Design of UAV Cooperative Countermeasure Decision System

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Keywords: UAV Formation, Cooperative Confrontation, Task Allocation, Trajectory Planning.

Abstract: This paper designs a UAV Cooperative Countermeasure Decision System. The system focuses on the effective integration of key technologies and algorithms such as multi-aircraft cooperative task assignment, multi-aircraft cooperative track planning, and multi-aircraft cooperative formation control, and its effectiveness is verified through digital simulation. This paper mainly establishes a multi-machine cooperative task allocation algorithm based on satisfactory decision theory to achieve near-optimal task allocation among multiple UAVs under various mission and resource constraints; a UAV path planning algorithm based on a fast heuristic search strategy realizes fast and efficient UAV path planning and real-time path re-planning in a dynamic environment; a multi-machine cooperative formation flight and reconfiguration control algorithm based on induced routes is used to realize UAV formation flight formation control; finally, the feasibility of the key technologies and algorithms of the system is verified through visual simulation.

1 INTRODUCTION

With the rapid development of UAV technology, multi-UAV cooperative combat has become one of the important forms of combat in the future. In the cooperative combat of multiple UAVs, it is very important to effectively coordinate and control the task execution and flight path planning of multiple UAVs to improve operational efficiency.

In the past, UAV's task assignment and flight path planning have been widely studied. In the field of task allocation, experts and scholars have put forward centralized task allocation mathematical models such as multi-traveling salesman problem (Secreat B R, 2001), vehicle routing problem (O'Rourke K P, 2001), multi-choice knapsack problem (Li Xiangmin, 2014), mixed integer linear programming problem (An S, 2014), dynamic network flow optimization model (Zhu D, 2013), and distributed task allocation models such as multi-agent decision theory and market mechanism distributed Markov distribution constraints. In the field of route planning, algorithms such as optimal control method, roadmap method, grid method and artificial potential field method are also proposed. However, there are relatively few comprehensive studies on cooperative task assignment, flight path planning and formation control of multi-UAVs. Therefore, in view of the cooperative confrontation scenario of UAV formation, this paper designs a UAV Cooperative Countermeasure Decision System to support multi-UAV rative operations, and focuses on the key technologies and algorithms such as multi - UAV cooperative task assignment, multi - UAV cooperative flight path planning and multi - UAV cooperative formation control.

2 UAV COOPERATIVE COUNTERMEASURE DECISION SYSTEM

The UAV cooperative countermeasure decision system aims to support multi-UAV cooperative operations, to achieve effective coordination and control among multiple UAVs, and to improve operational efficiency and mission execution ability.

2.1 System Architecture

The UAV cooperative countermeasure decision system mainly includes four modules, and each module has the following functions

Task assignment module: responsible for establishing the mathematical model of multi-aircraft cooperative task assignment according to the types and requirements of combat tasks, including cost model and constraint model. Using the algorithm based on satisfactory decision theory, the

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approximate optimal task assignment of multiple UAVs under different task and resource constraints is realized.

Path planning module: Considering the high dynamic and real-time requirements of UAV cooperative operations, an UAV path planning algorithm based on fast heuristic search strategy is established, which can meet the constraints of threat avoidance, platform performance, system resources and mission requirements. The module can realize fast and efficient path planning and real-time path re-planning of UAV in dynamic environment.

Formation control module: aiming at improving the cooperative penetration efficiency and task execution efficiency of UAV, a multi-aircraft cooperative formation flight and reconfiguration control algorithm based on guidance routes is established. According to the actual flight state and the formation configuration error between UAVs, different formation control strategies and methods are adopted to realize rapid formation assembly, synchronization and formation.

Simulation and verification module: this module is used to verify the key technologies and algorithms of the system. Collaborative countermeasure strategy can be generated for different mission scenarios and visual simulation can be realized.

