Design and Optimization of a Novel Cooperative Control Strategy for Uav Formation Flight

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***Abstract*: In an unmanned aerial vehicle (UAV) formation flight, the wingman UAV is responsible for maintaining a specified formation with the lead aircraft, avoiding collisions with other UAVs in the group, and ensuring that all units reach the designated mission point in alignment with operational objectives. This paper introduces a novel cooperative control strategy specifically designed for UAV formation flights. This approach assures effective following of the lead UAV by the wingman UAVs considering the fully autonomous of each UAV supported by intelligent decision mechanisms. In addition, timely arrival at the mission point in accordance with the mission requirements of all UAVs can be guaranteed. Moreover, safety is prioritized throughout the formation process without compromising mission success. The implementation of this proposed cooperative control approach is shown in this paper, demonstrating autonomous management of UAV formations and ensuring both mission fulfillment and flight safety. Numerous MATLAB-based simulation results have been conducted to validate the proposed methodology, confirming its accuracy and effectiveness.**

Keywords. Cooperative Control, UAV formations, Dynamic Adjustment, Flight Safety.

I. Introduction

Drones, or unmanned aerial vehicles (UAVs), are primarily controlled via radio remote control or onboard programming [1-5]. UAVs possess distinct advantages such as adaptability, high safety, relatively low costs, and excellent concealment, which have led to their widespread application in both civilian and military fields [6-10]. Coordination among multiple UAVs enhances task execution efficiency far more than a single UAV can achieve. Consequently, the development of UAV formation flight control technology has attracted considerable attention, focusing essentially on two areas: formation assembly and maintenance [11-15].

Two principal approaches exist for UAV formation assembly: offline trajectory planning and online trajectory control. Offline trajectory planning, while comprehensive, suffers from slower real-time adaptation and lacks flexibility due to its fixed nature, resulting in diminished resistance to disturbances. Conversely, online trajectory control allows for real-time adjustments of parameters, such as speed, heading, and altitude, to achieve concurrent arrival at a target. For instance, the shortest route for each UAV is designed based on the Dubins algorithm, necessitating precise path tracking and speed modulation [16-21]. The PH route planning algorithm is applied for real-time control of UAV trajectories through distributed estimation techniques [22-28].

Control methods primarily involve two approaches: centralized and distributed control. Centralized control, prevalent in earlier research [29-31], demands comprehensive state sharing of all UAVs, aiming to derive a globally optimal solution. While this leads to favorable control outcomes, it presents significant drawbacks, such as vulnerability to control center failures and high communication demands, especially in larger systems [32-35]. Moreover, distributed control enables UAVs to communicate solely with neighboring units, thus enhancing robustness, albeit with somewhat reduced control effectiveness [27-32].

Formation maintenance allows a multi-UAV fleet to recover and sustain a stable formation after one or more UAVs temporarily deviate. This capability is vital for applications like ground target tracking, where the precision of formation significantly influences accuracy. Research in this area includes obstacle avoidance strategies, aerodynamic interactions, and coordinated maneuvers. In [35-40], the mathematical models governing adjacent UAVs in a formation are interdependent and can be categorized into decoupled and coupled components. Robust control techniques are applied to decoupled segments, while an enhanced distributed control approach is employed for coupled aspects. The leader-follower strategy is typically adopted for formation integrity, where one UAV responds to commands from a ground operator while the others mimic its movements. This minimizes computational complexity and utilizes established control methodologies for straightforward implementation.

In addition, in the context of performing tasks, UAVs operating in formation primarily rely on formation controllers or predefined flight paths to maintain their spatial arrangement. However, given the dynamic nature of task requirements, traditional formation control methods often fail to ensure effective mission completion. Additionally, during autonomous flights, UAVs face challenges such as navigation inaccuracies and atmospheric disturbances, which can lead to deviations from intended flight paths. These discrepancies pose safety risks, including dangerous proximity to other UAVs and potential collisions. However, conventional formation flying strategies frequently neglect these critical factors, resulting in notable gaps between theoretical models and practical implementations.

