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Spatiotemporal Trajectory Planning for Multi-Aircraft Terminal Operations in UAM Considering Wake Effects and Dynamics

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***Abstract*—Urban Air Mobility (UAM) will drive a three-dimensional transformation of urban transportation and logistics. However, high operational density, heterogeneous aircraft types, and complex environmental conditions present significant safety risks in UAM terminal airspace during takeoff and landing. This paper addresses the multi-aircraft spatiotemporal trajectory planning problem in UAM terminal airspace by proposing a trajectory planning scheme that combines the Dynamic Window Approach (DWA) with A* algorithm. Compared to existing studies, this paper considers the dynamics of eVTOLs and the wake vortex effect between multiple aircraft. Additionally, GeoSOT3D encoding is employed to effectively resolve the myopic issue in DWA. Simulation results demonstrate that the proposed method significantly mitigates wake vortex interference and optimizes terminal airspace resource utilization through horizontal and vertical maneuvers, greatly enhancing both takeoff/landing safety and operational efficiency.**

Keywords- Urban Air Mobility; eVTOL; terminal control; wake effect; trajectory planning; dynamics;

I. INTRODUCTION

With the rapid advancements in intelligent and electrification technologies, coupled with the acceleration of urbanization, Urban Air Mobility (UAM) has emerged as a transformative force in the three-dimensional evolution of urban transportation and logistics systems. UAM encompasses a range of heterogeneous platforms, including multi-rotors, compound wings, tilt-rotor eVTOLs, and both integrated and modular flying cars, all of which offer flexible and efficient solutions for diverse scenarios. However, compared to traditional civil aviation, UAM faces significantly more complex traffic management, especially in areas with high operational density, such as near takeoff and landing stations. Studies indicate that the average takeoff and landing intensity during peak hours at UAM stations can reach 31.77 operations per minute, far exceeding that of conventional airports [1]. This high-density operation results in significant interference among heterogeneous aircraft, increasing risks from wake turbulence and conflicts, and imposing greater demands on safety management.

Traditional civil aviation control models, including tower control, approach control, and area control, monitor various flight stages. However, in urban airspace, where the environment is constrained, low-level, and densely trafficked, a dual control structure—comprising "terminal control" and "airspace control"—will prove more efficient for UAM operations (Fig. 1). Airspace control focuses on the allocation of airspace resources and supervises the flight of eVTOLs along designated air routes, while terminal control focuses on the cylindrical airspace surrounding stations, ensuring the safe and efficient movement of multiple aircraft between ground and air routes. This involves adjustments to parameters such as altitude, speed, and heading.

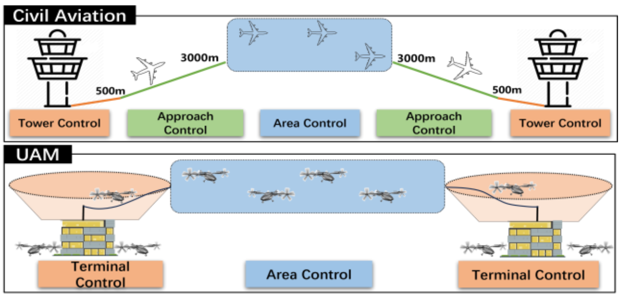


Figure 1. Civil Aviation and UAM Management Process

In UAM's takeoff and landing management, structured airspace solutions achieve separation of multiple aircraft through various altitude and radius layers and hover waiting points [2][3][4]. However, these solutions are often affected by urban buildings and result in prolonged high-energy hovering for eVTOLs. Route guidance strategies alleviate traffic at intersection points by regulating speed, or by establishing takeoff and landing paths with different angles and speeds, optimizing multi-aircraft operations through appropriate sequencing [5][6][7]. Nevertheless, existing research often overlooks the dynamic characteristics of eVTOLs and the interference between aircraft, particularly the wake turbulence effects from fixed-wing eVTOLs. The failure to account for actual flight paths raises concerns about the safety of separation strategies. Additionally, the rigidity of layers, hover points, and routes prevents optimal use of takeoff and landing airspace and underutilizes the benefits of gliding in winged eVTOLs.

