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COOPERATIVE PATH PLANNING AND ADJUSTING STRATEGY FOR UAVs WITH STRICT TIME CONSTRAINT

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Abstract

Multi-UAVs cooperative operations with strict time constraint have become a common form for future application, including simultaneous arrival/attack, UAVs formation, collaborative search and target tracking, and other time-constrained cooperative tasks. The methods of time-constrained path planning based on ant colony algorithm is proposed in this paper to improve the efficiency and effectiveness of time-constrained path planning. Three strategies for multi-UAVs time adjustment are demonstrated, including takeoff time adjustment, discrete speed adjustment, and hovering for waiting strategy. Three-UAV simultaneous arrival path planning and adjustment process based on the presented method is simulated to explain the cooperation method and the operation effective of the strategies.

Keywords: Unmanned Aerial Vehicle,cooperative path planning, time-constrained, adjustment strategies

1. General Introduction

With the rapid development of unmanned aerial vehicle (UAV) technology, UAVs have been widely used in military reconnaissance, regional search, environmental surveys, and other fields to perform “Dull, Dirty, Dangerous, and Deep (4D)” tasks.Advantages of UAVs include highly mobile, adaptable, and high survivability, no risk of casualties, and low manufacturing and maintenance costs[1-5]. Multi-UAVs cooperative operations have become a common form of future warfare to accomplish tasks that cannot be completed by a single platform, improving the efficiency of self-confidence tasks[6,7].

Strict time constraint is an important feature of multi-UAVs cooperative mission, including simultaneous arrival/attack, UAVs formation, collaborative search and target tracking, and other time-constrained collaborative tasks.It is usually necessary to fly to the designated target point with an expected time window, or simultaneous approach, or coordinated wave approaches[8-10]. Strict time constraint poses challenges to the path planning of drones, including the maneuverability of cooperative aircrafts, flight speeds, and different threat environment[11,12]. The main difficulties could be summarized as follows: (1) In the traditional path planning method, the time constraint is usually used to limit the time to reach the target, and in the time critical path planning, the time planning for each path point are restricted;(2) In the traditional track planning method, the path is usually planned firstly and then subsequently allocated to meet the flight time constraints, while the time-constrained path planning needs to directly use the time constraint as a planning indicator; (3) In the path planning based on strong time constraints, the conflict judgment and resolution strategy needs to be solved and executed quickly, which requires high real-time online planning capability of the aircraft.

The research of multi-UAVs collaborative planning with strong time constraints are limited. The related concepts and methods on path planning could be applied in order to solve the problem, such as single-UAV feasible path generation under complex environment and dynamic constraints, fast multi-UAVs coordinated path planning, spatial conflict judgment and resolution strategies.

A review of these methods with a comprehensive mathematical discussion is presented in [13]. The Conflict Detection and Resolution (CDR) problem has also been studied extensively[14], including speed assignment method, Mixed Integer Linear Programming (MILP), Ant Colony Optimization (ACO) algorithms, Particle Swarm Optimization (PSO), etc.. The typical time-space conflict resolution method in the civil aviation field and the air traffic control field could be referred to time critical cooperative path planning and adjusting strategy for UAVs[15,16], including neural network-based parameter algorithms, flight-based and constrained track prediction algorithms, track prediction algorithm based on circular track and isometric track. However, the multi-UAV's path planning problem is different from the civil aviation field's track planning problem, which is more complicated for the environments, objectives and real-time online resolving requirements.

In order to enhance the overall operational effectiveness and survivability of multi-UAVs collaborative path planning, time critical cooperative path planning method and adjusting strategy were investigated. The paper is organized into six sections. Section 2 states the problem to be solved herein, including the typical time critical mission, the framework of time-space collaborative path planning problem, and the mathematical formulation. Then the methods of time-constrained path planning based on ACO and planning smoothing method based on Dubins algorithm are presented in Section 3. Three strategies for multi-UAVs time adjustment are demonstrated in Section 4, including takeoff time adjustment, discrete speed adjustment, and the hovering for waiting strategy. Three-UAV simultaneous arrival path planning and adjustment process based on the presented methods are simulated and discussed in Section 5. Section 6 concludes the paper. Work in this paper could support the multi-UAVs path planning with a strong time-constrained mission, including simultaneous arrival/attack, autonomous formation, collaborative search and target tracking, and other time-constrained multi-UAVs collaborative tasks.

2. Modeling of time critical multi-UAVs cooperative path planning problem

The problem of time-critical path planning is modeled to perform multi-UAVs collaborative mission. Firstly, several collaborative missions with spatial and time constraints are introduced to motivate the problem presented in this paper. Secondly, the framework of collaborative path planning based on decoupled space and time is adopted. Thirdly, the mathematical formulation of the problem is provided, including the goal function and constrains.

2.1 Time critical cooperative missions

Unmanned Aerial Vehicle (UAV) has been playing an increasingly important role in civilian and military applications. The use of homogeneous or heterogeneous UAVs connected by means of a communication network is required to execute more challenging missions. In particular, the cooperative missions require that each UAV follows a feasible path, and then the team maintain a desired timing plan to ensure that all vehicles execute collision-free maneuvers and arrive at final destinations at the same or different time[5,17,18]. Several collaborative missions with spatial and time constraints are explained as follows.

(1) Simultaneous arrival/attack. To compress the enemy’s detection probability and penetrate the air defense system, the UAV swarms are proposed to arrive the target from different directions at the same time, regardless of the difference of starting points, penetration environment and physical constraints of each UAV. The spatial and time constraints are critical for the simultaneous arrival/attack mission.