To mitigate these shortcomings and improve mission reliability, a novel cooperative control strategy is proposed for UAV formation flight in this paper. The effective following of the lead UAV by the wingman UAVs considering fully autonomous of each UAV supported by intelligent decision mechanisms can be assured by the proposed method. Moreover, timely arrival at the mission point in accordance with the mission requirements of all UAVs can be further guaranteed. In addition, safety is prioritized throughout the formation process without compromising mission success.

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Above all, this strategy not only streamlines task execution but also enhances formation safety throughout the flight by incorporating intelligent decision-making mechanisms that support full autonomy in UAV maneuvers.

II. Time-consistent formation control strategy

A common UAV formation scenario is depicted in Figure 1, illustrating a chain pilot-follow approach.

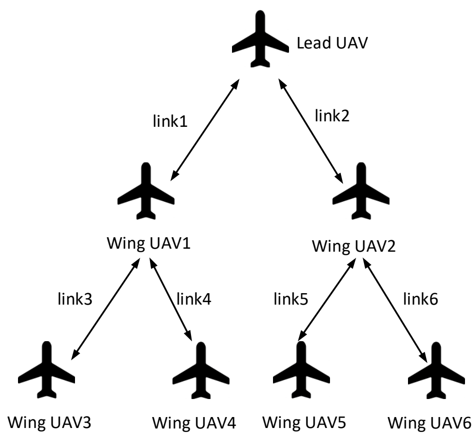


Figure 1. UAV formation network topology diagram.

To achieve optimized UAV trajectories, the position of each mission area point P_i is determined based on minimizing and maximizing flight paths.

Represented in Figure 2, this method connects two points that intersect the turning circle to find the tangent point P_{i+1}.

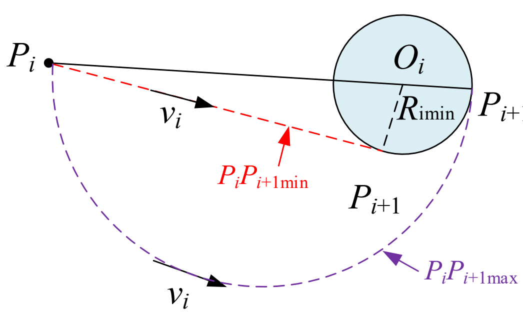


Figure 2. The shortest and longest flight paths of the i^{th} UAV.

By applying the previously mentioned path-solving methodology, the maximum possible UAV trajectory is computed. The length P_iP_{i+1} corresponds to each point P_i. $\angle O_iP_iP_{i+1}$ of $\triangle O_iP_iP_{i+1}$ can be calculated, which can be obtained as follows:

$$\angle O_iP_iP_{(i+1)} = \arcsin(\frac{R_{i\min}}{P_iO_i}) \tag{1}$$

The shortest length $P_iP_{i+1\min}$ can be obtained as follows:

$$P_iP_{(i+1)\min} = P_iO_i \cdot \cos\left(\arcsin(\frac{R_{i\min}}{P_iO_i})\right) \tag{2}$$

The longest length $P_iP_{i+1\max}$ can be obtained as follows:

$$P_iP_{(i+1)\max} = P_iO_i + R_{i\min} \tag{3}$$

The flight speed of i^{th} UAV v_i can be calculated:

$$v_i = \frac{dP_iP_{i+1}}{dT_i} \tag{4}$$

When the UAV has sufficient fuel, it can choose path $P_iP_{i+1\max}$. When the fuel is not abundant, it needs to select path $P_iP_{i+1\min}$.

The UAV's current speed v_i and the expected task completion time T_i are employed to ascertain a point P_i that aligns closest with the desired trajectory, considering fuel efficiency.

