Fine-Grained Urban Low-Altitude Airspace Gridding with Dynamic Event Response and Vertical Air-Route Corridors

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Abstract:

With the rapid growth of urban low-altitude applications, traditional airspace management approaches based on simple altitude limits and static no-fly zones can no longer meet the demands of high-density and highly dynamic operations. To address this issue, this study proposes a fine-grained gridding method for urban low-altitude airspace with dynamic event response and vertical flight corridor constraints. First, a unified three-dimensional grid model is constructed on the basis of an urban 3D digital twin platform, and the grid scale and update cycle are determined by jointly considering clearance requirements and safety separation. Second, a method for injecting static and dynamic attributes is established to achieve the unified representation and continuous updating of terrain, buildings, no-fly and restricted zones, wind fields, temporary restrictions, as well as occupancy and release information within the grid. Third, fixed-geometry and dynamically open vertical flight corridors are designed to support controlled cross-layer flight transitions and reduce the risk of vertical conflict propagation. An experimental system is developed using a typical high-density urban area in Yuehai Subdistrict, Nanshan District, Shenzhen, as the case study. The results show that the proposed method can achieve stable spatial discretization, accurate attribute loading and updating, and clear organization of cross-layer flight. The proposed method provides a unified technical framework for low-altitude airspace representation, state management, and operational governance in complex urban environments.

1. Introduction

In recent years, unmanned aerial vehicle platforms and autonomous sensing and navigation capabilities have improved significantly. As a result, low-altitude airspace has gradually evolved from a traditional environment characterized by single-aircraft, low-frequency, and short-range flights into a complex operational space in which multiple types of aircraft coexist, multiple tasks are executed concurrently, and multiple stakeholders participate collaboratively (Hamissi and Dhraief, 2024; Bauranov and Rakas, 2021). The continued growth of new urban services, including urban inspection, emergency rescue, power grid and pipeline inspection, logistics delivery, traffic sensing, environmental monitoring, and public safety support, has made urban low-altitude airspace an emerging infrastructure space that requires long-term governance, refined operation, and intelligent scheduling (Schuchardt et al., 2023). In this context, the organization and governance of urban low-altitude operations are undergoing a fundamental change. Conventional management approaches based on simple altitude limits, static no-fly zones, manual approval, and temporary local coordination are becoming increasingly inadequate for future high-density, routine, and dynamic low-altitude traffic operations (Lee et al., 2023).

Flight management in densely built urban space differs significantly from that in traditional civil aviation airspace (Aposporis, 2024). Urban low-altitude airspace has a smaller spatial scale, while building height differences are more pronounced, terrain variation is more evident, block morphology is more fragmented, and urban canyon effects are more prominent (Yang et al., 2024). As a result, the usability of airspace within the same urban area is highly uneven. In addition, the urban low-altitude environment is far more dynamic. Local wind fields, sudden control measures, temporary no-fly restrictions, and emergency task insertion can change airspace accessibility within a short period (Pongsakornsathien et al., 2025). For this reason, urban low-altitude airspace requires a new mode of representation and organization. Traditional methods centered on macroscopic airspace boundaries, fixed altitude bands, or a limited number of routes are often too coarse for urban environments (Wang et al., 2025a). They cannot adequately describe building clearance, local risk, temporary restrictions, or changes in operational state. In particular, under concurrent multi-UAV operations, if a sufficiently fine, updatable, and measurable spatial representation is unavailable, route planning, conflict detection, capacity management, and dynamic scheduling will lack a common foundation (Sengupta et al., 2025).

Airspace gridding aims to discretize continuous three-dimensional low-altitude space into a set of grid cells with clear rules, unique identifiers, extensible attributes, and updatable states (Yang et al., 2024). Each grid cell represents not only a geometric location and spatial extent, but also flight-related attribute information such as terrain constraints, building blockage, airspace availability, and risk. In this way, urban low-altitude space is transformed from a continuous space that is difficult to compute and manage directly into a discrete state space that can be computed, updated, and scheduled (Bauranov and Rakas, 2021). For unmanned traffic management systems, airspace grids are not merely a basic spatial representation. They are also a core medium linking digital twins, task scheduling, route planning, conflict detection, operation monitoring, and control intervention.

However, the application of airspace gridding to urban low-altitude scenarios still faces several key challenges. First, grid scale is difficult to determine. If the grid is too coarse, it cannot capture building distribution, permanent no-fly boundaries, or local risk differences, which may lead to distorted environmental representation and then affect path selection and safety assessment. If the grid is too fine, it will impose heavy pressure on data storage, state updating, and scheduling complexity, thus reducing system real-time performance and engineering feasibility. Second, the attribute information carried by existing spatial grids is generally incomplete. Many studies remain at the level of geometric representation or simple obstacle representation, and a unified attribute framework that can simultaneously support static environmental constraints and dynamic operational states has not yet been established. This limits the ability of the grid to truly support real-time flight management. Third, the constraint representation for cross-layer flight remains unclear. In real operations, UAVs do not always fly within the same altitude layer. Height transitions are common, especially in dense building areas, no-fly-zone detour scenarios, and multi-task convergence scenarios. If cross-layer transitions lack clear, unified, and controllable access rules, vertical conflict propagation can easily occur.

