAV hives, corresponding contingency areas, segregated pedestrian–cargo corridors, and an emergency landing zone (Fig. 12). Each hive is two-dimensionally offset from the centerline of its contingency area (where *D* is the full footprint of the hive); the FATO and SA of the hive are used together with those of the contingency area. The dimensional parameters of the remaining components are given in Fig. 13.

2. Terminal airspace design. Merging the advantages of ring and route network structures, we propose a layered outer-ring inner-network configuration that satisfies the requirements of multipad operations and emergency landing (Figs. 14 and 15).

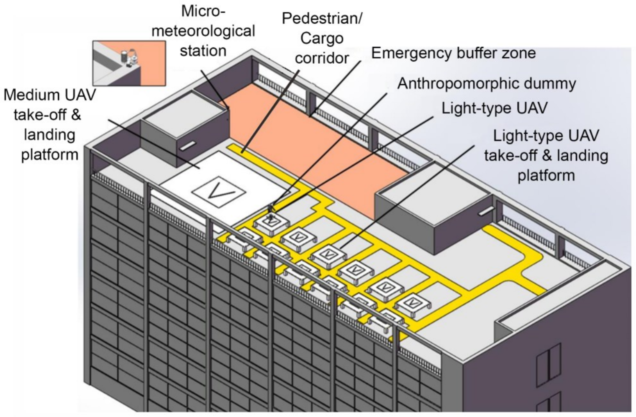


Fig. 12 Schematic layout of multitype UAV VTOL infrastructure incorporating an emergency landing zone

In Fig. 14, the proposed terminal airspace is horizontally divided into holding, maneuvering, and docking zones. The holding zone contains approach-holding points (12) that can be stratified by altitude. No fixed routes are laid out in the maneuvering zone between the holding zone boundary (11) and docking zone boundary (21); paths are generated dynamically, e.g., via dueling deep Q-network (DQN) (Garcia et al., 2023) or FastMDP (Bertram and Wei, 2020); however, flight levels must match those of the holding points to balance efficiency and safety (Sunil et al., 2015, 2017; Hoekstra et al., 2016; McCarthy et al., 2020; Pang et al., 2020). Vertically, the airspace comprises an emergency landing layer, multilevel approach layer, and a departure layer.

Inbound UAVs leave a holding point, fly through the maneuvering zone at an approach layer altitude to the assigned spot in the docking zone, and descend vertically to the pad (31). In an emergency, an aircraft enters directly at the emergency layer inlet and lands in the emergency zone. Outbound flights lift off from the pad, climb within a straw-shaped departure corridor to the departure layer, and exit via the departure gate.

3. ATM scheduling. For this public UAV VTOL infrastructure, we propose a multioperator coordination architecture. The arrival and departure booking workflow (Fig. 16) allows operator *B* to query available slots for pad *A*, reserve 10:00–11:00, and receive automatic artificial intelligence (AI) approval that locks the resources; a conflicting request by operator *A* is declined with alternative suggestions.

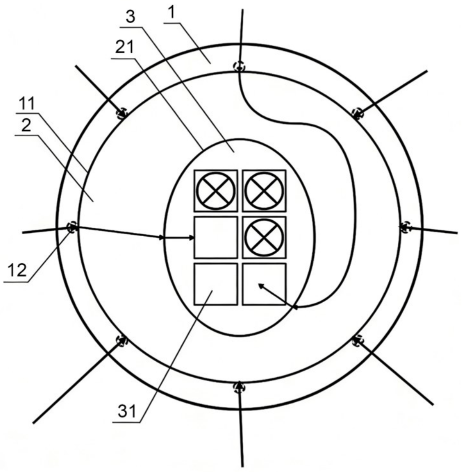


Fig. 14 Plan view of the layered outer-ring inner-network terminal airspace

The multioperator take-off coordination process is shown in Fig. 17. Operator *B*'s departure flight via route *A* must complete pre-departure checks in advance. At the scheduled take-off time, clearance is requested from the VTOL infrastructure system. After the system intelligently confirms that the UAV meets the take-off criteria, the request is approved. During take-off, operator *B* must continuously report the UAV status until take-off is complete. Concurrent requests by operator *A* trigger a "route unavailable" notification until resources are freed and preparations are finalized.