III. Speed dynamic adjustment strategy

In UAV formation, the lead aircraft's maneuvers take precedence. Thus, wingman UAVs must proactively avoid entering the lead aircraft's threat zone to mitigate collision potential. This requires establishing an avoidance speed directed from the lead aircraft toward the wingman. By superimposing this avoidance speed with the dynamic maneuvering speed, wingmen can effectively evade the lead aircraft.

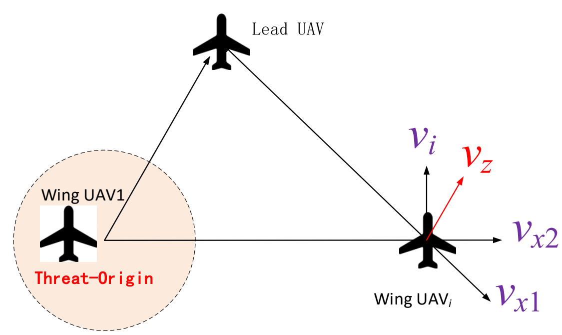


Figure 3. The shortest and longest flight paths of the i^{th} UAV.

Figure 3 shows the shortest and longest flight paths of the i^{th} UAV. To evade the lead UAV, the UAV$_i$ developed an avoidance velocity component v_{x1} until the distance between the UAV$_i$ and the lead UAV meets safety requirements. Simultaneously, to evade lead UAV$_1$, the UAV$_i$ developed an avoidance velocity component v_{x2} until the distance between the UAV$_i$ and the UAV$_1$ meets safety requirements.

Utilizing a dynamic fractional velocity model v_x, minimum fuel costs can be adjusted to navigate clear of both the lead aircraft and approaching UAVs. The velocity v_z to avoid collisions can be articulated as:

$$\overrightarrow{v_z}(t) = \overrightarrow{v_i}(t) + \overrightarrow{v_{x1}}(t) + \overrightarrow{v_{x2}}(t) \tag{5}$$

$$\begin{aligned} &R_{leadi} = \sqrt{(x_{lead} - x_i)^2 + (y_{lead} - y_i)^2 + (z_{lead} - z_i)^2}, \\ &R_{leadi} \in (R_{lead\min}, +\infty] \end{aligned} \tag{6}$$

where k_i is a parameter adjustable based on the actual flight mission and R_{imax} defines the lead aircraft's operational radius.

IV. The proposed novel cooperative control strategy

According to regulations stipulated by Civil Aviation, a hazardous approach for aircraft is defined by specific lateral and vertical distance thresholds. UAV formation flights must prioritize both timely arrival at mission points and safety. This is achieved through an intelligent cooperative control strategy facilitating autonomous formation management.

$$S = \int_{t_{ok}}^{t_{ok}+T_0} \left(v \pm \Delta v_k\right) dt \tag{7}$$

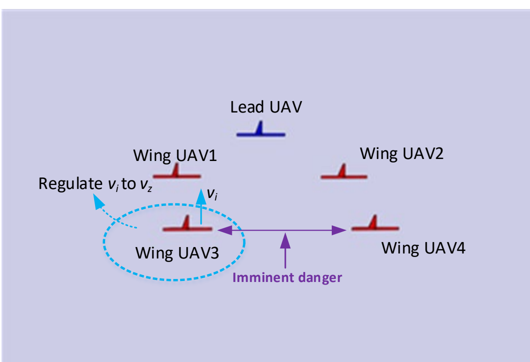
Adjustments in-flight strategy can be achieved by incrementally modifying climbing and descending speeds. To prevent abrupt maneuvers, changes in speed $\triangle v_{ki}$ are controlled in increments of 5~10 km/h until the adjusted trajectory complies with $S \in \left[P_i P_{i+1\min}, P_i P_{i+1\max}\right]$.