Against this background, this study proposes a fine-grained urban low-altitude airspace gridding method with dynamic event response and vertical air-route corridors. A fine-grained three-dimensional grid is established under a unified spatial reference. Static and dynamic attributes are then injected into the grid in a rule-based manner. On this basis, a flight corridor and node governance system with fixed geometry and dynamic opening is constructed. The main contributions of this study can be summarized in three aspects. The main contributions are as follows.

(1) A fine-grained three-dimensional grid model for urban low-altitude is proposed. Under a unified reference, the study presents a practical approach for determining grid scale and time step while balancing risk representation accuracy and computational cost, thereby providing an operable discrete representation for complex low-altitude space.

(2) A collaborative injection mechanism for static and dynamic attribute information is established. This mechanism integrates relatively stable environmental constraints and time-varying operational constraints into the grid state in a unified manner.

(3) A set of rules for fixed-geometry, dynamically open low-altitude vertical flight corridors and intersection nodes is designed. The method explicitly requires that cross-layer flight must be completed through designated corridors, and it suppresses flight interference through governance rules.

Overall, this study aims to establish a reproducible, scalable, and verifiable technical framework for high-density and highly dynamic urban low-altitude operations without significantly increasing geometric complexity.

2. Related Work

2.1 Grid Partitioning and Attribute Representation of Urban Low-Altitude Airspace

In recent years, with the continued advancement of research and regulatory development in Unmanned Aircraft System Traffic Management (UTM), the European U-space framework, and Advanced Air Mobility (AAM), the organization of urban low-altitude airspace has gradually shifted from coarse management based on uniform altitude limits and local no-fly zones to a refined representation oriented toward computation, allocation, and dynamic updating (Wang et al., 2025a). Existing reviews indicate that the main technical paradigms for low-altitude airspace organization include gridding, stratification, and networking. Among them, gridding has become an important research direction for complex urban scenarios because it can conveniently accommodate multi-source information such as the built environment, operational risk, capacity constraints, and time-varying states (Sengupta et al., 2025; Xu et al., 2025).

In specific methodological studies, researchers have begun to introduce urban digital twins, three-dimensional geographic information, and multi-source risk information into discrete modeling of low-altitude airspace. Pang et al. incorporated third-party risk into the cost model for UAV path optimization, showing that urban low-altitude route planning has moved from simple obstacle avoidance to a comprehensive trade-off between risk constraints and operational cost (Pang et al., 2022). ElSayed et al. developed an airspace discretization and trajectory optimization framework for high-density urban scenarios based on a digital twin city model and geofencing constraints, indicating that digital twin-driven three-dimensional airspace discretization already has strong engineering potential (ElSayed and Mohamed, 2024). Oh et al. proposed a comprehensive urban airspace assessment method from the perspectives of population exposure and airspace availability, highlighting the importance of high-resolution urban data for identifying flyable airspace (Oh and Yoon, 2024). Zhao et al. further evaluated the operational risk of advanced low-altitude transportation systems from the perspective of risk fields, promoting the evolution of environmental risk representation from discrete constraints to continuous risk distributions (Zhao et al., 2024). Since 2025, related studies have paid greater attention to the integrated modeling of three-dimensional airspace units and multi-source attributes. Feng et al. constructed a low-altitude airspace grid by combining vertical and horizontal partitioning, and injected building structure, population density, and composite risk into the grid for path planning and capacity assessment (Feng et al., 2025). Vincent-Boulay and Marsden discussed the spatial modeling of complex airspace risk factors based on a discrete global grid system (Vincent-Boulay and Marsden, 2025). Wang et al. proposed a three-dimensional low-altitude airspace risk assessment method based on multi-source data and pointed out that the same horizontal location may present significantly different risk levels at different altitude layers (Wang et al., 2025b). Wang et al. further introduced safety margin estimation into the low-altitude grid model and attempted to establish a link between risk representation and path safety redundancy (Wang et al., 2025c).

2.2 Low-Altitude Flight Corridors and Cross-Layer Governance

Low-altitude corridor research has progressively shifted from the planning of isolated flyable routes to the design of structured aerial networks for high-density urban operations. Existing studies suggest that corridor-based and network-based organization is more suitable than fully free flight because it enables directional flow control, capacity allocation, node coordination, and rule-based operation in complex urban airspace (Pongsakornsathien et al., 2025). Within this line of work, He et al. developed a corridor-based route network planning method for urban air delivery (He et al., 2022), while Li, Hansen, and Zou integrated path planning, conflict resolution, and airspace resource allocation into a unified traffic management framework for urban parcel delivery (Li et al., 2022). Subsequent studies further extended this direction to bi-level route network planning (Li et al., 2023), three-dimensional route and intersection design for multirotor UAVs (Li et al., 2024b), multilane intersection planning (Nagrare et al., 2024), and signalized conflict management through a digital traffic light strategy (McCorkendale et al., 2024). At the network level, congestion pricing (He et al., 2024), congestion-constrained airspace network design (Stuive and Gzara, 2024), and backup-capacity-oriented network planning (Wei et al., 2024) have been introduced to improve operational robustness and efficiency, while route network planning has also been examined from both construction and optimization perspectives (Li et al., 2024a). More recent studies have incorporated explicit risk constraints into corridor design (Lozano Tafur et al., 2025) and highlighted the high-dimensional coupling and computational complexity of city-scale air corridor planning (He et al., 2025). These studies collectively indicate that low-altitude corridor research has evolved toward an integrated framework involving network design, node control, congestion management, and risk-aware governance. However, the design of vertical corridors for cross-layer UAV operations, together with explicit rules for layer opening, capacity coordination, and node-level control, remains insufficiently addressed.