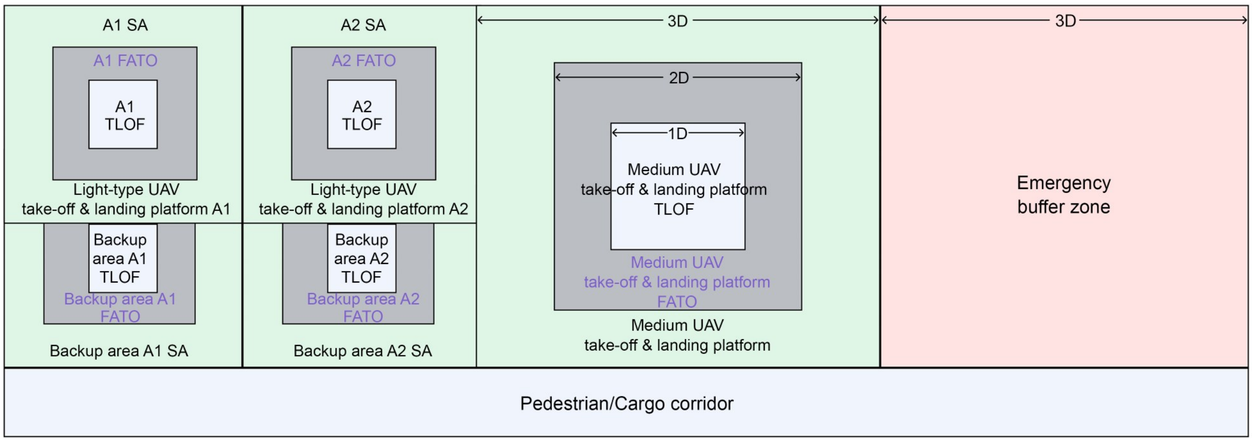


Fig. 13 Dimensional parameters of the surface layout of the VTOL infrastructure

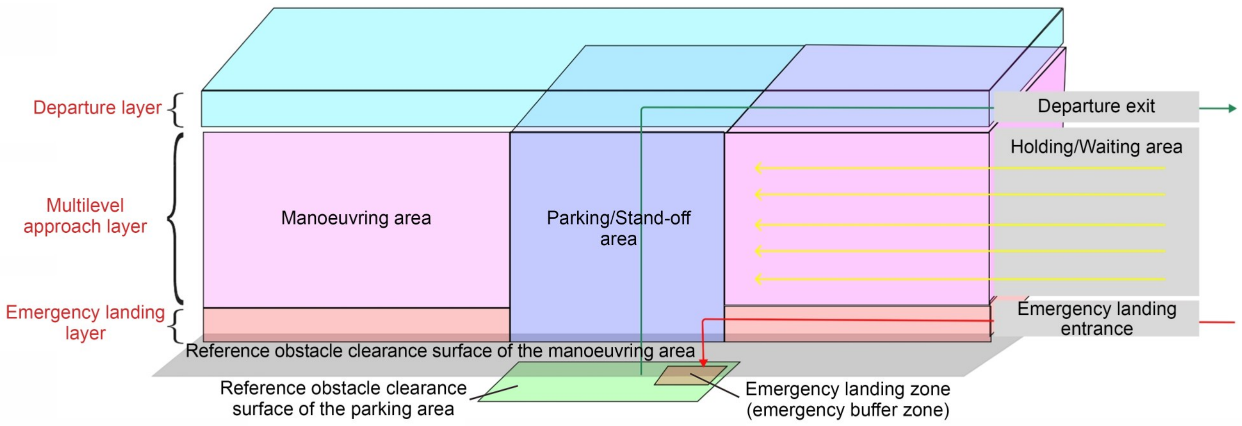


Fig. 15 Elevation view of the layered outer-ring inner-network terminal airspace

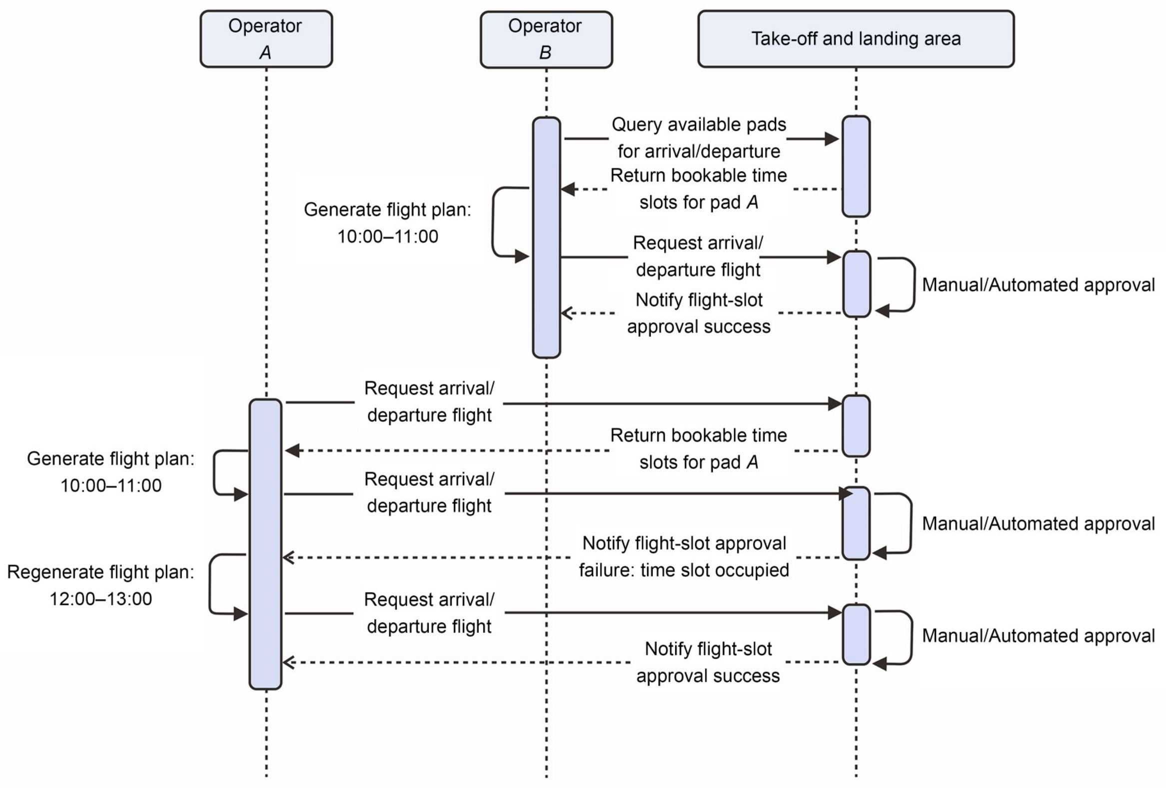


Fig. 16 Coordination workflow for multioperator arrivals and departures at the public UAV VTOL infrastructure

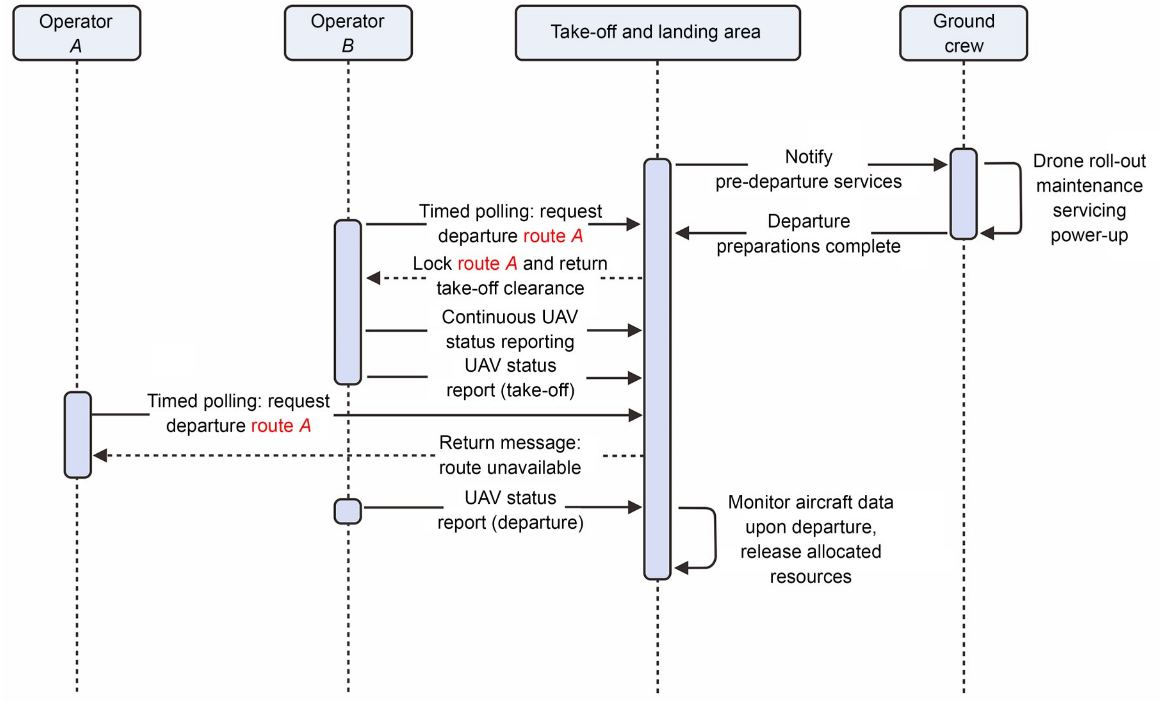


Fig. 17 Multioperator take-off coordination workflow at the public UAV VTOL site infrastructure

The multioperator landing coordination process is shown in Fig. 18. When operator *B*'s UAV needs to return to the public VTOL infrastructure, this infrastructure completes pre-arrival preparations for the UAV in advance. Once the UAV reaches the approach holding point in the terminal airspace, operator *B* requests landing clearance from the system. After confirming that the UAV meets the landing criteria, the system approves the request. During landing, operator *B* must continuously report the UAV status until landing is complete. For concurrent requests by operator *A*, the system provides other available routes to guide it to alternative pads.