(2) UAVs formation and reconfiguration. Multi-UAVs operating in an intensive and predefined formations could offer revolutionary capabilities, improve situation awareness,ant reduce manpower requirement. The synchronization of timing and collision avoidance are urgently required during the formation, maintenance and reconfiguration flight, which is very difficult under complicate dynamic constrains and task.

(3) Collaborative search and target tracking. Several small tactical UAVs equipped with complementary vision sensors could be used to detect and identify an improvised explosive device moving along a road. Cooperative control can ensure a satisfactory overlap of the field-of-view footprints of the vision sensors along the road, thus increasing the probability of target detection. In thecollaborative search and target tracking mission, the UAVs should maintain an equal interval or

circumferentially distribute around the target with strict time constrains.

(4) Heterogeneous UAVs scouting and attack mission. In order to adapt complex battlefield environments, heterogeneous UAVs swarm could flexibly configure with different types of aircrafts and different payload to generate flexible and changeable combat capabilities. Take the scouting and attack mission for example, the reconnaissance UAVs should search, detect, and locate the target before the attack aircrafts perform follow-up fire-attack tasks. The heterogeneous swarm cooperative mission has strict flight time limits on the aircrafts.

(5) Aerial sequential auto-landing. A fleet of aerial vehicles must arrive at the assigned glide path in prespecified safe-guarding time intervals, which must be maintained when the vehicles fly along the glide slope.

2.2 Framework of collaborative path planning based on decoupled space and time

Time critical cooperative path planning and adjustment problem could be described: according to the known environmental threat distribution, the starting point, the target area, and the coordinated target reach time, the optimal path should be solved for each UAV to avoid the threat source and reach the target point with critical time constrains. To simplify the time-space collaborative path planning problem, the decoupled space and time framework is researched to decompose the time-space four-dimensional planning process into single-UAV optimal track generation with complex environment and constraints.

The block diagram of the collaborative path planning based on decoupled space and time is shown in Fig. 1. The task process is based on the idea of separating space and time. Firstly, a set of feasible space paths and a corresponding set of speed curves are generated for each single UAV. And then, the space is separated from time, the velocity variable is treated as an additional degree of freedom in the time dimension. The drone converges and follows the planned path as much as possible to achieve physical feasibility. Finally, relying on the information interaction of the underlying communication network, the speed and track of each drone are adjusted according to the desired speed curve.The entire UAV swarm meets the time requirements of the coordinated task.

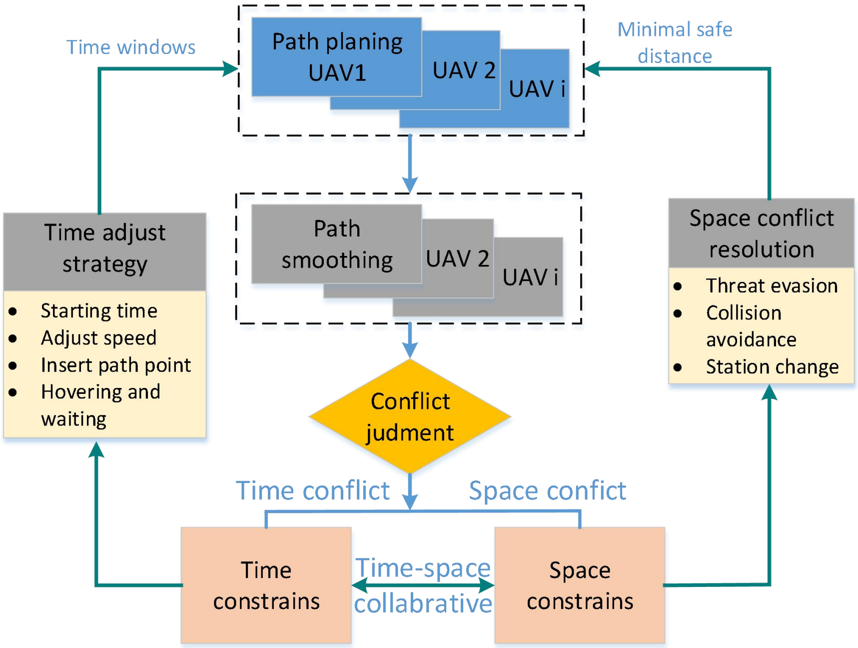


Figure 1 – framework of collaborative path planning based on decoupled space and time

2.3 Mathematical formulation

The mathematical formulation of the time critical cooperative path planning and adjustment problem could be explained as follow. In a certain planning space Ω, the flight path combination $Path^* = (P_1, P_2, \cdots, P_M)$ from the initial position S^* to the target position G^* is generated on time for the entire UAV swarm $V_1, V_2, \cdots, V_M$ (*M* is the number of unmanned aerial vehicles). The maneuverability constraints of the UAVs, the cooperative constraints of path collision-free constraints and time coordination should be maintained. The cost of the entire UAVs system is minimized. That is:

$$\begin{aligned} &\bar{C}(Path^*) = \min_{p} \bar{C}(P) = \min_{p} \begin{pmatrix} C_1(P) \\ C_2(P) \\ \vdots \\ C_M(P) \end{pmatrix} \\ &\text{s.t.} \quad g_i(p_i^*) \geq 0 \quad (i = 1, 2, \cdots M) \\ &\qquad \bigcap_{i=1}^{N} \left([t^i_{\min}, t^i_{\max}] \right) \neq \varnothing \\ &\qquad d_{ij\min}(t_k) \geq d_s \quad (i, j = 1, 2, \cdots M, i \neq j) \end{aligned} \tag{1}$$