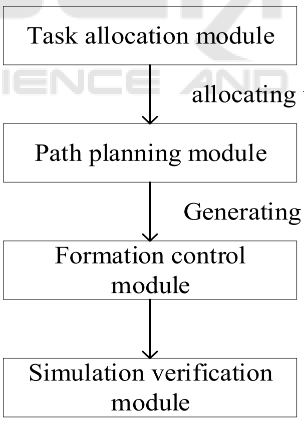


Figure 1: Framework of UAV countermeasure decision system.

2.2 Multi-UAV Cooperative Task Assignment

In this paper, a multi-machine cooperative target assignment algorithm(Liao Mo, 2007) is adopted, and the system framework of the algorithm is shown in the figure, which consists of multi-machine target assigners and individual UAVs. The part contained in the oval virtual frame belongs to the management decision-making part of UAV, which is generally realized by UAV ground control unit.

The single-machine target manager receives the attack target distributed by the multi-machine target distributor, and sends this task target to the path planner, who plans the path to execute the task; At the same time, the single-machine target manager is also responsible for providing a group of satisfactory UAV individuals for the multi-machine target distributor, and allocating parameters for each attack target, such as path length, path threat, attack efficiency, attack threat, etc. The calculation of these parameters requires calling the path planner and evaluation module.

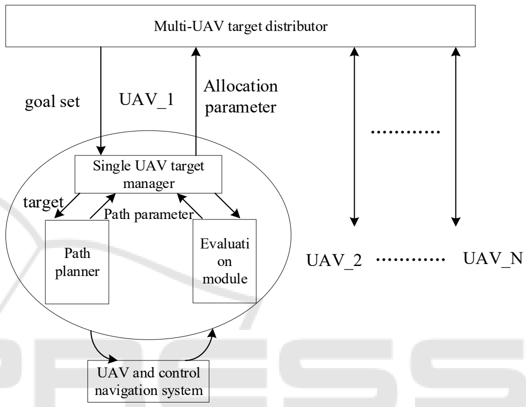


Figure 2: Framework of Multi-machine Collaborative Task Allocation System.

The multi-machine target allocator sends the target set and parameters to be allocated to each single machine target manager, calculates the global optimal allocation scheme according to the satisfactory set and allocation parameters provided by each single machine, determines the targets to be attacked by each single machine, and then delegates them to the single machine for execution.

The evaluation module of single machine gives the parameters of UAV's destruction probability, danger probability and so on. The path planner calculates the flight path according to the mission objectives and battlefield conditions of the single aircraft, and gives the path length and threat cost. The influence of various threats such as radar, weapons, no-fly zone, electromagnetic zone and bad weather zone on the battlefield is considered, and the planned route, corresponding path length and threat are given.

2.3 Multi-UAV Cooperative Path Planning

Each plane corresponds to a path planner. The coordination and control system of the flight detachment is a large-scale system composed of corresponding small aircraft systems, and the key to its coordination is to determine the best time for the detachment to reach the attack target. The solution to this large-scale system is generally to adopt the distributed control method of decomposition and coordination, decompose the corresponding problems in layers, let the planners of each aircraft carry out relevant calculations, and use an aircraft computer or assign a computer to undertake the coordinated calculation task. The strategy of decomposition is to select coordination variables and determine coordination functions.

Take the coordinate variable ETA (Estimated Time until Arrival), and record it as t_a. The coordination is the comprehensive cost of the team (including fuel consumption and threat cost), with the aim of minimizing coordination.

Suppose there are n planes attacking the same target. For the No. i plane, there are.

Fuel cost:

$$J_{fi} = C_{fi} L_i \tag{1}$$

Threat cost:

$$J_{ti} = C_i\left(\frac{L_i - L_{hi}}{v_i}\right) + C_{hi}\left(\frac{L_{hi}}{v_i}\right) \tag{2}$$

Comprehensive cost:

$$J_i = J_{fi} + J_{ti} \tag{3}$$

Where: L_i is the flight path length, L_{hi} is the path length of the aircraft passing through the high threat area, and v_i is the aircraft speed. C_{fi} is the weighting factor of fuel cost, C_i is the weighting factor of path cost in low threat area and C_{hi} is the weighting factor of path cost in high threat area.