The multioperator process of arrival/departure emergency take-over coordination is shown in Fig. 19. When a UAV cannot land normally, operator *B* may apply for an emergency buffer zone. Applications are allowed if the UAV is on route or has departed from the route. In case of conflict with operator *A*, the system notifies operator *A* to halt take-off or formulate optimal landing decisions for already airborne UAVs. Upon successful application, operator *B* may opt to submit a landing request. After the emergency, the ground crew manages the scene, recovers the UAV, and determines if emergency resource usage has concluded.

At present, this conceptual framework remains at the theoretical design stage. To assess its effectiveness, this chapter conducts simulations to quantitatively compare the operational efficiency and airspace capacity of the proposed terminal airspace structure against a representative linear airspace configuration (Zhang et al., 2022a). The airspace structure introduced in this paper was contrasted with a typical line-shaped design, and the SimPy Discrete-Event Simulation Library in Python was used to run 100 simulation trials for a fleet of 100 UAVs (Fig. 20). Reflecting current low-altitude application scenarios, the simulations restricted attention to a single representative category of small multirotor UAVs with an MTOW not exceeding 25 kg. In linear airspace, UAVs fly and hold sequentially along a

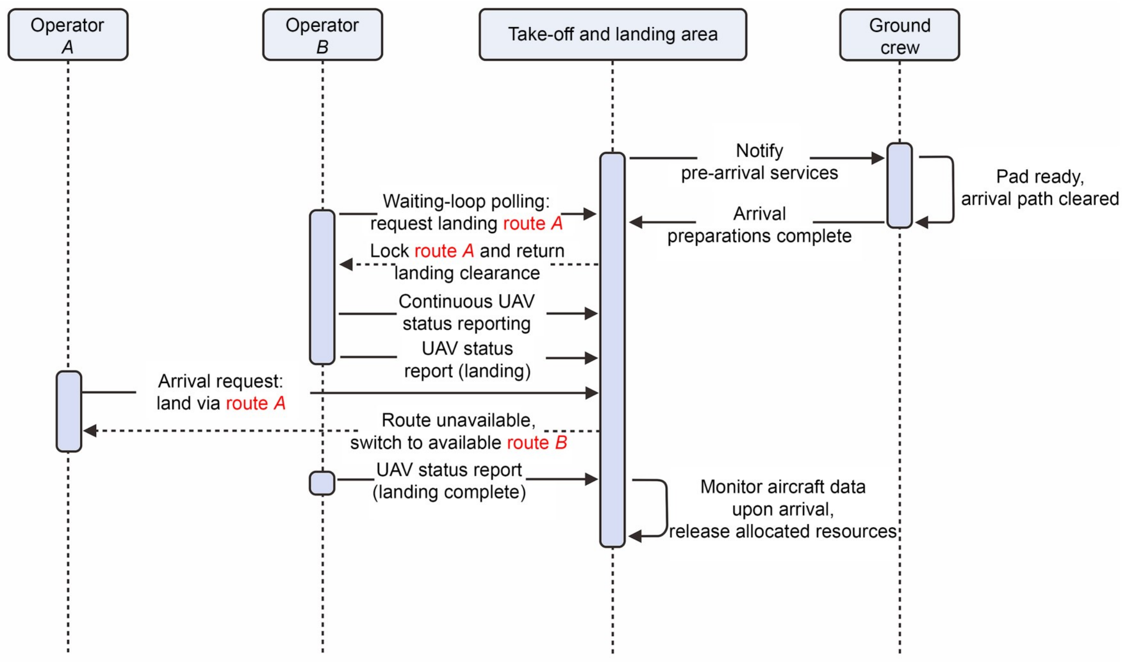


Fig. 18 Multioperator landing coordination workflow at the public UAV VTOL infrastructure