In summary, although current research on urban low-altitude airspace has made substantial progress in grid partitioning and attribute representation on one hand, and in corridor planning and node control on the other, a clear gap still exists between the two directions. More specifically, the granularity of low-altitude airspace discretization is still difficult to unify. Existing spatial grids still lack attribute information that can directly support flight management, especially integrated representations for static constraints, dynamic events, time-stamped states, and update sequences. At the same time, for UAV cross-layer flight, the geometric organization of vertical corridors, opening rules, capacity linkage mechanisms, and node coordination constraints remain insufficiently clear. For this reason, constructing a unified three-dimensional grid for urban low-altitude operations, injecting both static and dynamic attributes into the grid, and further establishing vertical corridors and governance rules for cross-layer flight are not only theoretically necessary but also of strong practical engineering significance.

3. Methods

3.1 Design of a Fine-Grained Three-Dimensional Grid Model for Urban Low-Altitude Operations

This study uses a realistic urban 3D digital twin platform as the basis for a unified discrete representation of urban low-altitude operational space. Urban low-altitude environments are characterized by complex building morphology, coupled operational constraints, and frequent state updates. For this reason, a regular three-dimensional grid is constructed under a unified spatial reference. Zoning and stratification are further introduced to enhance airspace representation. A unified grid supports stable spatial indexing. It also facilitates consistent integration with the digital twin platform, the flight management platform, and subsequent path planning and scheduling algorithms, see in Figure 1.

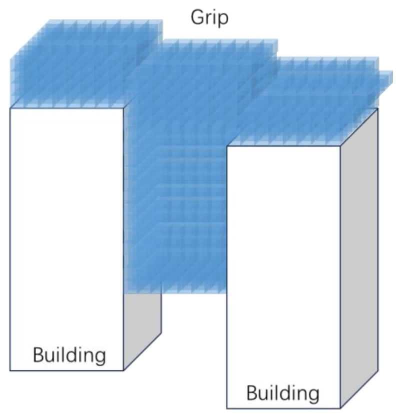

Figure 1. Schematic illustration of the spatial grid partitioning.

Let the horizontal extent of the study area be $[X_{\min}, X_{\max}] \times [Y_{\min}, Y_{\max}]$, and let the vertical operating range be $[Z_{\min}, Z_{\max}]$. Under the unified reference, a fixed horizontal resolution s and a fixed vertical resolution h are adopted. The grid cell $G_{i,j,k}$ is represented by its centre location as:

$$G_{i,j,k} = (x_i, y_j, z_k), x_i = X_{\min} + \left(i + \frac{1}{2}\right) s, y_j = Y_{\min} + \left(j + \frac{1}{2}\right) s, z_k = Z_{\min} + \left(k + \frac{1}{2}\right) \cap\ 1) \quad (1)$$

where i, j , and k are the discrete indices along the three coordinate directions. Each grid cell has a fixed size of $s \times s \times h$. Compared with interval-based boundary definitions, Eq. (1) uses a centerpoint representation with fixed dimensions. This form is more convenient for subsequent state updates. Building footprints, terrain boundaries, no-fly zones, wind effects, corridor extents, and corridor open states are all mapped onto this unified grid.

The grid resolution must balance risk representation accuracy and implementation cost. If the grid is too coarse, building boundaries, clearance conditions, and local restrictions cannot be represented accurately. This will reduce the accuracy of route planning and airspace control. If the grid is too fine, the number of grid cells increases rapidly, and the costs of state maintenance and computational scheduling also increase. To address this issue, the grid resolution is constrained by building clearance, safety separation, and environmental variation. Let d_{clr}^{xy} and d_{clr}^{z} denote the clearance control scales in the horizontal and vertical directions, respectively. Let v_{xy} and v_z denote the typical horizontal and vertical speeds of the aircraft. Let T_{sep} denote the minimum safety separation time. Let d_{env}^{xy} and d_{env}^{z} denote the environmental variation scales in the horizontal and vertical directions. The unified grid resolution is then defined as:

$$s = \min\left(d_{clr}^{xy}, v_{xy} T_{sep}, d_{env}^{xy}\right), h = \min\left(d_{clr}^{z}, v_z T_{sep}, d_{env}^{z}\right) \quad (2)$$

Equation (2) indicates that the horizontal and vertical grid resolutions should not exceed the upper limits required for effective risk representation. The objective is not to produce the finest possible discretization. Instead, the aim is to obtain a set of unified resolutions that can be implemented in practice while satisfying clearance representation, safety awareness, and environmental resolution requirements.