This paper proposes a multi-aircraft takeoff and landing spatiotemporal trajectory planning method that considers the wake turbulence effects and dynamic characteristics of eVTOLs. The method enhances the efficient use of airspace resources around stations while ensuring safety. By using Geo-SOT3D encoding for airspace rasterization and storing wake turbulence intensity data, we combine Dynamic Window Approach (DWA) and A* algorithms. An evaluation function, incorporating angle, distance, time, and penalty terms, is designed to solve low-risk trajectories based on known 7-dimensional states, while respecting the eVTOL's controllability and dynamics. This approach integrates implicit and explicit risk cost, balancing global optimality with computational efficiency.

II. METHODOLOGY

A. Airspace Discretization

Low-altitude airspace discretization serves as the foundational core for low-altitude traffic management. By dividing the airspace into independently computable grids and assigning reasonable codes, it becomes easier to efficiently manage airspace resources and flight activities. In this paper, we apply an improved Geo-SOT3D encoding method for airspace division [8]. This approach is based on a tree-like recursive structure, where the encoding length is proportional to the spatial partition depth, denoted as k. The longer the encoding, the greater the depth, resulting in finer spatial resolution. In the k^{th}level of partitioning, each grid is subdivided into xyz smaller subgrids, and the total number of grids at the k-th level is $x^k \cdot y^k \cdot z^k$.

The advantages of Geo-SOT3D encoding for airspace division at takeoff and landing stations are as follows: 1) Simplified querying of neighboring grids for any given grid. In each parent grid, the positions of specific subgrids are fixed. 2) Facilitates quick extraction of feature information from lower-depth regions. For example, for a level-5 grid encoded as E2WT4, information from lower-level grids such as E2W and E2WT can be read to rapidly grasp the risk status of a larger airspace area.

B. Wake Vortex Modeling for eVTOLs

During flight, the pressure difference between the upper and lower surfaces of a wing on a winged eVTOL generates airflow that extends along the direction of motion, creating counter-rotating vortices at the wingtips. These vortices can interfere with the control of other aircraft and potentially lead to flight accidents.

Numerical simulation methods, such as those based on the Reynolds-Averaged Navier-Stokes (RANS) equations, Large Eddy Simulation (LES), and Detached Eddy Simulation (DES), have been widely used to study the generation and evolution of wake vortices. Additionally, efficient computational methods, including the three-phase (3P) dissipation model and the P2P rapid computation model, have been developed for vortex modeling. In this paper, we adopt the [9] method to model the wake vortex of winged eVTOLs, where vortex intensity is given by Equation (1).

$$\Gamma(t, \Delta x) = D(\Delta x)\Gamma_0 e^{-\alpha \frac{tD(\Delta x)\Gamma_0}{2\pi b_0^2}} \tag{1}$$

Equation (1) indicates that wake vortex intensity is not only influenced by the size and flight speed of the eVTOL but also depends on temporal and spatial factors. Throughout the flight, the eVTOL continuously generates wake vortex effects, which are further impacted by the wake vortices of other eVTOLs. Given that the takeoff and landing trajectories consist of multiple discrete waypoints, and the airspace is also discretized into grids, it is necessary to discretize the spatiotemporal characteristics of wake vortices.

In this study, we assume that at each trajectory sampling point, the wake vortex generated at the wingtips can be approximated as a thin slice region, within which the grid points are affected by the vortex. Over time, the wake vortex intensity decays until it falls below a certain threshold. To determine the affected range, we employ a vector projection method. Assuming the wingtips move from point A to point B within a time interval Δt, for a grid center point C in the airspace, if the projection length of vector $\overrightarrow{AC}$ onto vector $\overrightarrow{AB}$ is smaller than the magnitude of $\overrightarrow{AB}$, then the wake vortex generated at the wingtips will affect point C.