Wherein, the planning space Ω , the initial position S^* and the target position G^* could be expressed as

$$\begin{aligned} &\Omega = \left\{ (\mathrm{x}, \mathrm{y}, \mathrm{z}) \middle| 0 \leq x \leq \max X, 0 \leq y \leq \max Y, 0 \leq z \leq \max Z \right\} \\ &S^* = \left(S_1(x, y, z, t), S_2(x, y, z, t), \cdots, S_M(x, y, z, t) \right) \\ &G^* = \left(G_1(x, y, z, t), G_2(x, y, z, t), \cdots, G_M(x, y, z, t), \right) \end{aligned} \tag{2}$$

And the flight path of each aircraft is represented by a sequence of spatial position points containing time.

$$P_i = \begin{Bmatrix} S_i(x, y, z, t), p_{i1}(x, y, z, t), p_{i2}(x, y, z, t), \cdots \\ , p_{iK-1}(x, y, z, t), G_i(x, y, z, t) \end{Bmatrix} \tag{3}$$

where *K* is the number of path points.

In Eq.(1), $g_i(p_i^*) \geq 0$ denotes the maneuverability constraints of the UAVs, including the minimum path segment length， minimum turning radius, maximum flight range, fight speed, and height.

$$g_i(p_i^*) \geq 0 \quad \text{means} \quad \left| \begin{array}{c} l_k \geq l_{\min} \\ \phi_k \leq \phi_{\max} \\ \sum_k \| l_k \| \leq L_{\max} \\ v_{\min} \leq v \leq v_{\max} \\ \cdots \end{array} \right. \tag{4}$$

Furthermore, $\bigcap_{i=1}^{N} \left([t^i_{\min}, t^i_{\max}] \right) \neq \varnothing$ indicates the time-collaborative constrain, where $[t^i_{\min}, t^i_{\max}]$ expresses the window for expected target arrival time of *i*-th vehicle. and $d_{ij\min}(t_k) \geq d_s$ characterizes the path collision-free constraints, In which d_s denotes the minimum safe distance among the UAVs.

3. Path planning and smoothing for multi-UAVs cooperative mission

In time-critical multi-UAVs cooperative path planning problem, time dimension is added into traditional 3D trajectory planning. However, the expansion from three-dimensional to four-dimensional also increases the difficulty of the path planning work to adapt the preliminary planning algorithm about the collaborative constrains of space and time. According to the model and mathematical formulation of time-critical multi-UAVs cooperative path planning problem, the time-constrained path planning is generated efficiently using a modified ant colony algorithm and smoothed by Dubins algorithm.

3.1 Time-constrained path planning based on multi-colony ACO algorithm

Ant colony optimization (ACO) is a probabilistic, heuristic optimization technique inspired by the way ants make and find the path from colony to food. It has strong robustness and distributed computing characters. When the ant colony algorithm is used in path searching, it shows a natural law of “survival of the fittest”. The search quality can be improved continuously. The positive feedback mechanism makes the algorithm evolve to the global optimal direction. Additionally, the distributed search mode can shorten the search time and can be parallelly implemented. Therefore, the ant colony algorithm is a suitable method for solving complex combinatorial optimization problems, such as path planning problems [19].

To solve the time-critical multi-UAVs cooperative path planning problem, a multi-colony ACO path planning algorithm is proposed based on the modified ant colony algorithm by using co-evolution concept. The number of ant colonies in the algorithm is consistent with the number of UAVs. In the multi-colony ACO, there are more than one colony to work distributively for the same problem and share their local colony knowledge with other colonies[20].

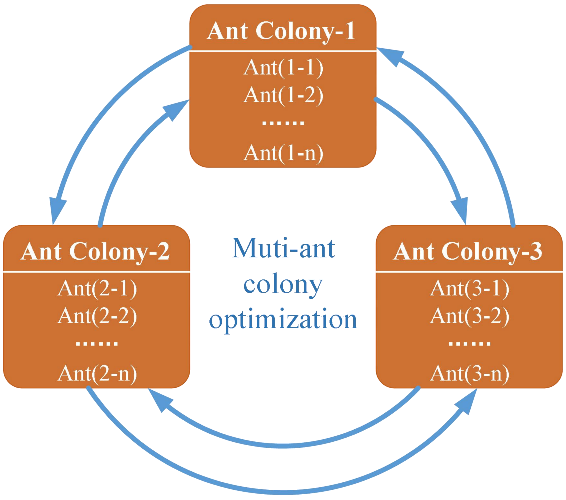


Figure 2 – Principle of multi-colony Ant colony optimization algorithm

Before the algorithm is performed, the ant colony in the algorithm is in one-to-one correspondence with the unit in the unmanned aerial vehicle cluster. When each ant subgroup constructs an optimal trajectory for its corresponding drone, the single locator is used. The state transition rule and the pheromone update strategy in the planning method are then used to determine whether the standard track rules need to be adjusted through the track comprehensive cost function, thereby constructing multiple paths in accordance with the coordination constraints. The steps are:

STEP1: Initialize the ant subgroups and related parameters;

STEP2: Execute STEP3-STEP5 for each ant subgroup;