The comprehensive cost of the team J is

$$J = \sum_{i=1}^{n} J_i = \sum_{i=1}^{n}\left[C_{fi}L_i + C_i\left(\frac{L_i - L_{hi}}{v_i}\right) + C_{hi}\left(\frac{L_{hi}}{v_i}\right)\right] \tag{4}$$

And satisfy the constraint conditions:

$$\begin{gathered} v_{min,i} \le v_i \le v_{man,i} \\ J_{fi} \le F_i \\ J_{ti} \le T\mathrm{h_i} \\ t_a \le T_s \end{gathered} \tag{5}$$

Where $\mathrm{F_i}$ is the fuel limit, $\mathrm{Th_i}$ is the acceptable threshold of aircraft danger, and $\mathrm{T_s}$ is the minimum time limit for completing the attack mission.

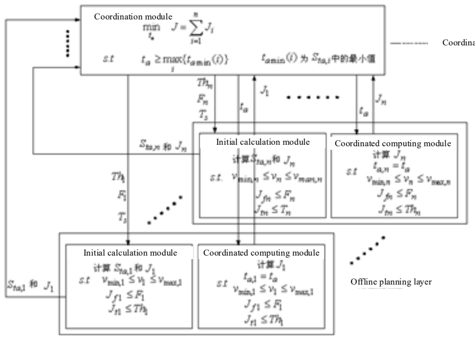


Figure 3: Hierarchical structure of multi-UAV coordinated path planning.

The hierarchical decomposition coordination structure of flight path coordination planning process is shown in Figure 3, which can be divided into superior coordination layer and lower path planning layer. Where $S_{ta,i}$ is the destination arrival time set of the num.i plane.

The next calculation of hierarchical planning can be put into the path planner of each UCAV, and the calculation can be divided into two modules: initial calculation module and coordinated calculation module.

The multi-machine coordinated path planning algorithm comprises the following steps:

The initial calculation module carries out path planning according to the fuel limit $\mathrm{F_i}$, the acceptable threshold of danger $\mathrm{Th_i}$ and the minimum time $\mathrm{T_s}$ to complete the attack task given by the superior $\mathrm{S_{ta,i}}$, and calculates the arrival time set of the corresponding aircraft according to different flight speeds to get the corresponding cost $\mathrm{J_i}$.

The coordination module of the coordination layer determines the coordination variables according to the arrival time set of each aircraft participating in the assembly $\mathrm{S_{ta,i}}$ and the corresponding cost $\mathrm{J_i}$, and according to the principle of meeting the minimum total comprehensive cost $\mathrm{t_a}$.

The coordination variables $\mathrm{t_a}$ are sent to the lower planning layer, and the coordination calculation module in the planning layer plans the flight route of the corresponding aircraft and calculates the corresponding flight speed and minimum comprehensive cost.

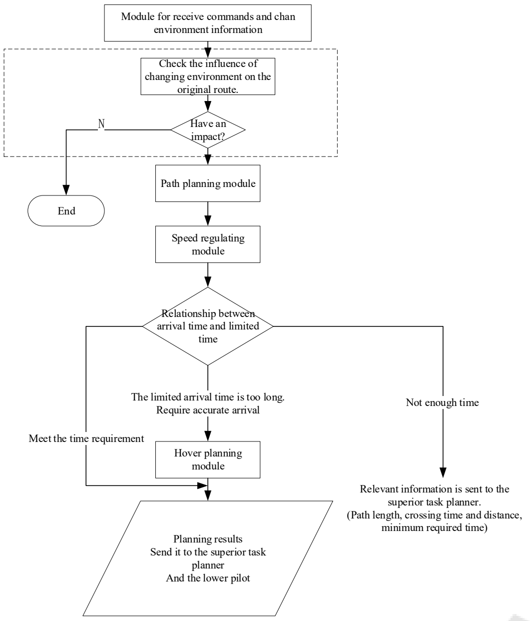


Figure 4: Coordinated path planner algorithm flow.