C. Trajectory Planning for eVTOLs in Terminal Area

Trajectory planning for eVTOLs in takeoff and landing airspace presents unique challenges:

1) *Large variations in state variables. For example, during descent, an eVTOL transitions from high-speed cruise to low-speed flight, with significant vertical displacement.*
2) *Dynamic constraints must be considered. Changes in speed and heading must take into account the eVTOL's maneuverability and comfort, to avoid potential conflicts between multiple aircraft and large trajectory errors.*
3) *Predefined strategic scheduling. Typically, takeoff and landing times are pre-scheduled for eVTOLs. Trajectory planning should avoid significant early or delayed arrivals.*

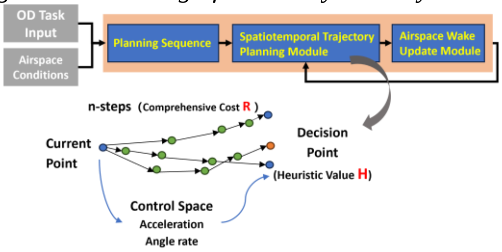


Figure 2. Spatiotemporal Trajectory Planning

To address these challenges, this paper proposes a joint trajectory planning scheme that combines the Dynamic Window Approach (DWA) and A* search algorithm. The DWA incorporates dynamic constraints to ensure that the planned trajectory is executable, while the A* heuristic and cost functions help avoid wake vortex risks and bring the trajectory closer to the target state. Fig. 2 illustrates the workflow of the trajectory planner. In the context of multi-aircraft coordinated takeoff and landing, the trajectory planning is performed sequentially for each aircraft based on priority. Planned trajectories will affect the spatiotemporal allocation of airspace resources, and the generated wake vortices will influence the trajectory planning of subsequent eVTOLs.

The combined approach of DWA and A* is well-suited for addressing the spatiotemporal joint trajectory planning problem of multiple eVTOLs in the terminal area of UAM. In the following, the applicability is illustrated using the approach and landing scenario as an example, while noting that the same principles are equally applicable to the takeoff phase. First, the approach and landing process in the terminal area is highly task-oriented, with strict constraints on the states and time windows of access and target points, typically determined by strategic scheduling. The A* algorithm can effectively capture such mission-driven planning requirements, for example, by prioritizing maneuvers that enhance landing efficiency in the event of eVTOL delays. Second, due to significant variations in eVTOL dynamic parameters—especially in terms of speed and acceleration—DWA optimizes the trajectory under dynamic constraints, ensuring the executability of planned paths. In addition, risks such as multi-vehicle wake vortices in the terminal area are difficult to model continuously and exhibit significant spatiotemporal dynamics. By discretizing the airspace into grids to construct a risk heatmap and embedding the risk values into the cost function, the safety and robustness of multi-eVTOL approach and landing operations can be effectively improved.

In single-vehicle trajectory planning, the control space is discretized through the acceleration, heading angle rate, and pitch rate of the eVTOL, generating new decision points after each time step. The size of the control space determines the number of new decision points and sub-paths. Decision point selection is based on the cost of the sub-paths and the deviation between the new decision point and the target state. The planning ends when the updated point reaches the target area.

The heuristic function of the trajectory planner is defined in (2)—(6) and consists of four components: distance $h_{distance}$, heading angle h_γ, time h_t, and penalty h_{punish}. Equation (3) defines the distance heuristic, which calculates the vertical and horizontal distances between the current and target points. Here, d_{xy} is the remaining horizontal distance, d_0 is the initial horizontal distance, z_0 is the initial vertical distance, z_c and z_g are the current and target z-axis coordinates, respectively. Equation (4) defines the heading heuristic, where γ is the angle between the vector $\vec{b}$ pointing from the current point to the target and the target's heading vector $\vec{c}$, projected onto the horizontal plane. Equation (5) estimates the remaining flight distance of the eVTOL; when the angle γ is large, the triangular method is used, with β representing the horizontal projection angle between the current trajectory vector $\vec{a}$ and the vector $\vec{b}$. Equation (6) provides the time heuristic, which considers the difference between the current and target times, where v_c and v_g are the current and target speeds, t_c and t_g are the current and target times. h_{punish} is a manually designed penalty term that includes high penalties for anticipated delays and penalties for exceeding maneuvering capabilities in terms of acceleration.

