Research on the Algorithm of Online Route Re-planning for UAV Formation

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Abstract. In order to solve the real-time and robust problem of online flight path re-planning when UAV encounters new threat sources in the course of navigation, an online flight route re-planning algorithm based on sparse A* algorithm is proposed. Based on the threat model of UAV, the online route re-planning strategy is analyzed. When the UAV detects a new threat in the course of navigation, according to the current position of the UAV formation and the position of the threat source, a route that can safely bypass the threat source is quickly re-planned. In order to meet the requirements of real-time and robustness, the node expansion and update strategy of the improved sparse A* algorithm and the hierarchical planning combined with the size step size are adopted. The simulation system of UAV formation navigation is established to verify the process of online route re-planning. The number of expansion nodes and convergence time of algorithm before and after the improvement are compared, and the track accuracy of fine planning based on rough planning is compared. The experimental results show that the improved algorithm can speed up the search speed and meet the real-time requirements of online route re-planning.

1. Introduction
Under the premise of considering the various navigation constraints of UAV, a better navigation path is planned between the starting point and the target point. UAV path planning can be divided into offline planning and online planning [1]. Offline route planning is to plan the route for UAV when the threat area of battlefield environment is known. However, UAV will encounter various emergencies in actual flight, such as obstacles not appearing in offline map [2]. The above situation will cause the offline planned track unable to reach the expected target point and meet the requirements of the combat task. UAV needs to have the ability of online path re-planning when detecting new threat areas. The solution methods of UAV track problem are mainly divided into graph theory method and grid algorithm, such as voronoi algorithm based on graph theory [3-4], PRM algorithm [5-6], grid based A* algorithm and dynamic planning algorithm [7-8]. In this paper, aiming at the problem of online path re-planning in actual flight, the threat model of UAV combat environment is established firstly, then the method of online path re-planning is analyzed, and the speed of generating new path is accelerated by the improved strategy based on sparse A* algorithm [9], which meets the real-time requirements of online path planning and enhances the robustness of UAV navigation. Because UAVs work in the form of formation, this paper also considers the online path re-planning [10-11] under the condition of formation. Finally, the simulation is carried out.
2. Operational environment analysis

2.1. Threat model and system analysis
All threat sources, including missiles and radars, are assumed to be circular areas with different radii according to different threat levels [12-13]. All static threats are known during offline planning, and the complete track can be obtained through offline planning. In the process of UAV formation flying, obstacles not appearing in offline map can be detected and updated to the map used for planning route.

2.2. Constraint analysis
The UAV formation will be constrained by its own performance in the process of actual operation. It mainly includes the maximum range constraint, the maximum turning angle, the minimum step constraint and the minimum turning radius constraint.

In this paper, the minimum turning radius constraint [14] and the maximum turning angle constraint [15] are considered. The turning radius is the three consecutive nodes generated during the search in Figure 1. The extensible condition is:

\[ R < r_{\text{min}} \]  

(1)

\( r_{\text{min}} \) is minimum turning radius.

![Figure 1. Minimum turning radius constraint.](image)

2.3. Analysis of online re planning strategy of track
In this paper, when planning the UAV formation track, a global route is generated offline. When a new threat is encountered in the course of actual navigation according to the current position of the original global track and the newly updated threat area in the map. According to the track points on the original route, part of the track is re planned. The global track is still dominated by offline planned track. In this way, UAV formation can avoid new threats in actual navigation.

3. Online route re planning based on hierarchical sparse A* algorithm

3.1. The strategy of sparse A* algorithm
A* algorithm is a heuristic algorithm, which selects the cost function of the extended node algorithm by dividing the planning area into units and comparing the cost value of the units.

\[ f(n) = (1 - \omega) * g(n) + \omega * h(n) \]  

(2)

Among them, the actual path cost from the current node to the starting point, the heuristic cost from the current node to the target point, the weighting factor, and the total cost of the node.

In the node table update strategy, add a node detection strategy. If the new extended node is dominated by the existing node, it will not be retained; if the new node dominates the existing node, it will replace the previous controlled node; if the new node and all existing nodes are not dominated, it will be retained. Through the node dominance detection strategy, sparse A* algorithm no longer expands useless nodes, and improves the efficiency of the algorithm.
In the node expansion strategy, in order to obtain a node that is close to the height of the planned target point in the search point during the search process, when the height of the target point is different, if the height of the target point is within the current reachable range, expand it, add a node that can reach the height of the target point on the basis of the original height node, and regard it as the node that is in the original height node with the target point on the basis of this, add a node that can reach the height of the target point, and regard it as a point at the same height with the target point, so that in the process of spatial search, the nodes at the same height with the target point can be expanded and simplified on the two-dimensional map. Then it can simplify the judgment of the convergence conditions of subsequence.