When it is necessary to re-coordinate the multi-aircraft path planning due to environmental changes, if the planned route of an aircraft cannot meet the constraints, it should be chosen to give up participating in the multi-aircraft assembly and return to a designated waypoint instead.

If the minimum ETA of the $No.i$ plane is t_{amin}, the ETA time of the team t_a is:

$$t_a = max\{t_{amin}(i)\} \tag{6}$$

2.4 Multi-Aircraft Cooperative Formation Flight

This paper adopts a multi-UAV formation control method based on induced route (WU, 2016), assuming that each UAV knows its expected position in the formation before the formation task begins. In the formation mode, the captain obtains the expected route information and tracks the flight of the route, and the wingman calculates his own control instructions through the state of the captain and the expected position information of the local plane.

In the formation control algorithm based on guidance route, the wingman's own control command is a local guidance route, and the wingman can track its expected position by tracking this guidance route in real time. The expected position of wingman in the formation can be described by the lateral distance D_w, forward distance D_f and height difference D_h of the relatively long aircraft, which is positive to the right and backward, as shown in Figure 6.

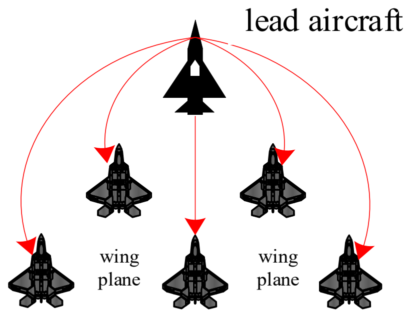


Figure 5: Coordinated path planner algorithm flow.

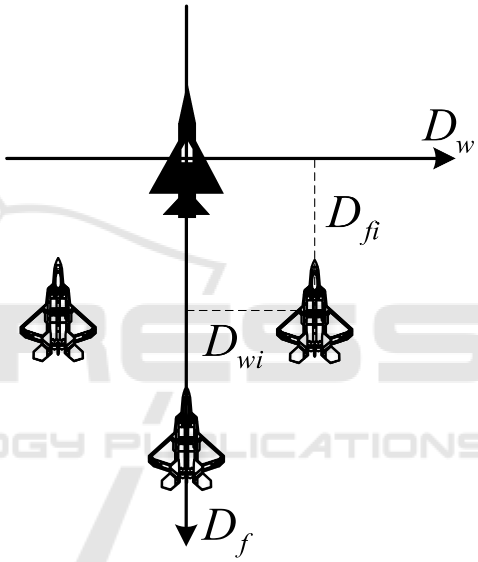
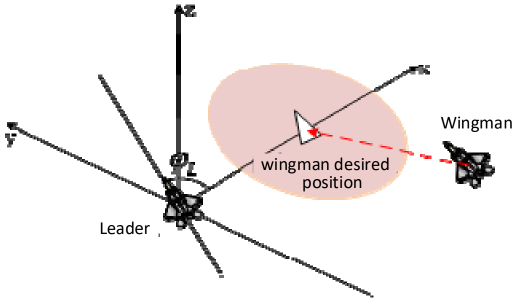
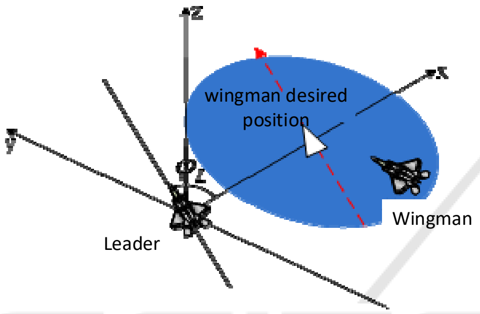


Figure 6: UAV expected position description.