STEP3: According to the state transition rule of the stand-alone plan, each ant subgroup performs the track planning for the corresponding UAV;

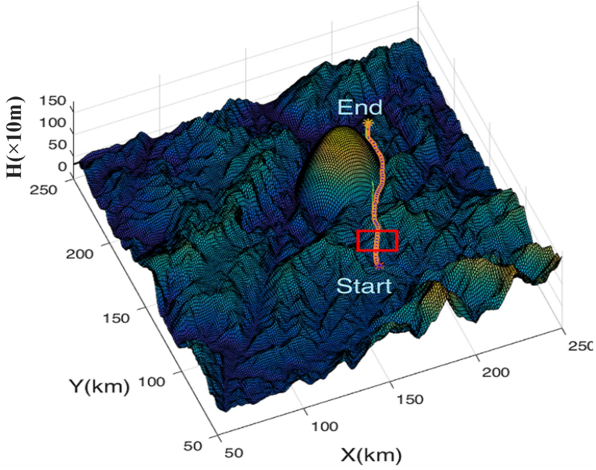
STEP4: After the end of the iterative process, the pheromone structure is updated according to the result of searching for the track;

STEP5: When the number of iterations reaches the upper limit specified by the ant subgroup, the difference between the searched optimal track and the previous result is less than the specified threshold, the iteration is stopped, otherwise, the process goes to STEP3;

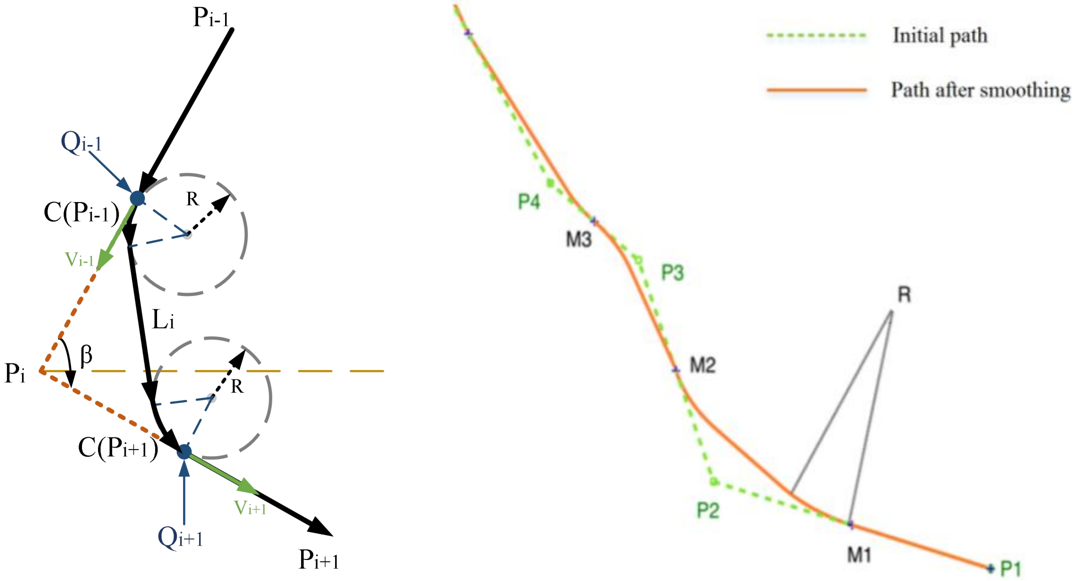
STEP6: After the ant subgroups have completed the above steps, determine whether the number of iterations reaches the maximum number of iterations of the group, or whether the difference between the integrated track cost and the previous search cost is less than the standard deviation, and if so, stop the iteration, otherwise we-determine standard track length and jump to STEP2.

3.2 Planning smoothing method based on Dubins algorithm

Since the initial track obtained by the initial path search algorithm is a broken line connected by a short straight line, there is a corner at each joint of the segmented track. As shown in Fig.3, between the three path points P_{i-1}, P_i, P_{i+1}, the path obtained by the ant colony planning algorithm is a fold line $P_{i-1}-P_i-P_{i+1}$, which has a corner $\angle P_{i-1}P_iP_{i+1}$. If UAV moves along this fold line, the speed at the corner is required to be abrupt, and the corresponding acceleration is infinite, which cannot be realized. The flight stability will be seriously affected. Therefore, the Dubins algorithm is used to smooth the polygonal track and generate a smooth trajectory that conforms to the dynamic constraints on the basis of the initial trajectory.



(a) Example of path planning based on ACO



(b) path smoothing method based on Dubins (c) Path segment before and after smoothing

Figure 3 – Planning smoothing method based on Dubins algorithm

In Fig.3(b), the broken line marked by the short dashed line is the initial track $P_{i-1}-P_i-P_{i+1}$, and the solid line curve $P_{i-1}-C(P_i)-P_{i+1}$ is the smooth track. The track length smoothing is taken using the LSL type Dubins trajectory for an example. The process of path smoothing is as follows:

(1) Identify the line segments that need to be smoothed (Take $P_{i-1}-P_i-P_{i+1}$ for example);

(2) Determine the midpoint sum of the line segment $P_{i-1}P_i$ and the line segment P_iP_{i+1} respectively, then the coordinates of point Q_{i-1} and Q_{i+1} can be obtained and the velocity direction at point Q_{i-1} and Q_{i+1} is consistent with the original velocity direction of the initial path;

(3) Determine the minimum turning radius R and use the Dubins trajectory planning method for smooth track planning between Q_{i-1} and Q_{i+1}.