Low-altitude operational states vary in both space and time. Therefore, the grid model must include a unified control cycle. Let the time scale required for safety control be αT_{sep} , where $0 < \alpha \leq 1$. Let T_{upd} denote the update period of dynamic layers,

T_{com} the allowable delay for state synchronization, and T_{dyn} the characteristic time scale of significant state change. The control cycle is defined as:

$$\Delta t = \min(\alpha T_{sep}, T_{upd}, T_{com}, T_{dyn}) \quad (3)$$

Equation (3) ensures that the update frequency can satisfy the most critical safety requirement while avoiding excessive system burden caused by overly frequent updates. Equations (1) to (3) establish a unified space-time reference. In space, the urban low-altitude airspace is represented by fixed three-dimensional grid cells. In time, all states are updated under the same control cycle. On this basis, each grid cell can be associated with a zone label and a layer label, such as core operational zone, transition zone, and peripheral zone, as well as regular operating layer, transition layer, and restricted layer. These zone and layer semantics do not change the grid geometry. They only strengthen management-oriented representation across different areas and altitude layers.

3.2 Injection of Static and Dynamic Attribute Information

After the unified three-dimensional grid is established, attribute information is mapped into the grid in two categories, namely static attributes and dynamic attributes. Static attributes mainly correspond to terrain, building footprints and heights, and permanent no-fly or restricted zones. Dynamic attributes mainly correspond to wind field changes, temporary restrictions, occupancy, and release states that evolve over time. This distinction is necessary because the two types of attributes differ in data source, update frequency, and management meaning. Static attributes describe the inherent environmental characteristics of a grid cell. Dynamic attributes describe the actual operational state of a grid cell within the current control cycle.

To provide a unified representation, a static attribute vector is first defined for each grid cell:

$$\mathbf{S}_{i,j,k} = [b_{i,j,k}, n_{i,j,k}, c_{i,j,k}, p_{i,j,k}, r_{i,j,k}] \quad (4)$$

where $b_{i,j,k}$ indicates whether the grid cell is occupied by terrain or buildings, $n_{i,j,k}$ indicates whether the cell belongs to a permanent no-fly or restricted state, $c_{i,j,k}$ denotes the clearance margin, $p_{i,j,k}$ denotes the basic support level of communication and navigation, and $r_{i,j,k}$ denotes the semantic label of the zone-layer category to which the grid cell belongs. Equation (4) does not define a complicated high-dimensional model. It defines a set of basic attributes that directly support flight management. Based on these attributes, the system can first determine whether a grid cell has candidate accessibility under static conditions. For example, a grid cell occupied by a building located in a permanent no-fly zone, or lacking sufficient clearance should in principle be excluded from the available flight space.

On the basis of static attributes, dynamic attributes are further injected in an event-driven manner. Wind changes, temporary restrictions, and occupancy or release states all have explicit activation times, spatial ranges, and end conditions. Without an event-based mechanism, state sources can easily become mixed and difficult to trace. Let the set of dynamic events acting on grid cell $G_{i,j,k}$ at time t be denoted by $\mathcal{E}_{i,j,k}(t)$. The dynamic attributes of this grid cell within the current control cycle are expressed as:

$$\mathbf{D}_{i,j,k}(t) = [w_{i,j,k}(t), q_{i,j,k}(t), u_{i,j,k}(t), v_{i,j,k}(t)] = \Phi(\mathcal{E}_{i,j,k}(t)) \quad (5)$$

where $w_{i,j,k}(t)$ denotes the wind impact intensity, $q_{i,j,k}(t)$ denotes the temporary restriction state, $u_{i,j,k}(t)$ denotes the current occupancy level, $v_{i,j,k}(t)$ denotes the release state, and $\Phi(\cdot)$ denotes the event aggregation and state mapping function. Equation (5) shows that dynamic attributes are not assigned independently. They are generated by mapping all active events under a unified rule set. Therefore, they have clear sources and clear temporal boundaries.

Among the dynamic attributes, occupancy and release are the key variables that connect state representation with capacity management. Let $a^{+}_{i,j,k}(t)$ denote the number of flight activities entering grid cell $G_{i,j,k}$ during the control cycle $[t, t + \Delta t)$. Let $a^{-}_{i,j,k}(t)$ denote the number leaving the cell during the same period. Let $o_{i,j,k}(t)$ denote the current occupancy. The occupancy state at the next time step is updated as:

$$o_{i,j,k}(t + \Delta t) = \max\{0, o_{i,j,k}(t) + a^{+}_{i,j,k}(t) - a^{-}_{i,j,k}(t)\} \quad (6)$$

Equation (6) provides a simple recursive relation. It turns grid occupancy from a static label into a state variable that evolves continuously with flight activities. This variable directly affects the subsequent capacity update and accessibility judgment.

After the occupancy update is completed, static constraints and dynamic constraints are coupled to determine the actual operational state of the grid cell at the current time. Let $C^{0}_{i,j,k}$ denote the basic accessibility capacity under static conditions. Its value depends on the zone type, altitude layer, and baseline environmental conditions. Considering the effects of wind and temporary restrictions, the dynamic capacity of the grid cell in the current cycle is defined as:

$$C_{i,j,k}(t + \Delta t) = C^{0}_{i,j,k}(1 - \lambda_w w_{i,j,k}(t))(1 - \lambda_q q_{i,j,k}(t)) \quad (7)$$

where λ_w and λ_q are the influence coefficients of wind and temporary restrictions on capacity, respectively. Let the static accessibility indicator of the grid cell be:

$$\chi^{0}_{i,j,k} = \mathbf{1}(b_{i,j,k} = 0)\mathbf{1}(n_{i,j,k} = 0)\mathbf{1}(c_{i,j,k} \geq c_{\min}) \quad (8)$$