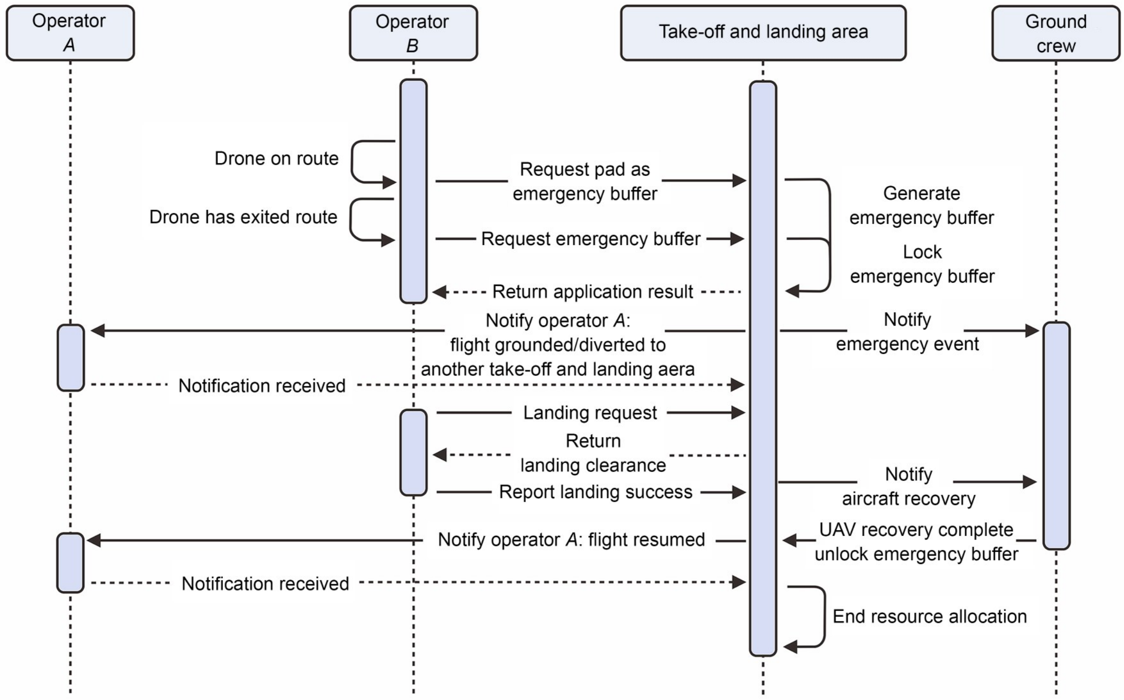


Fig. 19 Emergency handover coordination workflow for multioperator arrival–departure operations at the public UAV VTOL infrastructure

single horizontal and vertical route segment at the minimum required horizontal separation before landing on any available TLOF. In the ring-shaped airspace, UAVs first wait at designated holding points and then proceed to an available final approach point (FAP) and subsequently land on the corresponding TLOF.

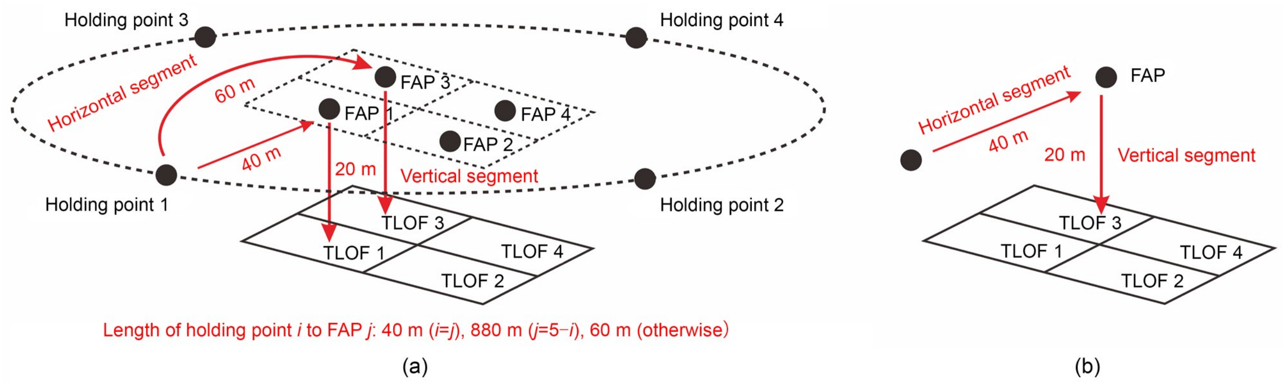
The following assumptions were made: UAVs enter the terminal airspace according to a Poisson arrival process, a minimum temporal separation must be maintained between any two UAVs within the airspace, and after landing, each UAV occupies a TLOF for a certain service time to emulate on-pad position adjustment and towing. The detailed simulation parameters are listed in Table 8. The simulation campaign evaluated the average waiting time of UAVs in two types of terminal airspace and the achievable airspace capacity under a specified upper bound on the average waiting time.

Fig. 21a presents quantitative results for the average waiting time. At Poisson arrival rates of 200, 250, and 300 UAVs per hour, the proposed airspace structure consistently yielded shorter average waiting time than the linear configuration. Moreover, an inspection of empirical distributions showed that the proposed design afforded more tightly clustered results, indicating that the ring-shaped terminal airspace was less sensitive to randomness in the arrival stream and exhibited higher robustness than its linear counterpart.

Fig. 21b provides a quantitative comparison of airspace capacity. The simulations were performed assuming a maximum allowable average waiting time of 90 s, with the capacity of a given airspace structure defined as the maximum number of UAVs per hour, for which the overall average waiting time (i.e., the mean of the per-trial average waiting time) remains at 90 s (Zhang et al., 2022b). With the increasing arrival rate, the overall average waiting time increased for both airspace designs. For the proposed ring-shaped structure, the overall average waiting time reached 90 s at a Poisson arrival rate of 262 UAVs per hour, which corresponds to an airspace capacity of 262 UAVs per hour. According to the same criterion, the capacity of the linear airspace was estimated as 228 UAVs per hour. Thus, the proposed design achieved superior airspace capacity.