3.2. **Stratification strategy**

Although the track planning efficiency of sparse A* algorithm is significantly higher than that of standard a* algorithm. However, when the UAV plan the flight path, due to the large scale of the map and the various tasks of the target, it puts forward higher requirements for the real-time performance of the algorithm. Sparse A* algorithm may fall into the phenomenon of local search or dimension explosion. Only the improvement of sparsity of track planning can not effectively meet the requirements of real-time. Therefore, the idea of hierarchical programming can be applied to sparse A* algorithm.

3.2.1. **Rough planning.** First of all, a rough path planning is quickly solved by using the global map and threat idea, that is, a track point set is planned by using the large length sparse A* algorithm. Due to the use of large step algorithm to plan the basic path, the speed of rough planning is much faster than that of standard sparse A* algorithm. The size of the large steps depends on the size of the map to be planned and the situation of the threat area. All kinds of constraints in the process of route planning are not considered temporarily in the process of rough planning.

Rough planning mainly solves the problem that the algorithm falls into local search and dimension explosion. In the process of path planning, the efficiency of the whole algorithm will be reduced by planning all threat areas in small steps. Compared with the actual situation, there is little difference in real-time, accuracy and security of planning route. Therefore, rough programming can solve the problem of local search and dimension explosion. At the same time, it improves the efficiency of the algorithm.

3.2.2. **Fine planning.** For the path planning algorithm, various constraints need to be considered in the planning process. Adding constraints to search space can effectively eliminate invalid points. In this paper, two constraints are considered, the minimum turning radius constraint and the maximum turning angle constraint.

![Hierarchical route planning strategy](image)

*Figure 2. Hierarchical route planning strategy.*
Due to the use of large steps, the route generated in the rough planning process may have a large turning angle and a small turning radius. The planning track of some sections may not be smooth enough. In order to solve this problem, it is necessary to optimize the large step size quadratic programming. In this paper, a fine programming algorithm is proposed, that is, the small step long sparse A* algorithm. In the fine planning, the starting point and the ending point of the planning are the road point set which does not meet the constraint requirements of the track, and then the rough planning route between the two track points is planned for the secondary fine planning. The constraints of the track are considered in the fine planning, and the infeasible route in the rough planning is adjusted and modified to ensure the feasibility of the final track. Fine planning is carried out on the basis of rough planning, and there is no need to re-plan the existing route. The planning process is relatively simple and will not fall into the problem of local search and relative explosion gain.

Fine planning is a combination of rough planning and small step length planning. The secondary fine planning does not need to be carried out in every track segment, but only needs to be completed to ensure the feasibility and superiority of the track planning method. Thus, an optimal planning trajectory which is more in line with the demand is obtained.

4. Online route re-planning

4.1. Online route re-planning method

As shown in Figure 3, firstly, a global route is generated offline according to the known map using the hierarchical sparse A* path planning algorithm. The UAV formation navigates according to the generated global track to ensure that the information of the combat environment can be detected in real time during the voyage. When the UAV detects a new threat in the combat environment, it needs to update the threat to the map and judge whether it will affect the offline route. If it will affect the current flight path, it needs to take the current track point as the starting point and the original unaffected track point as the target point to plan the track online, so as to ensure the track segment that needs to be re-planned as short as possible, the planning time is further reduced. According to the above process, online re-planning of tracks is carried out, so as to plan new tracks to complete the target task.

![Figure 3. Online route planning process.](image-url)
4.2. **Online route re-planning of formation**

UAV usually appears in the form of formation in combat. In this paper, formation is organized according to the virtual center method.

The virtual structure method is used to determine the target position of each UAV in the formation to prevent the single UAV from leaving the formation. Use virtual pilots to maintain the flexibility of the whole formation. On the basis of tracking the trajectory of a virtual UAV, the virtual UAV in trajectory tracking is used as the virtual leader in formation control by using the combination of virtual structure and virtual leader shown in the figure. The reference position of any UAV in formation can be determined by its corresponding formation vector. In the formation navigation, as long as the formation vector remains unchanged, the virtual rigid body of the whole formation remains unchanged, and the formation of UAV remains unchanged.

Through the formation control method of virtual center method, the reference position of any UAV relative to the virtual navigator can be determined at any time. When the virtual pilot tracks the planned route, the virtual route of the UAV relative to the planned route can be obtained by connecting the reference position of each time of the UAV. As long as each UAV in the formation tracks its own virtual route, it can keep the whole UAV formation in a specific formation. The given path of trajectory tracking is a curve about time. The UAV needs to reach the designated position at the specified time, emphasizing the synchronization of time and space. The reference path of the UAV formation is a planned route with time attribute.

![Formation mode of virtual center method.](image)

In route planning, it is necessary to consider whether the track of each UAV in the formation can smoothly pass through the threat area, not only whether the virtual center point is outside the threat area, but also whether each UAV in the formation is outside the threat area.