Then the accessibility of the grid cell in the current cycle can be written as:

$$\chi_{i,j,k}(t + \Delta t) = \chi^{0}_{i,j,k}\mathbf{1}[o_{i,j,k}(t + \Delta t) < C_{i,j,k}(t + \Delta t)] \quad (9)$$

where $c_{\min}$ is the minimum clearance threshold and $\mathbf{1}(\cdot)$ is the indicator function. Compared with a fully expanded form, Eq. (9) compresses the static conditions into $\chi^{0}_{i,j,k}$. This shortens the formula while preserving the same physical meaning. Equations (8) and (9) together show that the grid state no longer describes only spatial existence. It also indicates whether the grid cell is flyable at the current moment and how much traffic it can support.

Through Eqs. (4) to (9), the model achieves a unified transition from static environmental constraints to dynamic operational states, see in Figure 2. Static attributes define the basic boundaries of each grid cell. Dynamic attributes modify the current state in an event-driven manner. The occupancy update reflects the real-time operational load. Capacity correction and

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accessibility judgment transform these attributes into state variables that can be directly used by path planning, scheduling, and control modules. At the end of each control cycle, the system generates a time-stamped grid-state snapshot and incrementally publishes the grid cells whose states have changed. In this way, the grid system becomes not only a spatial partition, but also an evolving carrier of low-altitude operational states.

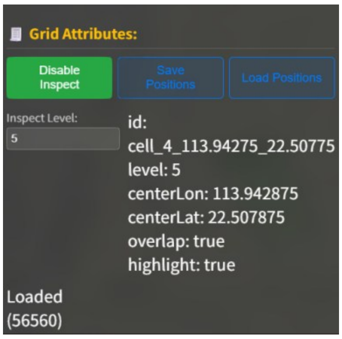


Figure 2. Schematic illustration of static and dynamic attributes.

3.3 Design and Rules of Low-Altitude Vertical Flight Corridors

After the grid model and attribute injection are completed, unrestricted climb, descent, and cross-layer flight are not allowed across all flyable grid cells. Under high-density urban operations, if aircraft are allowed to change altitude freely at arbitrary locations, vertical conflict accumulation can easily arise in hot spots, intersections, and task-converging areas. This would increase the complexity of surveillance, scheduling, and conflict resolution. To address this issue, this study proposes a design method for low-altitude vertical flight corridors. Fixed-geometry and dynamically open vertical transition channels are constructed on the basis of the unified grid. It is explicitly required that any aircraft changing altitude layers must use a vertical flight corridor rather than performing arbitrary climb or descent maneuvers in ordinary grid cells.

The low-altitude vertical flight corridor defined in this study is a set of contiguous grid cells selected and marked from the unified grid. The corridor is an organized subset of the grid. Its open state, capacity level, and operational constraints are all derived from the underlying grid states. The corridor geometry remains fixed. The main parameters include corridor width, lateral separation between adjacent lanes, vertical spacing between altitude layers, and the set of altitude layers that are allowed to open. Fixed geometry supports long-term planning and audit. It also helps maintain a stable spatial structure in practical systems. By contrast, dynamic changes are limited to layer opening and capacity adjustment. This improves the ability of the system to respond to environmental changes and operational disturbances, see in Figure 3.

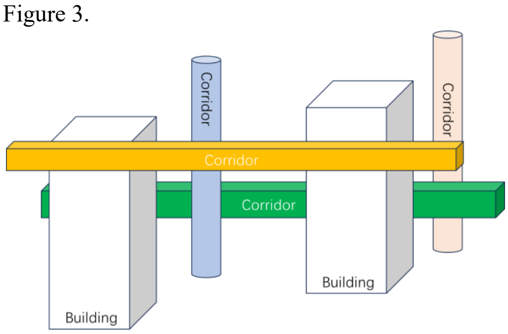


Figure 3. Schematic illustration of the spatial corridor configuration.

Let Γ_m denote the set of grid cells corresponding to the m-th vertical flight corridor. The effective residual capacity of this corridor at time $t+\Delta t$ is defined as:

$$Q_m(t+\Delta t) = \min_{G_{i,j,k}\in\Gamma_m} \{C_{i,j,k}(t+\Delta t) - o_{i,j,k}(t+\Delta t)\} \quad (10)$$

Equation (10) directly inherits the dynamic grid capacity $C_{i,j,k}(t+\Delta t)$ and the occupancy state $o_{i,j,k}(t+\Delta t)$ defined earlier. Its meaning is straightforward. The number of additional cross-layer flight activities that a vertical corridor can admit depends on the residual capacity of its most constrained grid cell. Vertical corridors usually occupy limited space, and the transition process requires continuity. Once a critical grid cell becomes overloaded, the entire transition process may be affected. Therefore, the bottleneck-capacity definition provides a robust representation of corridor capability.