$$H = h_{distance} + h_\gamma + h_t + h_{punish} \tag{2}$$

$$h_{distance} = c_{dis} \cdot \frac{d_{xy}}{d_0} + c_z \cdot \frac{|z_g - z_c|}{z_0} \tag{3}$$

$$h_\gamma = c_\gamma \cdot \gamma \tag{4}$$

$$RD = \begin{cases} c_{rd} \cdot d_{xy}\left(\frac{\sin(\beta)}{\sin(\gamma)} + \frac{\sin(\beta+\gamma)}{\sin(\gamma)}\right), if \sin(\gamma) \geq c_{\gamma\_rd} \\ d_{xy}, else \end{cases} \tag{5}$$

$$h_t = c_t \cdot \left|\frac{2 \cdot RD}{v_c + v_g} - (t_g - t_c)\right| \tag{6}$$

Equations (7) — (9) define the risk cost R, while (7) integrates the path cost and the consideration of future states. $R_{process}$ represents the risk cost for each control decision's path. However, considering only the path risk between the current step and the next step is shortsighted and does not fully utilize global information. By leveraging Geo-SOT3D encoding, the trajectory planner can quickly assess the state of a larger area around the current trajectory point. The implicit risk cost, as defined in (8), calculates the risk state of larger grid cells traversed after maintaining the current control decision for a period. Notably, the earlier a high-risk area is triggered, the higher the cost coefficient, indicating that the current decision may lead to more severe consequences. Finally, equation (9) combines the heuristic and risk cost as an evaluation metric for each decision step, thereby optimizing the trajectory planning process.

$$R = c_{r\_i} \cdot R_{implicit} + c_{r\_p} \cdot R_{process} \tag{7}$$

$$R_{implicit} = \sum_i \frac{2(n-i+1)}{(n+1) \cdot n} \cdot \frac{R_i}{T} \tag{8}$$

$$F = H + R \tag{9}$$

III. Experiments and Results

A. Experimental Setup

The experiment simulated three fixed-wing eVTOLs sequentially entering a terminal area from the same air route, performing approach and descent maneuvers, and eventually landing on the same pad within a Vertiport. Each eVTOL's flight state was represented by a seven-dimensional vector, including three-dimensional coordinates, time, velocity, heading angle, and pitch angle, with each variable constrained by the aircraft's dynamics. The simulation explicitly defined initial state vectors $\vec{O}$ at the terminal area entry point and final target state vectors $\vec{D}$ at the landing site for each eVTOL, creating clearly defined mission constraints for landing.

The experimental scenario, wherein three eVTOLs sequentially entered the terminal region via a common air route, aligns with the UAM management concept involving two primary control responsibilities: airspace and terminal management. Specifically, traffic from various UAM network directions converges into several predefined routes connected to the terminal region, with aircraft pre-sorted based on priority. Upon entering the terminal control area, eVTOLs execute complex maneuvers guided by control strategies to ensure safe and efficient takeoffs and landings.

In the simulation, the initial separation interval between each eVTOL entering the terminal region was approximately 7.5 seconds. This interval was deliberately set short, creating conditions prone to wake vortex interference to rigorously validate the effectiveness of the proposed approach under extreme scenarios. The experiment consisted of three comparative groups:

Group C (Baseline): The initial and target state vectors ($\vec{O}$ and $\vec{D}$) for all three eVTOLs were identical in spatial coordinates, heading, and pitch angles, differing only by fixed time intervals. The initial horizontal cruising speeds were approximately equal, with horizontal velocity approaching zero upon nearing the landing pad, followed by vertical descent. In terms of wake vortex risk, each eVTOL only considered local explicit risk, lacking predictive capabilities for distant or future risk scenarios.