According to the difference of position error between the current position of wingman and its expected position, different strategies are adopted to generate the guidance route to realize the UAV approaching its expected position quickly. When the wingman is far away from its expected position, the guidance route starts from the current position of the wingman and ends at the expected position (as shown in Figure 7.a), so that the wingman can fly to the expected position quickly; When the wingman is close to its expected position, the guidance route passes through the expected position of the wingman and is parallel to the current heading of the leader (as shown in Figure 7.b), so as to guide the wingman to approach the expected position smoothly. The relay switching mode is adopted for the switching of the two guidance routes, that is, the position error of the wingman when switching from the oriented guidance route to the parallel guidance route is smaller than that when switching from the parallel guidance route to the oriented guidance route.



(a) towards the guidance route



(b) Parallel induced routes

Figure 7: Guidance route generation strategy.

Suppose the current position of wingman is (x_1, y_1, h_1), its speed and heading angle are (v_1, φ_1), its expected position and speed are (x_e, y_e, h_e, v_e), the current position of leader is (x_L, y_L, h_L), and its speed and heading angle are (v_L, φ_L). Then the coordinates and speeds of two reference points on the guidance route are calculated as follows

$$\begin{cases} x_{l1} = x_1 + d_k(x_e - x_1) + \Delta l \cos(\varphi_L) \\ y_{l1} = y_1 + d_k(y_e - y_1) + \Delta l \sin(\varphi_L) \\ h_{l1} = h_1 \\ v_{l1} = v_1 \end{cases} \quad (7)$$

$$\begin{cases} x_{l2} = x_{l1} + \Delta l \cos(\varphi_L) \\ y_{l2} = y_{l1} + \Delta l \sin(\varphi_L) \\ h_{l2} = h_1 + k_h(h_e - h_1) \\ v_{l2} = v_e \end{cases} \quad (8)$$

Where the fixed distance Δl between two reference points is long enough, and d_k is a variable with a value between 0 and 1, whose value determines the position of the guidance route, and the guidance route can be translated between the current position and the expected position of the wingman by changing the value of d_k. During the formation of the formation, the value of the d_k is gradually increased from 0 to 1, guiding the wingman to gradually approach its expected position. The heading angle of UAV is defined as 0 in the east direction and positive in the counterclockwise direction. The expected position of wingman (x_e, y_e, h_e) can be described by the expected relative distance from the leader:

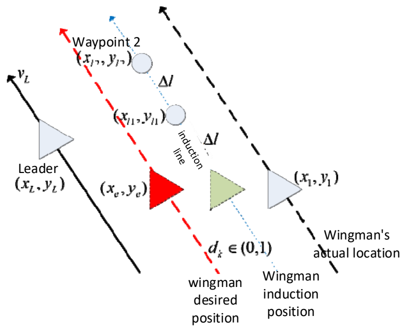


Figure 8: Generation principle of parallel induced route.

$$\begin{cases} x_e = x_L + D_{w1} \sin(\varphi_L) - D_{f1} \cos(\varphi_L) \\ y_e = y_L - D_{w1} \cos(\varphi_L) - D_{f1} \sin(\varphi_L) \\ h_e = h_L + D_{h1} \end{cases} \quad (9)$$

The expected wingman speed v_e is related to the relative distance of the long wingman along the induced route d_{L1}, the speed of the long wingman and the speed difference of the long wingman.

$$\{v_e = k_1 d_{L1} + v_L + k_2(v_L - v_1 \cos(\varphi_1 - \varphi_L)) \quad (10)$$

The control method of wingman tracking induced route is the same as that of long plane tracking given route, which is realized by UAV autopilot. The control of UAV is decoupled into three aspects: longitudinal channel control, lateral channel control and throttle lever position control. Classical PID control is adopted, and the normal overload command, roll angle speed command and throttle increment command are obtained according to the input route command, which are used as the input of UAV model.