The result with smooth trajectory is shown in the Fig.3(b) as $P_{i-1}Q_{i-1}$ - $C(P_{i-1})$ - L_i - $C(P_{i+1})$ - $Q_{i+1}P_{i+1}$. As the angle β changes, the type of Dubins smooth track is transformed in the four basic forms of Dubins, including LSL, LSR, RLS, and RLR[21]. Since the initial trajectory is planned and the position and velocity directions of points Q_{i-1} and Q_{i+1} are known, and the preconditions for Dubins trajectory planning are met, a smooth and flyable path can always be generated. Fig.3(c) shows an example of path segments before and after smoothing. It can be seen that the smoothed path is more feasible and safe with the dynamic characteristics of the UAV, and roughly conforms to the initial path with small deviation from the initial path.

4. Three strategies for multi-UAVs time adjustment

In multi-UAVs collaborative tasks, because of the path smoothing as mentioned in the previous section, sudden obstacles or wind environment, or mission changes, the flight time error can be caused. Time adjustment is needed to coordinate the flight time and meet time window constraints. Three strategies for multi-UAVs time adjustment are investigated as follow, including takeoff time adjustment, discrete speed adjustment, and the hovering for waiting strategy.

4.1 Adjusting the takeoff time

The path planning of multiaircraft is divided into preplanning and real-time planning. For the time conflicts appearing in the preplanning, the complex and dangerous on-fly waiting or hurry-up can be converted into ground by adjusting the take-off time of the UAVs. With the takeoff time adjustment strategy, the time conflicts can be avoided safely with economy fuel consumption. The time of takeoff adjusting is the difference between the expected arrival time and the required arrival time.

$$\Delta T_{adj}^{i} = T_{\exp}^{i} - T_{req}^{i} \tag{5}$$

Wherein, the expected arrival time $T_{\exp}^{i}$ of i-th UAV can be calculated with the perplanned path length divided by the average cruising speed as $T_{\exp}^{i} = D_{per}^{i} / v^{i}$, and the required arrival time T_{req}^{i} is determined by the time constraints in (1).

4.2 Discrete speed adjustment

The short and uncertain time conflicts during flight can be digested with the speed adjustment strategy. The speeds of the UAVs can be adjusted in the available range based on the coordination information exchanged among the vehicles over a supporting communication. To reduce the difficulty of speed control, the discrete speed adjustment method on several segments of path is presented to maintain the relatively stable speed in a path segment.

Assuming that the aircraft is flying at path point P_i at time t_i with speed v_i, and the expected arrival time to path point P_k is t_k. The distance of preplanned path segment between path point P_i and P_k is D_{i-k}. If $t_k - t_i \neq D_{i-k} / v_i$, the time collision exists. Therefore the flight speed in path segment P_{i-k} can be adjusted as

$$v_{adj} = \frac{D_{i-k}}{t_k - t_i} \tag{6}$$

Additionally, in the process of speed adjustment, the flight speed constraints of the aircraft should be met:

$$v_{\min} \leq v_{adj} \leq v_{\max} \tag{7}$$

If the above inequality constraint cannot be met by the speed adjustment, that is, the flight performance of the aircraft can not support the speed adjustment, other adjustment strategies should be taken.

4.3 The hovering for waiting strategy

For aircraft that have not yet taken off, the strategy of changing the departure time can be adopted. For the aircraft during flight, the strategy of adjusting speed can be used for finite time conflict. However, when the required to adjust the time is too long, the strategy of adjusting the speed constrained by the controllable speed range might be insufficient. The hovering with waiting strategy is presented to release time-rich conflict for fixed-wing UAVs.

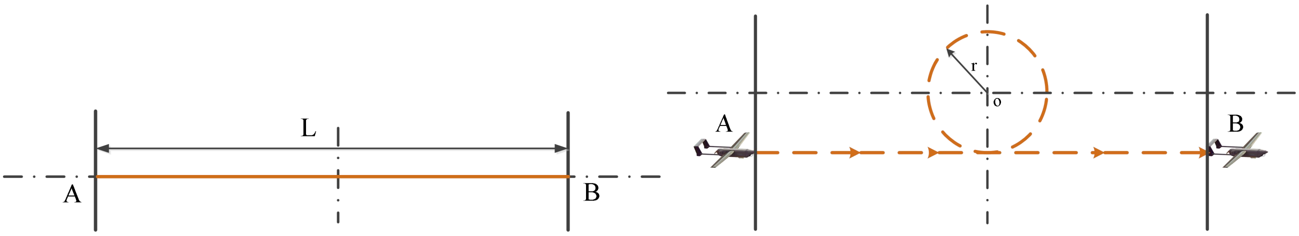
In the hovering for waiting strategy, an additional path point is added to the initial planned path to increase the flight range. However, space conflict risk cannot be neglected between the added path segment and the initial planned paths of other UAVs or environment obstacles. To reduce the space conflict risk, the added path point is designed to be as close as possible to the initial planned path. The Dubins trajectory with the aircraft minimal turning radius $r_{\min}$ is adopted to insert the middle path point, which can maintain the maximal distance between the initial path and the adjusted path is equal to $2r_{\min}$ .The principle of hovering for waiting strategy is illuminated in Fig.4.