V. Simulation verification

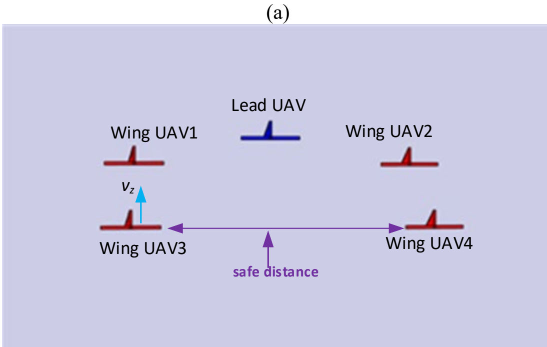
Numerous MATLAB-based simulation results are carried out, involving five UAVs to assess the proposed novel cooperative control strategy as follows.

A. Safe formation flight simulation

The proposed novel cooperative control strategy enabled safe formation flight via dynamic speed adjustments. As shown in Figure 4(a), a danger warning was triggered during close formation, which was mitigated in Figure 4(b) following successful speed adjustments.



(a)

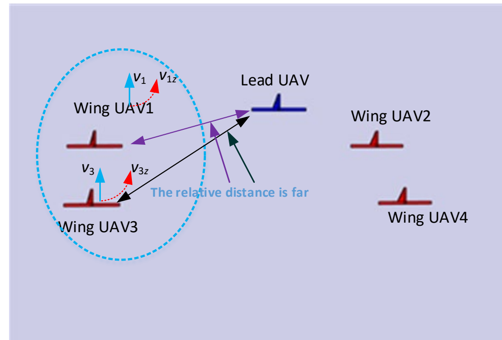


(b)

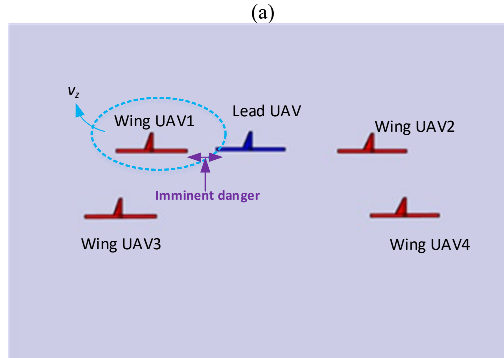
Figure 4. (a) The simulation of dynamic performance for five UAVs considering imminent danger scenario. (b) The simulation of five UAVs using dynamic speed adjustments strategy.

B. Mission command simulation

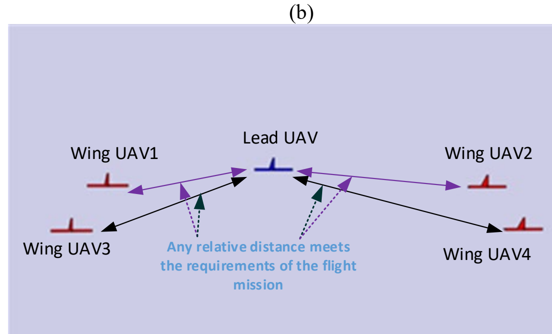
This novel cooperative control strategy ensured time-consistent formation control, illustrated in Figure 5(a) and Figure 5(b), where lower speeds compromised mission point arrival, while Figure 5(c) demonstrated successful adherence to mission timelines following the implementation of the strategy.



(a)



(b)



(c)

Figure 5. (a) The simulation of dynamic performance for five UAVs when the relative distance is far. (b) The simulation of dynamic performance for five UAVs considering imminent danger scenario. (c) The simulation of five UAVs using the proposed intelligent cooperative control strategy.

Above all, the proposed cooperative control strategy for UAV formation flights not only streamlines task execution but also enhances formation safety throughout the flight by incorporating intelligent decision-making mechanisms that support full autonomy in UAV maneuvers.

VI. Conclusion

This paper presents a novel cooperative control strategy for UAV formation flights, emphasizing timely mission completion and safety. Through dynamic adjustments to speed, the strategy ensures wingmen effectively follow the lead aircraft while meeting mission objectives. The efficacy and accuracy of the method are validated through the numerous MATLAB-based simulation results.

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