7 Future directions

Key technologies related to the land-side, air-side, and CNSI subsystems of VTOL infrastructure systems have been extensively researched, and numerous design methodologies and optimization strategies tailored to different classes of aircraft have been proposed.

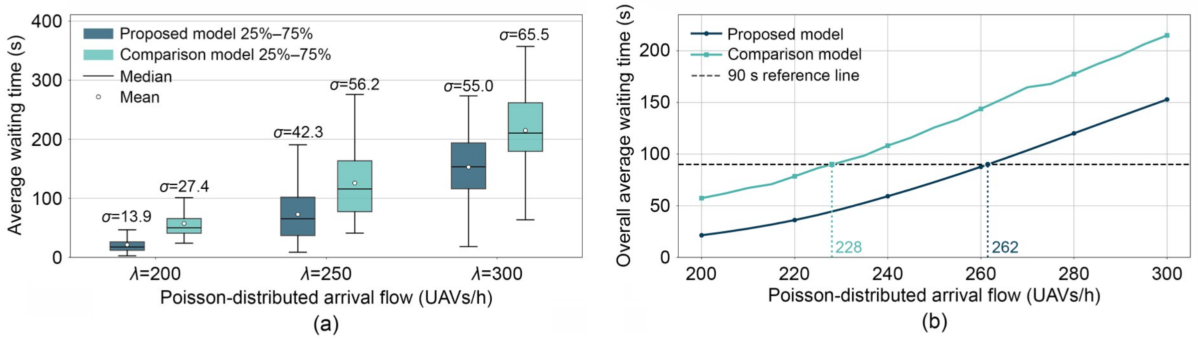


(a) (b)

Fig. 20 Schematic of the simulated airspace structures: (a) the terminal airspace; (b) the linear terminal airspace

Table 8 Simulation parameters

Parameter name	Parameter value	Parameter name	Parameter value
Number of TLOFs	4	Poisson arrival rate	200–300 h^{-1}
Flight speed of the UAV horizontal segment	5 $m\cdot s^{-1}$	TLOF service time	60 s
Flight speed of the UAV vertical segment	2 $m\cdot s^{-1}$	Number of UAVs	100
Simulation count	100	UAV's minimum flight separation	20 m



(a) (b)

Fig. 21 Quantified simulation results for the average waiting time (a) and airspace capacity (b)

Multiple countries have issued standards to regulate the construction and operation of VTOL infrastructure, while the industry is actively advancing practical deployment, with numerous VTOL infrastructure systems already built and in operation. However, many critical issues remain to be addressed. Below, we highlight prospective research directions for the key technologies underpinning VTOL infrastructure.

7.1 Ground-side technologies for VTOL infrastructure

The future structural design of VTOL infrastructure should focus on three main lines of research. First, the International Civil Aviation Organization (ICAO) should accelerate the development of harmonized standards that clearly specify the physical configurations, charging technologies, and related requirements for both eVTOL and UAV VTOL infrastructure to avoid substantial redundant costs arising from incompatibility during manufacturing, certification, and operation. Second, systematic studies are needed on retrofitting existing building rooftops into eVTOL infrastructure, including comparative reviews of national regulations and approval procedures, technical analyses of structural retrofit methods, assessments of building typologies suitable for conversion, and simulation-based modeling of wind fields and flight-path optimization. Such studies would underpin the standardization and evidence-based planning of retrofit-type VTOL infrastructure. Finally, the structural design of cabinet-type UAV VTOL infrastructure should be extended to incorporate interoperability with ground unmanned vehicles, enable coordinated air–ground intermodal operations, and thereby accelerate the practical deployment of low-altitude logistics distribution.

From the perspective of VTOL infrastructure layout, most current studies on topological design focus on single-objective optimization (Vascik and Hansman, 2019; Zelinski, 2020; Ahn and Hwang, 2022; Preis, 2023). Future work should advance toward multiobjective formulations that jointly optimize spatial utilization and throughput. Existing research typically assumes square-shaped sites for VTOL infrastructure (Zelinski, 2020; Li JF, 2023; Zhang et al., 2023a). Subsequent studies should broaden the design space to include circular, rectangular, and other nonsquare geometries and quantitatively analyze the relationships among site shape, the number and capacity of landing/TO zones, and the overall land take. At present, estimations of the minimum separation between functional zones heavily rely on computer simulation (Shen A et al., 2018; Wang BH et al., 2019; Liu C et al., 2022; Caprace et al., 2023; Meyer-Oehme et al., 2023; Ison, 2024; Larose et al., 2024). Experimental validation with real aircraft will be required to calibrate design parameters under realistic wind fields and aerodynamic interference conditions, ensuring the engineering applicability of the proposed layouts. Finally, future work should focus on the aerodynamic interference characteristics of different aircraft types during take-off and landing to provide a rigorous scientific basis for layout design at VTOL infrastructure shared by heterogeneous fleets.