On this basis, whether a cross-layer flight is allowed should be jointly determined by the corridor open state, the residual corridor capacity, and the node-control state. Assume that an aircraft plans to move from altitude layer k to altitude layer k' through corridor m. Let $\mathcal{L}_m^{\text{open}}(t+\Delta t)$ be the set of altitude layers opened in this corridor during the current cycle, and let $\Pi_m(t+\Delta t)$ denote the node-control permission state. The accessibility condition for cross-layer flight is written as:

$$\mathcal{A}_{k\to k'}^{(m)}(t+\Delta t) = \mathbf{1}\big(k,k' \in \mathcal{L}_m^{\text{open}}(t+\Delta t)\big)\mathbf{1}(Q_m(t+\Delta t) > 0)\mathbf{1}(\Pi_m(t+\Delta t)=1) \quad (11)$$

When $\mathcal{A}_{k\to k'}^{(m)}(t+\Delta t)=1$, the aircraft is allowed to complete the altitude transition through corridor m within the current cycle. Otherwise, it must wait for the next cycle, use another corridor, or remain at the current altitude layer. Equation (10) forms a clear progression with the previous equations. The grid model defines the spatial boundary. Attribute injection provides the current accessibility and capacity states. The corridor rule then gives the admission condition for cross-layer flight. As a result, vertical transition is no longer an arbitrary maneuver. It becomes a controlled behavior jointly constrained by grid states, corridor capacity, and node rules.

To maintain system stability, two basic governance principles are adopted. First, node phase adjustment and corridor layer-opening adjustment are not executed in the same control cycle. This prevents multiple control variables from changing simultaneously and causing abrupt local fluctuations. Second, safety constraints take priority over efficiency objectives. When strong wind, temporary restrictions, emergency task insertion, or excessive local occupancy occur, the system first guarantees minimum spacing, capacity limiting, and priority passage for critical missions. Maintaining maximum traffic efficiency is not the primary objective in such cases. In high-density low-altitude operations, this strategy may reduce throughput for a short time, but it improves overall stability and controllability.

Overall, this study does not build an independent corridor theory outside the grid system. Instead, the vertical flight corridor is treated as a structured extension built directly on the unified grid state. The core idea is clear. Corridor geometry remains stable. Open states change in response to environmental conditions. Corridor capacity is determined by the underlying grid states. Cross-layer transition follows an explicit admission rule. In this way, the low-altitude vertical flight corridor becomes a key infrastructure element for connecting altitude layers, maintaining low-altitude order, and supporting cross-layer operational governance.

4. Experiments

4.1 Experimental Overview

This study selected a typical urban block in Yuehai Subdistrict, Nanshan District, Shenzhen, as the experimental area. The study area is enclosed by Baishi Road, Shahe West Road, Dongbin Road, and Houhai Avenue, with a total area of about 6 km², see in Figure 4 below. It includes several representative urban functional zones, such as the Canghai Campus, Houhai CBD, the Coastal City commercial district, Shenzhen Bay Sports Center (“Spring Cocoon”), Talent Park, and the Science and Technology Ecological Park. The area is characterized by dense high-rise buildings, complex building layouts, clear spatial variation, and mixed urban functions. It is therefore a typical high-density urban low-altitude built-up area and is therefore highly representative of dense urban low-altitude environments. The experiment was developed on the Cesium platform. The urban 3D digital twin map of the study area was loaded into the prototype system. On this basis, the three-dimensional grid model was constructed, static and dynamic attributes were loaded, and low-altitude vertical flight corridors were generated and visualized. This experimental setting was used to verify the spatial discretization capability, attribute representation capability, and cross-layer flight organization capability of the proposed method in a complex urban environment. It also provides experimental support for future urban low-altitude traffic management applications.


(a) Orthophoto View (b) Oblique Perspective View

Figure 4. Experimental area in Yuehai Subdistrict, Nanshan District, Shenzhen: (a) orthophoto view; (b) oblique perspective view.

4.2 Visualization Results of the Fine-Grained Three-Dimensional Grid Model

In the experimental area, a low-altitude airspace grid was constructed using the fine-grained three-dimensional gridding method proposed in Section 3.1. The maximum modeling height of the grid was set to 375 m. According to the grid scale determination method presented in the methodology section, the final horizontal size of each grid cell was about 28.73 m × 28.73 m, and the vertical height was 41.25 m. Based on the three-dimensional urban base map loaded in the Cesium platform, the resulting grid model is shown in Fig. 5. Overall, the grid cells are evenly distributed, their geometric form is uniform, and the spatial organization is clear. The model can effectively cover different types of urban low-altitude environments within the study area, including high-rise building clusters, commercial complexes, airspace above major urban roads, and open waterfront areas.