3 SIMULATION SCENARIO AND VERIFICATION

3.1 Simulation Scenario

The blue UAV cooperates against the red target area, and the target distribution in the red target area is shown in Figure 9. Each assembly point can be equipped with 16 UAVs, which are divided into two categories: A is an electronic warfare UAV and B is a strike UAV, including 12 UAVs in Class A and 4 UAVs in Class B.. Class A UAVs need to fly in formation from the assembly point and perform jamming tasks, while Class B UAVs need to strike targets at fixed points. The schematic diagram is as follows:

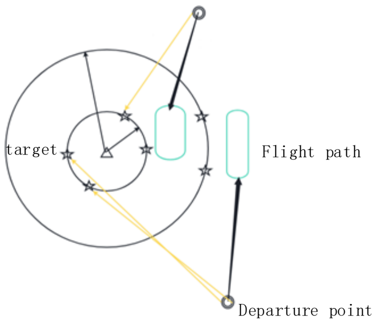


Figure 9: Schematic diagram of countermeasure scenario.

3.2 Simulation Results and Implementation

As shown below, the main interface of the system is mainly composed of five parts, namely, planning state display module, indicating state display module, simulation control module, two-dimensional situation display module and three-dimensional curve display module.

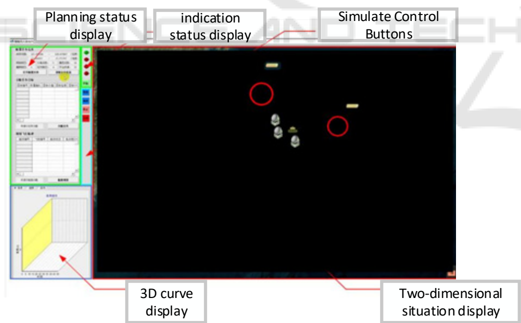


Figure 10: Countermeasure scenario.

1) 32 UAVs interfere with and attack 4 targets

There are two kinds of battlefield threats in scenario 1, one is radar target and the other is enemy weapon target, including 3 enemy radar targets and 1 enemy weapon target. There are two UAV groups in Blue (12 jamming UAVs and 4 attacking UAVs each), which take off from different locations and gather in designated airspace. After the collection is completed, form a designated formation and fly in formation. When the cluster reaches the target area, the cluster is separated, and then the respective cluster tasks are performed. In this scenario, there are four targets and eight attacking drones, and the task assignment of the targets to the drones is completed by collaborative task assignment algorithm to minimize the cost and maximize the benefits.

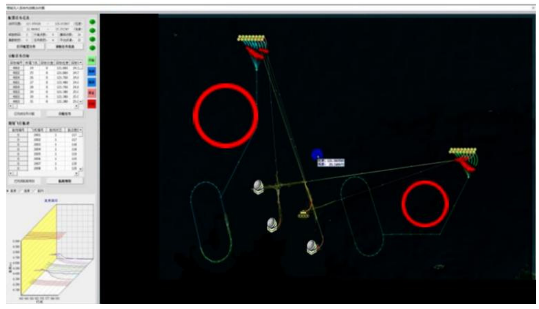


Figure 11: Simulation result 1.

2) 32 UAVs interfere with and attack 7 targets

There are two kinds of battlefield threats in scenario 2, one is radar target and the other is enemy weapon target, among which there are 6 enemy radar targets and 1 enemy weapon target. There are two UAV groups in Blue (12 jamming UAVs and 4 attacking UAVs each), which take off from different locations and gather in designated airspace. After the collection is completed, form a designated formation and fly in formation. When the cluster reaches the target area, the cluster is separated, and then the respective cluster tasks are performed. In this scenario, there are 7 targets and 8 attacking drones, and the task assignment of the targets to the drones is completed by collaborative task assignment algorithm to minimize the cost and maximize the benefits.

Figure 12: Simulation result 2.

4 CONCLUSION

In this paper, a decision-making system of UAV cooperative confrontation is designed, and the key technologies and algorithms such as multi-UAV cooperative task assignment, multi-UAV cooperative flight path planning and multi-UAV cooperative formation control are studied emphatically. The simulation results show that the system is effective and feasible in multi-UAV cooperative operations. The system provides a useful reference for cooperative countermeasure decision-making of UAV formation, and provides important support for improving operational efficiency and mission execution ability.

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