7.2 Airspace-side technologies for VTOL site infrastructure

Regarding obstacle clearance management at VTOL infrastructure, no unified standards governing obstacle limitations are available for UAVs. In practice, site selection still heavily relies on the manual avoidance of surrounding obstacles, and systematic design methodologies are lacking. Given the similarity between the VTOL profiles of UAVs and electric aircraft, future work could draw on the OFV concept developed for eVTOL infrastructure (Civil Aviation Safety Authority, 2022; European Union Aviation Safety Agency, 2022; Japan Civil Aviation Bureau, 2023; Civil Aviation Administration of China, 2024b) while tailoring the OFV geometry and dimensions to the specific characteristics of UAVs, including their size, navigation accuracy, and resilience to disturbances. Relevant research directions include the dynamic envelope modeling of take-off and landing, statistical characterization of trajectory deviations, and quantitative assessment of ground-collision risk, facilitating the development of air-side protection schemes that can be adapted to different vehicle types and operating environments.

In terms of terminal airspace design, most existing studies are based on idealized assumptions (Kleinbekman et al., 2018, 2020; Zeng GQ et al., 2019; Bertram and Wei, 2020; Cui et al., 2020; Shao Q et al., 2021; Shao MX, 2021; Song K et al., 2021; Song K and Yeo, 2021; Zeng YX et al., 2021; Chen et al., 2023; Song K, 2023; Lei et al., 2023; Lei, 2023; Zahn et al., 2023; Yang et al., 2024; Zhao and Yuan, 2024) and do not fully capture complex real-world scenarios such as the partial loss of usable terminal airspace due to obstacle intrusion or prevailing strong winds that effectively render certain approach directions unavailable. Future work should therefore focus on terminal airspace structures and operating rules resistant to such complexities to ensure flexible and safe airspace utilization. The delineation of terminal airspace must more explicitly integrate environmental considerations along two dimensions. On one hand, minimum separation distances from high-voltage transmission lines and other sources of electromagnetic interference should be defined to shield operations from adverse environmental effects. On the other hand, appropriate stand-off distances from sensitive ground receptors, such as hospitals and schools, should be established to mitigate noise pollution and privacy risks associated with frequent VTOL operations and thereby enhance the alignment between airspace design and the urban environment.

For ATM and operational scheduling in VTOL infrastructure, future research should be tightly coupled with terminal airspace design and focus on multipad, multitype, and multioperator scenarios with large numbers of arriving and departing vehicles. Theoretical models must jointly account for aircraft performance parameters, flight dynamics characteristics, real-time state feedback, and contingency procedures. In addition, VTOL operations inevitably induce local flow field perturbations; under high-density traffic, aerodynamic interactions among multiple vehicles may notably affect recovery scheduling in the terminal area. Consequently, future work should explicitly incorporate intervehicle aerodynamic interference when designing dispatch strategies for clearing backlogs to simultaneously ensure the safety and timeliness of scheduling in high-density airspace.

7.3 CNSI technologies for VTOL infrastructure

1. Communication. Current research often relies on idealized assumptions, failing to capture the complexity of real-world scenarios. For eVTOL infrastructure, future research must establish 3D low-altitude coverage and dynamic beamforming models. Critical tasks include the derivation of synchronization and queue consistency

conditions for cellular-private-satellite multilink collaboration, establishment of upper bounds for end-to-end latency and availability, and construction of coexistence interference evaluation criteria alongside unified key performance indicators (KPIs). For UAV VTOL infrastructure, research should focus on the joint optimization of energy consumption and reliability under urban near-ground occlusion constraints. This task will involve the development of probabilistic models for multilink collaborative handovers, provision of verifiable upper bounds for latency and drop rates, and formulation of mission-level KPIs and scenario-based experimental designs.

2. Navigation. For eVTOL infrastructure, a robust integrity, continuity, and availability assessment framework suitable for urban multipath and electromagnetic interference environments is essential. Future works should refine fault detection, isolation, and recovery mechanisms for multisource fusion, propose relative navigation strategies under GNSS-denied conditions, define error propagation and calibration strategies for landing reference maintenance, and quantify constraint transmission from navigation performance to protection volumes, procedural parameters, and surface scheduling safety margins. For UAV VTOL infrastructure, research should advance the fusion integrity assessment of visual-inertial-near-field references, derive error propagation expressions for online recalibration and long-term stability, and clarify the relationship between navigation metrics and the constraints on protection volumes and flight procedures.