According to the hovering for waiting strategy, the added flight distance is determined, using the hovering radius and circles n , as

$$D_{add} = 2n\pi r_{\min} \tag{8}$$

And the adjust time can be calculated as'

$$\Delta t = \frac{D_{add}}{V_{ave}} \tag{9}$$



（a） initial planned path （b） hovering with minimal turning radius $r_{\min}$

Figure 4 – Principle of hovering for waiting strategy

4.4 Comparison of three time adjusting strategies

Focusing on the time contradiction caused by path smoothing, unexpected environmental obstacles, and multi-UAVs space conflict resolution, three time adjusting strategies have been proposed, i.e., the time adjustment strategy including adjusting the take-off time and adjusting the flight speed and hovering for waiting strategy. The characteristics of different time adjustment mechanisms are analyzed and compared in Tab.I.

TABLE I. COMPARISON OF THREE TIME ADJUSTING STRATEGIES

Strategy	Advantage	Disadvantage	Scope of application
Adjusting the take-off time	Safe and flexible	Only applicable to the drones before takeoff	The UAV has not yet taken off. Through the pre-planning calculation of the track, time coordination cannot be achieved with other strategies.
Adjusting the flight speed	On-fly adjusting	The speed range and the adjustment time are limited.	The small time error after takeoff can be covered within specification range.
Hovering for waiting	A long time error can be repaired	There must be a buffer area that allows the hovering.	The waiting time needs to be consumed, and the track passes through a terrain buffer that can be hovered.

The basic strategy selection ideas are proposed: for the path conflicts appearing in the preplanning or when the UAV voyage differs greatly from other UAVs, the take-off time is adjusted before the aircraft takes off, and the complex air waiting is converted into the ground waiting; for the track conflict or time error after takeoff, the flight speed can be adjusted within the flight speed range to enable the UAV to reach the destination at the specified time; when the aircraft has taken off, and the time required for adjustment is large, hovering for waiting strategy is taken. The above three time adjustment strategies can be combined to realize the time adjustment of multi-UAVs coordinated track planning under different working conditions. For the complex situation of multiple

UAVS and even multilevel tasks, the above three strategies can be combined.

5. Simulation example: three-UAV simultaneous arrival path planning and adjustment

5.1 Initial conditions

In a 200km×200km area, the three UAVs UAV1, UAV2, and UAV3 are taken off from different starting points, and they are required to simultaneously reach the mission area to perform tasks at the same time. The planning space model with SRTM(Shuttle Radar Topography Mission) data combined with a threat radar. The position information and flight parameters of the three UAVs are given in Tab.II. The planning space, starting position of UAVs, and the final task execution area are illuminated in Fig.5. There is a flat buffer area for each UAV to safely where hovering and waiting is allowed.

TABLE II. SIMULATION CONDITIONS OF THREE UAVS COOPERATIVE MISSIONS

NO.	Starting point (x, y, h) (km)	Final point (x, y, h) (km)	Minimal speed(m/s)	Maximize speed(m/s)
UAV1	(100,160,1)	(200,200,1)	20	30
UAV2	(130,60,1)		20	30
UAV3	(130,240,1.2)		15	25

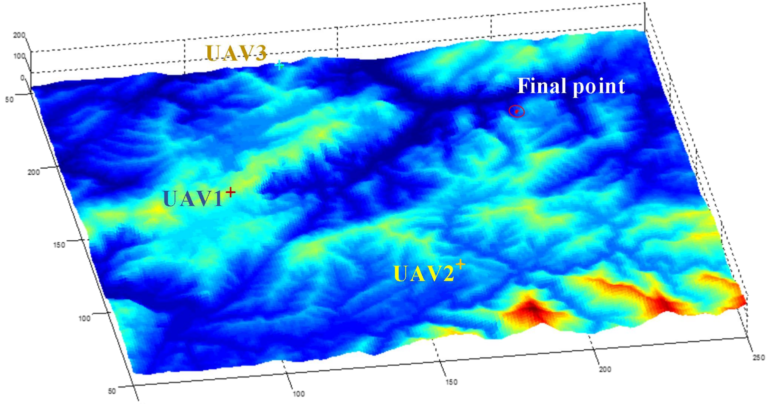
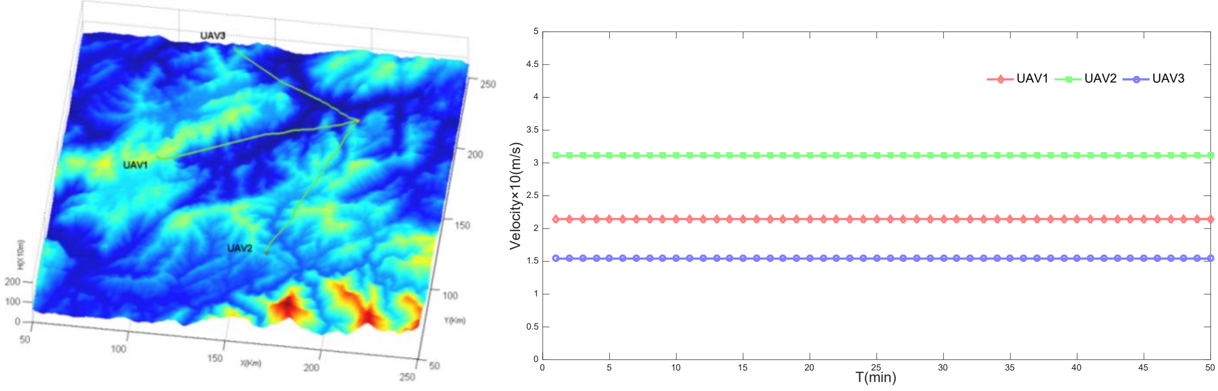


Figure 5 – Environment based on SRTM and initial condition of UAVs

5.2 Simulation result

The preplanning of the cooperative path is carried out based on the modified multi-ant colony algorithm, and the speed requirement for simultaneous arrival is calculated and shown in Fig.6.