Group A: Built upon Group C by incorporating implicit risk considerations, allowing eVTOLs to perceive not only immediate local risks but also broader spatial and temporal wake vortex risks.

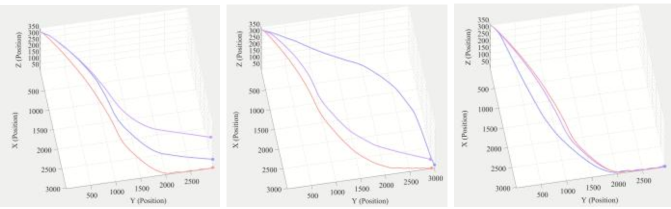
Group B: Based on Group A, maintained identical heading angles for all three eVTOLs upon entering the terminal area but altered the desired final heading angle of the second eVTOL above the landing pad. This simulated feasibility for eVTOLs to mitigate wake vortex risks by varying landing orientations within the terminal area.

The above experimental setup was implemented in Python and executed on a computing platform equipped with an Intel I9-14900HX processor and 32 GB of RAM.

B. Results and Analysis

Figure 3 (a), (b), and (c) illustrate the spatiotemporal trajectories of three eVTOLs under experimental groups A, B, and C, respectively. The red, blue, and purple lines represent the first, second, and third eVTOLs entering the terminal area and preparing for descent in sequence.

In group C, all three eVTOLs share the same target heading (see Figure 3(c)), and only local explicit risk within a limited scope is considered. The results show that the second eVTOL (blue) rapidly adjusted its heading, thereby increasing its horizontal separation from the leading aircraft and effectively avoiding wake vortex interference. As the wake effect from the first eVTOL gradually diminished, the third eVTOL (purple) was able to closely follow the trajectory of the first and quickly approach the landing point. However, due to the limited scope of risk perception, the three eVTOLs landed in close sequence at the end of their trajectories, which increased the operational risk.



(a) (b) (c)

Figure 3. eVTOL Flight Trajectory

Group A considers both explicit and implicit risks (Figure 3(a)). The results indicate that the following eVTOLs could anticipate that merely increasing horizontal separation was insufficient to fully avoid wake vortex risks. Consequently, a strategy of increasing vertical separation was adopted. By following descent trajectories with different slopes, the aircraft established distinct altitude layers before reaching the vertiport. The latter eVTOLs maintained higher altitudes, which effectively mitigated the impact of downwash during vertical descent and significantly improved overall flight safety.

In group B, building upon group A, the target heading of the second eVTOL at touchdown was further adjusted (see Figure 3(b)), so that each eVTOL ultimately landed according to its pre-set heading. The resulting trajectories exhibited both horizontal and vertical separation maneuvers, which minimized mutual interference and notably enhanced safety during approach and landing. Additionally, setting different target headings improved the airspace utilization in the terminal area. It is noteworthy that, compared to group A, the three eVTOLs in group B had lower altitudes upon arrival at the landing pad, reducing the risk of lift loss due to long-term vertical descent in wake turbulence. Overall, the heading adjustment strategy balanced safety with higher airspace efficiency.

Figure 4 shows the time evolution of key state variables for the three eVTOLs during the approach and descent phases across all groups. The results demonstrate that, when both explicit and implicit risks are considered, the system can predict wake vortex interference in advance and guide following aircraft to increase their altitude, as indicated by a decreased rate of change in the z-direction. This enables effective avoidance of wake zones. Moreover, comprehensive risk awareness significantly reduced fluctuations in flight variables, thus improving the stability of the flight process and passenger comfort. In contrast, when implicit risks are not considered, subsequent aircraft experienced more frequent and larger state variable fluctuations, necessitating more frequent adjustments.