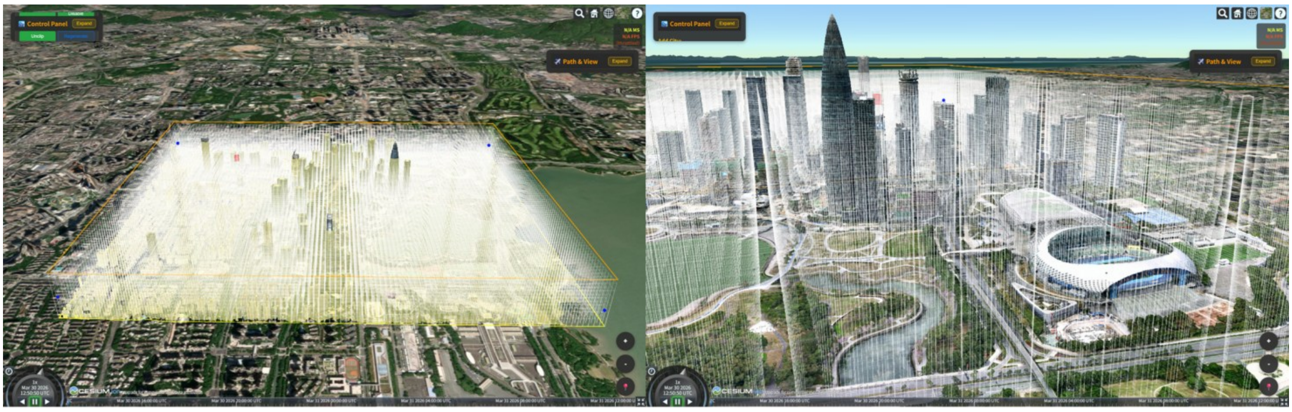
The visualization results indicate that the constructed grid model has strong spatial continuity and structural integrity. A unified scale is applied in both the horizontal and vertical directions, and no grid break, displacement, or geometric inconsistency is observed across different areas. This ensures consistency and comparability in low-altitude spatial representation. The model also captures the three-dimensional spatial hierarchy of the experimental area. Dense high-rise zones and relatively open spaces are represented within the same grid framework, which provides a stable basis for subsequent attribute integration. In addition, each grid cell has a clear spatial index and layer relationship, making the model suitable not only for visualization but also for route planning, risk assessment, state updating, and corridor association. The experimental results further show that the proposed fine-grained three-dimensional grid model shows strong practical feasibility. The selected grid scale balances the need to represent complex urban environments with the computational cost of the system. It avoids both boundary distortion caused by coarse discretization and the computational burden caused by over-refinement. Overall, the model provides a standardized and effective basis for discrete modelling, attribute attachment, and vertical corridor construction in complex urban low-altitude environments.

4.3 Experimental Results of Attribute Information Injection

After the fine-grained three-dimensional grid model was established, static and dynamic attributes were injected into the experimental system. Their loading results were verified through interactive grid selection. As shown in Fig. 6, the selected grid cell is highlighted in red, and its attributes are displayed in the left panel. The results show that each grid cell can record and display longitude and latitude, grid layer, current wind speed, temporary restriction status, overlap occupancy indicator, and dynamically updated attributes. This confirms that the grid is not only a discrete spatial unit, but also a state unit carrying multi-dimensional operational information.

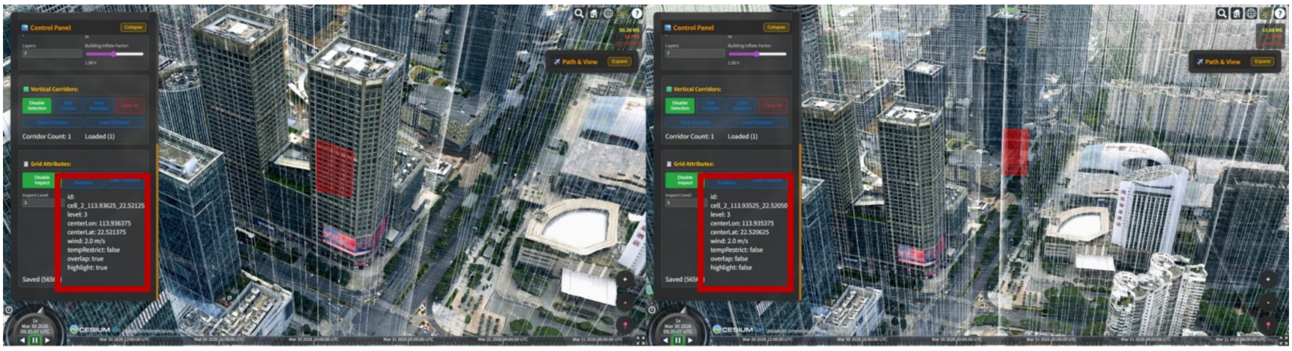
Figure 6(a) presents a blocked area occupied by a building. In this case, the overlap occupancy indicator is shown as “occupied,” while the temporary restriction state remains “unoccupied.” This indicates that the grid is inaccessible because of static spatial obstruction rather than a temporary event, which is consistent with the real scene and with the static-priority constraint logic of the proposed method. By contrast, Fig. 6(b) shows an open grid cell without building blockage. Its overlap occupancy indicator is “unoccupied,” indicating that the cell is currently accessible to UAVs. In both cases, the coordinates of the selected grid cells match their actual positions on the base map, confirming the correctness of the mapping between spatial grids and recorded attributes.

More importantly, the experiment demonstrates the dynamic update capability of the proposed attribute model. Although the grid layer remains structurally stable, attributes such as wind speed, temporary restriction status, overlap occupancy, and dynamic attribute margin can change over time. Therefore, the grid is no longer a static spatial partition. It becomes an operational state carrier that evolves continuously with environmental and operational changes. This allows the same grid cell to present different accessibility conditions and operational constraints at different times, thereby supporting dynamic scheduling, conflict warning, and path adjustment. Overall, the results show that the proposed collaborative injection mechanism for static and dynamic attributes can operate stably on a three-dimensional digital twin platform and can effectively unify spatial representation and operational state expression.