3. Surveillance. For eVTOL infrastructure, research must model channel loading and collision probabilities for ADS-B in high-density operations and propose congestion mitigation methods. Methodologies for evaluating the detectability and false alarm control of ISAC and millimeter-wave systems under near-ground clutter and occlusion conditions are also required. For UAV VTOL infrastructure, the detectability and interface availability of remote ID in urban environments should be addressed by establishing coverage models driven by receiver sensitivity, occlusion, and channel contention. Furthermore, methods for noncooperative track maintenance, time reference consistency, and identity verification using millimeter-wave primary radar and air-to-air vision fusion should be investigated.

4. Information services. The minute-level nowcasting and uncertainty characterization of microscale wind fields should be advanced. Spatiotemporal alignment and cross-source calibration processes for multisource data should be refined, and electromagnetic environment models should be coupled with link budgets and dynamic updates of 3D obstacle databases. Ultimately, a multisource assimilation and uncertainty characterization system for microweather, obstacles, and electromagnetic environments should be established to enable probabilistic outputs for nowcasting, data version governance, and the publication of open benchmarks and evaluation metrics covering urban scenarios.

Future research should also focus on the integration of security and airworthiness, specifically designing risk assessments and security assurance levels driven by threat modeling, constructing diverse orchestration and observable resilience metrics for multilink systems (5G, private networks, and satellite), and developing cross-source integrity monitoring and trusted timing for GNSS, differential positioning, vision, ultra-wideband (UWB), and radar. By establishing unified interfaces and evaluation benchmarks and strengthening log forensics and security assurance evidence chains, the industry can shorten certification cycles, reduce lifecycle costs, promote cross-vendor interoperability, and enhance public and insurer acceptance through interpretable metrics, thereby supporting city-scale networked operations.

7.4 Integration of LLMs and UAM

LLMs are autoregressive models that are primarily based on the Transformer architecture and capable of understanding and generating natural language. As the LLM technology matures, its integration with UAM is deepening, with practical applications expanding in scope and form. Moraga et al. (2025) integrated LLMs with UAV-based surveillance systems and Internet of Things (IoT) sensors, demonstrating the potential of UAV-enhanced IoT frameworks for adaptivity and LLM-enhanced frameworks for smart cities. Gong et al. (2025) combined deep RL with LLM reasoning to propose a UAV trajectory planning algorithm aimed at ensuring safety, economic efficiency, and compliance in low-altitude airspace. Although this algorithm provided effective decision support for challenges such as dynamic obstacles and energy consumption, its adaptability in complex urban environments requires further validation. Sadik et al. (2025) proposed an intelligent, holistic architecture incorporating LLMs to manage UAM complexity; this framework operates semi-autonomously to facilitate real-time coordination between air taxis, ground transport, and vertiports.

The relationship between LLMs and UAM is becoming increasingly synergistic, as reflected by preliminary achievements in technical breakthroughs, scenario applications, and ecosystem construction. Driven by supportive policies, iterative optimization of core technologies, and growing public acceptance, the application of LLMs in UAM is expected to expand into critical areas such as vertiport scheduling and CNSI management. This expansion will provide essential technical support for enhancing the operational efficiency and safety of UAM systems, ultimately reshaping the future of urban mobility.

8 Conclusions

Progress in the key technologies for VTOL infrastructure in UAM is reviewed from ground-side, airspace-side, and CNSI perspectives, and an innovative design framework for a public UAV VTOL infrastructure serving multiple operators is proposed based on the multitype high-density characteristics of future operations. On the ground side, the framework extends the existing single-pad single-aircraft model by introducing a multipad composite layout that includes an emergency landing zone. On the airspace side, it combines the advantages of ring and route network structures to propose an outer-ring layered guidance concept with an inner dynamically allocated network. For public use scenarios, the framework presents a multioperator coordination architecture that covers arrivals and departures, routine take-off and landing, and emergency operations. This study provides a comprehensive understanding of VTOL infrastructure-related key technologies and useful insights and references for future research.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (No. U2333214).

Author contributions

Chenglong LI conceptualized the study, developed the overall framework, acquired the funding, provided key resources, and reviewed and edited the paper. Runming WANG curated the data, conducted the formal analysis, carried out the investigation, developed the methodology, prepared the visualizations, and drafted the original paper. Zhaoxuan ZHANG contributed to the investigation, curated the data, prepared the visualizations, and drafted the original paper. Yuan ZHENG contributed to the methodology and validation, and reviewed and edited the paper. Yang WANG contributed to the methodology, prepared the visualizations, and drafted the original paper. Rui YANG contributed to the methodology and validation, and reviewed and edited the paper.

Conflict of interest

All the authors declare that they have no conflict of interest.

Declaration on the use of generative AI tools

During the preparation of this work, the authors used ChatGPT to improve language. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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