（a）pre-planned path based on multi-colony ACO （b）Per-planning speed profile for simultaneous arrival

Figure 6 – pre-planning path based on modified multi-colony ACO

The speed of the UAV2 exceeds the speed range because its path is the longest, and the speed of the UAV1 is relatively low because its path is the shortest. In response to this situation, taking into account the urgency of the mission requirements and time, first adjust the UAV2 take-off time. After calculation, UAV2 takes off 27 minutes earlier, so that its flight speed just reaches the speed limit. At this time, the speed diagram of the three drones is shown in Fig.7.

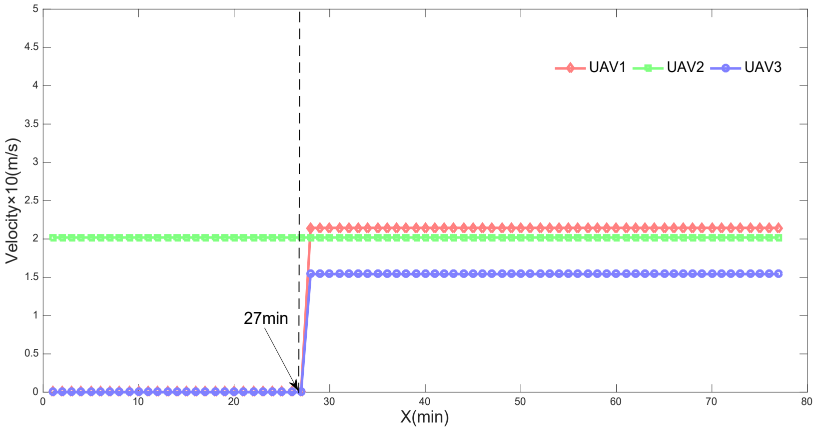
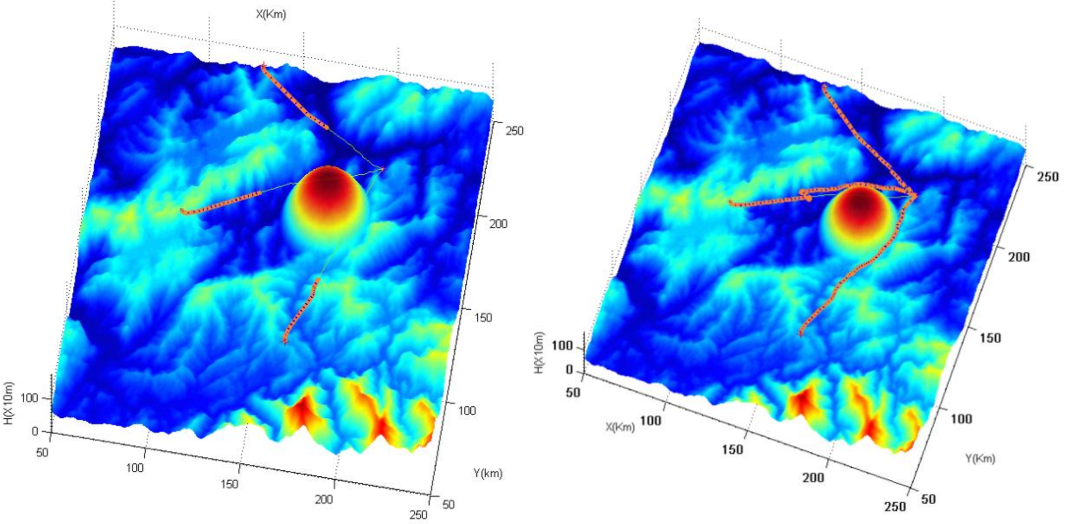


Figure 7 – the takeoff time of UAV2 is adjusted to reduce the speed required

20 minutes after UAV1 takeoff, an air-defense radar appears on the perplanned paths of UAV1 and UAV2, and the paths are replanned for UAV1 and UAV2, as shown in Fig. 8. To bypass the air defense radar threat, the path length of UAV1 and UAV2 is increased. To arrive the final point simultaneously, the flight speed required is calculated again, which is shown in Fig.9.



(a) An air defense radar appears suddenly (b) path replanning for UAV1 and UAV2

Figure 8 – Path replanning for UAV1 and UAV2 caused by sudden air defense radar threat