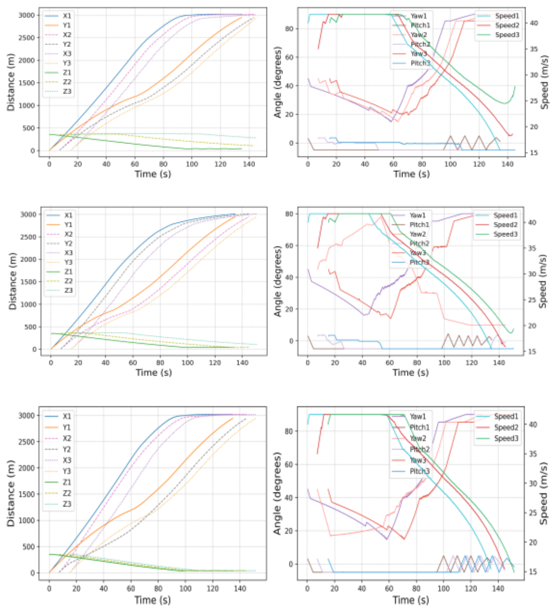


Figure 4. eVTOL Time-Varying State Variables

Table 1 summarizes the cumulative wake vortex risk values encountered by the three eVTOLs during the entire approach and landing process in each experimental group. A higher risk value indicates greater exposure to wake effects and lower flight safety. It should be noted that the wake vortex risk value reflects relative safety, not the probability of an actual accident. In the experiments, based on relevant studies such as [9], a safety threshold for wake vortex risk was set, and the trajectory planning ensured that no eVTOL entered high-risk zones. Since the first eVTOL has no preceding aircraft, its cumulative risk is zero. In group A, where both explicit and implicit risks are considered, the cumulative wake effect was significantly reduced and flight safety was enhanced. The second eVTOL effectively mitigated wake impact by slowing its descent, while the third eVTOL, due to mission time constraints and maximum cruise altitude limits, experienced some exposure to the second aircraft's wake in the terminal area, but overall safety still exceeded that of considering only explicit risk. Group B, by adopting differentiated target headings, achieved coordinated use of both horizontal and vertical airspace, resulting in the lowest cumulative risk and optimal safety among all groups.

Table 1. Wake Risk Values of Different Experiment Groups

Group	***1st eVTOL***	***2nd eVTOL***	***3rd eVTOL***
A (Two Risk)	0	0.3978	4.6391
B (Two Risk + Different $\vec{D}$)	0	0.2630	0.7595
C (Baseline)	0	2.6751	6.5116

IV. CONCLUSION

This paper focuses on the multi-aircraft spatiotemporal trajectory planning problem in UAM terminal control. Due to factors such as high-density operations, significant state changes, complex environments, and heterogeneous aircraft types, the takeoff and landing phases are crucial for the safe and efficient operation of UAM systems. eVTOL fleets face safety challenges such as spatiotemporal intersections and wake vortex interference within the limited terminal airspace. To address this issue, this paper proposes a spatiotemporal trajectory planning scheme combining DWA and A* algorithm. The proposed method integrates the flight dynamics of eVTOLs with a spatiotemporal wake vortex risk cost function, generating safe, efficient, and feasible flight trajectories under seven-dimensional state constraints at both the initial and final stages. Experimental results demonstrate that the proposed method effectively utilizes the spatiotemporal resources of the terminal airspace, allowing eVTOLs to avoid wake vortex impacts through horizontal and vertical maneuvers, significantly enhancing the safety of multi-aircraft flight trajectories. Future work will focus on: 1) modeling and integrating heterogeneous aircraft types, considering the impact of environmental factors such as gusts on eVTOL takeoff and landing; and 2) improving the solution algorithm framework by integrating machine learning methods to enhance real-time solving performance.

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