5. **Experiment results**

In order to verify that the algorithm can solve the problem of on-line path re-planning of UAV formation. The path planned by this algorithm needs to keep a safe distance from the threat area on the map, reach the target accurately and meet new threats when the UAV formation is sailing, so that online path re-planning can be carried out. The simulation platform adopts Intel Core i5-200 @ 2.20hz processor, and the simulation environment is ROS under Linux. In the map environment of 10km × 12km, the simulation experiment of UAV formation online path re-planning is carried out. Select (0, 0) as the starting point and the other three points (3, 3), (2.5, 6.6), (9, 11) as the target points on the map. The offline track planning results are obtained by simulation and the convergence time of the track is compared.
Through the comparison between Figure 5 and Figure 6 and the data in Table 1 and table 2, the offline track of the planning office has changed. On the basis of the original sparse A* algorithm, the number of nodes expanded by the algorithm is reduced and the convergence speed of the algorithm is reduced by optimizing the node expansion update strategy and the layering strategy.
It can be seen from figure 7 that after the convergence speed of the algorithm is improved, the length of the planned route can be shortened, and the safety of the route can still be guaranteed, with good robustness. Through the establishment of simulation system, when UAV encounter new threat sources in the course of navigation, they need to change the pre-planned track. Figure 8 shows the online track re-planning results of three UAV formations in the formation of equilateral triangle formation. The green track is the track of virtual pilot point, and the track of UAV in the formation is obtained by geometric relationship according to the track of virtual pilot point. UAV formation when a new threat source is detected, part of the pre-planned track can be re-planned to successfully avoid new obstacles and reach the predetermined target point.

![Figure 8. Online route re-planning result.](image)

6. Conclusion
For the requirements of real-time, task adaptability and robustness of UAV route planning based on sparse A* algorithm. The node expansion and update strategy of sparse A* algorithm is optimized, and the path planning strategy based on hierarchical idea is constructed, which ensures the real-time and robustness of the planning. For UAV formation online route re-planning performance research. The simulation results show that the layered strategy is effective. The simulation results show that the algorithm can effectively improve the real-time and robustness of the algorithm, shorten the planning time, and realize the online route re-planning of UAV, which has high engineering application value.

References
[1] Stöcker C, Bennett R, Nex F, et al. Review of the Current State of UAV Regulations [J]. Remote Sensing, 2017, 9 (5): 459.
[2] Austin R. Unmanned aircraft systems: UAVs design, development, and deployment [J]. Journal. publications. chestnet. org, 2010, 79 (50): 31-36.
[3] Levcopoulos C, Katajainen J, Lingas A. An Optimal Expected-Time Parallel Algorithm for Vornoi Diagrams. [C] // WorkshoponSwat. 2014.
[4] Dehne F K H A. On O (N^4) Algorithm to Construct all Vornoi Diagrams for K Nearest Neighbor Searching [C] // Automata, Languages and Programming, 10th Colloquium, Barcelona, Spain, July 18-22, 1983, Proceedings. DBLP, 1983.
[5] Koleva Y, Yoshinov B, Nikolova S. Impact of deep oscillation in the complex PRM algorithm of pain management [J]. Annals of Physical & Rehabilitation Medicine, 2014, 57: e253.
[6] Liu Yang, Zhang Weiguo, Li Guangwen. Path planning research based on improved PRM algorithm [J]. Computer application research, 2012 (01): 110-112 + 145.
[7] Xu Y, Yue W, Su K. the bdd-based dynamic a* algorithm for real-time replanning [C] // 3d International Workshop on Frontiers inAlgorithmics. 2009.
[8] Zhan W, Wang W, Chen N, et al. Path Planning Strategies for UAV Based on Improved A* Algorithm [J]. Geomatics & Information Science of Wuhan University, 2015, 40 (3): 315-320.
[9] Molchanov A, Kortunov V, Mozolyuk S. A real-time system for detection and avoidance of dynamic obstacles for micro UAVs [C]/.
[10] Wada Y, Kuwana K. A numerical method to predict flame fractal dimension during gas explosion [J]. Journal of Loss Prevention in the Process Industries, 2013, 26 (2): 392-395.

[11] Solodov A, Williams A, Hanaei S A, et al. Analyzing the threat of unmanned aerial vehicles (UAV) to nuclear facilities [J]. Security Journal, 2017 (3): 1-20.

[12] Wang N J, Zhang D F, Zhou L J. Path Planning for Vehicle with Constraint on Turning Radius among Obstacles [J]. Key Engineering Materials, 2011, 450: 128-132.

[13] Liu Chang, Wang honglun, Yao Peng, et al. Modeling and analysis of UAV dynamic collision zone for air threat [J]. Journal of Beijing University of Aeronautics and Astronautics (7): 80-87.

[14] Thompson P A. Maximum turning angle across an oblique shock[J]. Aiaa Journal, 2015, 9 (7): 1436-1436.

[15] Meng Z, Huang P, Jie Y. Trajectory planning for hypersonic vehicle using improved sparse A* algorithm [C] // IEEE/ASME International Conference on Advanced Intelligent Mechatronics. 2008.