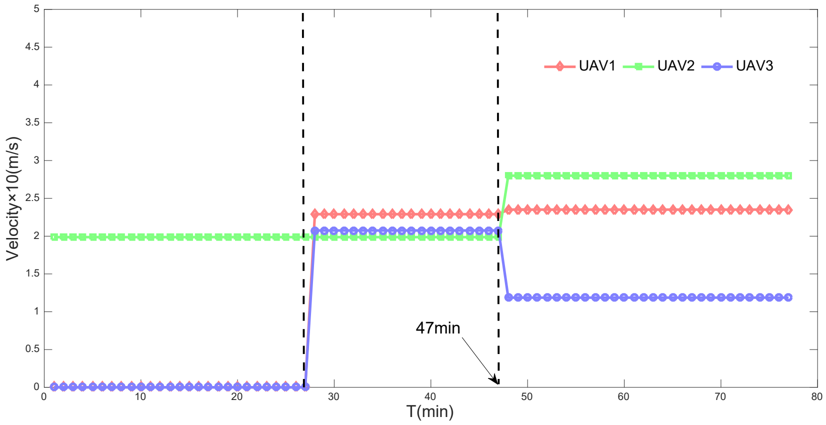
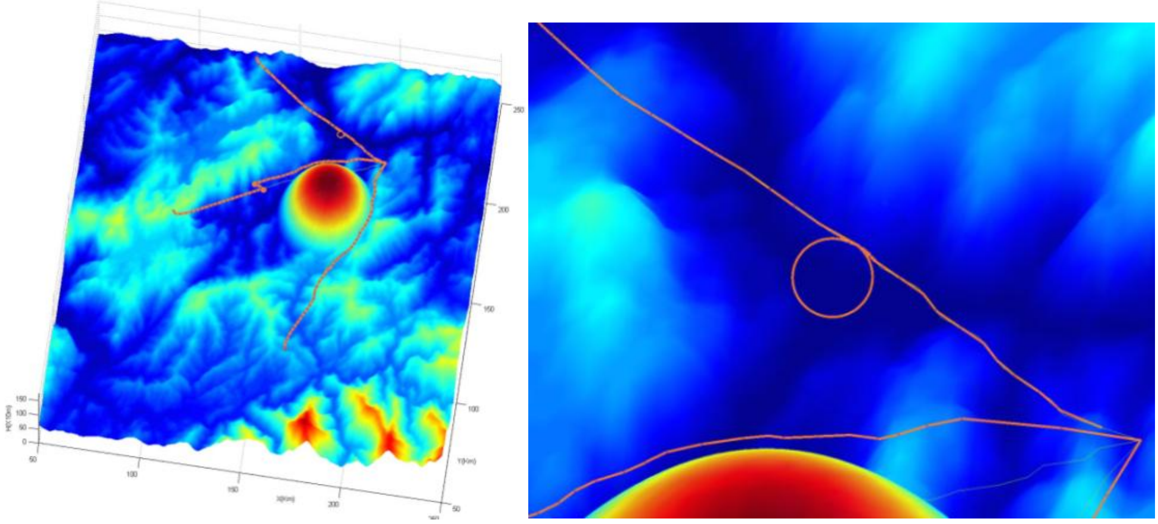
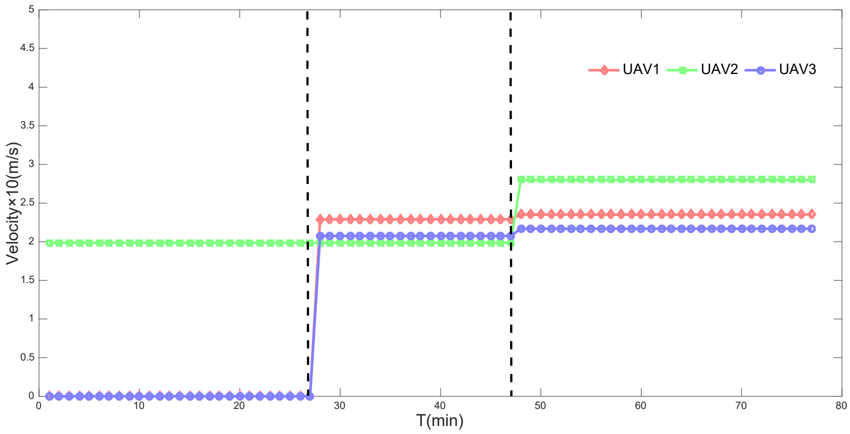


Figure 9 – Speed adjustment as an air defense radar appears suddenly

It is apparent from the speed diagram that the speed of the UAV3 is lower than its minimal speed, which means that further time adjustment with other strategies is needed. Therefore, the hovering and waiting time adjustment strategy is adopted to UAV3, and the result is shown in Fig.10.



(a)Final planned paths （b）Zooming of the UAV3 hovering path



（c）Takeoff time adjusting and discrete speed adjusting result

Figure 10 – Final planned path results with different time-adjustment trajectories

6. Conclusions

Strict time constraints are an important feature of multi-UAVs cooperative operations, which poses challenges to the planning of drones. To enhance the overall operational effectiveness and survivability of multi-UAVs collaborative path planning time, critical cooperative path planning methods and adjusting strategies based on decoupled space and time are researched in this paper. The method of time-constrained path planning based on ant colony algorithm and planning smoothing method based on Dubins algorithm is adapted obtain the initial paths. Then, three strategies for multi-UAVs time adjustment, including takeoff time adjustment, discrete speed adjustment, and the hovering for waiting strategy, are proposed to solve the time constrains. An example of three-UAV simultaneous arrival path planning and adjustment is simulated to explain the cooperation method and the operation effective of the strategies. Work in this paper could support a strong time-constrained mission, including simultaneous arrival/attack, autonomous formation, collaborative search and target tracking, and other time-constrained multi-UAVs collaborative tasks.

To further improve the time critical cooperative path planning and adjusting strategy, the proposed method will be extended with considering other uncertainties, e.g., airspeed measurement error and current position estimation error, and the computing efficient of on-line path planning for increasing numbers of UAVs will be evaluated. In addition, the authors will consider the implementation and real-world testing of the proposed algorithm in a closed-loop intelligent control system.

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8. Copyright Statement

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