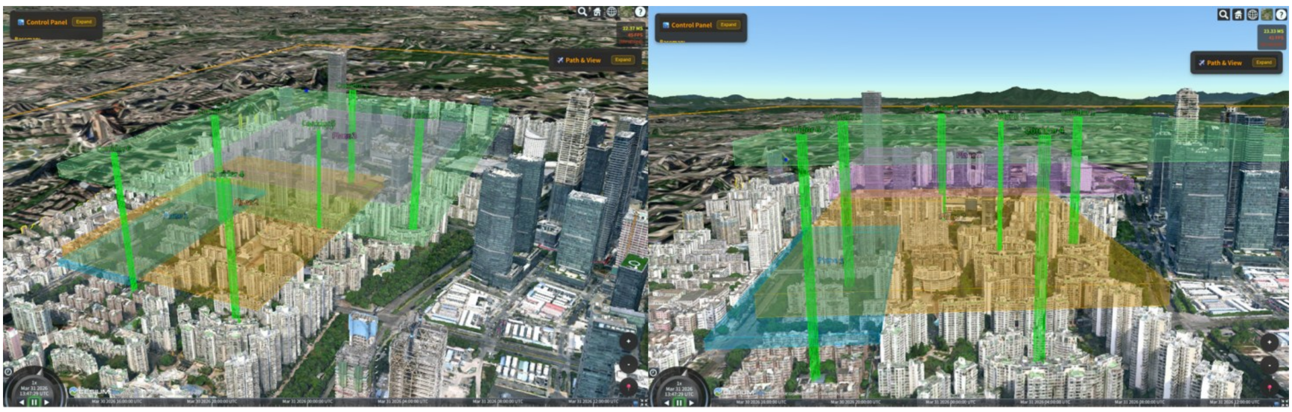
(a) Overall View of Spatial Grid Model (b) Detailed View Of Spatial Grid Partitioning

Figure 5: Visualization results of the fine-grained three-dimensional grid model



(a) Spatial Grids In Obstructed Areas Are Marked As Occupied (b) Spatial Grids In Flyable Areas Are Marked As Unoccupied

Figure 6: Experimental results of attribute information injection.



Design And Rule-Based Control Of Vertical Corridors

Figure 7: Schematic illustration of low-altitude vertical flight corridors.

4.4 Design and Rules of Low-Altitude Vertical Flight Corridors

Figure 7 presents the deployment of low-altitude vertical flight corridors in the experimental area. Based on the spatial structure of the study area, the distribution of typical tasks, and the transition demand between altitude layers, several vertical corridors with different sizes and capacities were arranged. These corridors are connected to horizontal flight platforms or horizontal flight channels, together forming a three-dimensional flight organization structure for urban low-altitude operations. The results show that vertical corridors are not isolated passages. Instead, they act as key nodes embedded in the gridded low-altitude operational system and support flight transitions between different altitude layers.

From a functional perspective, UAVs of different sizes can select appropriate vertical corridors for altitude adjustment according to their dimensions, mission requirements, and operating heights. Larger UAVs require corridors with greater spatial scale and higher carrying capacity, whereas smaller

UAVs can complete climb or descent transitions through smaller corridors. At the same time, the system explicitly enforces that UAVs may only fly within the horizontal platform corresponding to their current altitude. If an altitude change is needed, the aircraft must use predefined vertical corridors rather than climb or descend freely in ordinary grid regions. This converts cross-layer flight from a free behavior into a controlled one and reduces the risk of vertical conflict propagation in hotspot areas and intersections.

The results further show the management value of the proposed design. It concentrates altitude transitions into a limited number of explicit and monitorable channels, clarifies the connection between vertical corridors and horizontal platforms, and supports hierarchical organization for different aircraft types and mission scenarios. Overall, the proposed method improves the controllability of cross-layer flight and provides a basis for corridor capacity allocation, node control, conflict suppression, and mission priority management. From an engineering perspective, it helps transform free flight in complex low-altitude airspace into a structured operating mode with clear rules, controllable routes, and manageable states.

5. Conclusion

In summary, this study proposes a fine-grained urban low-altitude airspace gridding method with dynamic event response and vertical flight corridor constraints for high-density and highly dynamic urban low-altitude operation scenarios. Based on a realistic urban three-dimensional digital twin platform, the method constructs a fine-grained three-dimensional grid model under a unified spatial reference and presents a way to determine grid scale and control cycle while balancing risk representation accuracy and engineering cost. On this basis, a collaborative injection mechanism for static and dynamic attributes is established, enabling the unified representation and continuous updating of multi-source information, including terrain, buildings, no-fly and restricted zones, wind fields, temporary restrictions, occupancy, and release states. Furthermore, fixed-geometry and dynamically open low-altitude vertical flight corridors and their operational rules are designed, which define a controlled transition mechanism for cross-layer flight. Experimental results show that the proposed method can achieve stable spatial discretization, accurate attribute loading and dynamic updating, and clear cross-layer flight organization in complex urban built-up areas. It therefore provides unified support for low-altitude airspace assessment, path planning, capacity management, and operational governance. Overall, without significantly increasing geometric complexity, this study establishes a reproducible, scalable, and verifiable technical framework for future urban low-altitude traffic management systems.

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