UAV Formation Using a Dynamic Task Assignment Algorithm with Cooperative Combat

Ying Wang[1(✉)], Yonggang Li[1], Zhichao Zheng[1], Longjiang Li[2], and Xing Zhang[3]

[1] School of Communication and Information Engineering, Chongqing University of Posts and Telecommunications, Chongqing 400065, People's Republic of China
1062543772@qq.com

[2] School of Information and Communication Engineering, University of Electronic Science and Technology of China, Chengdu 611731, Sichuan, People's Republic of China

[3] State Grid Chongqing Electric Power Company Information Communication Branch, Chongqing 401120, People's Republic of China

Abstract. As the research model of Unmanned Aerial Vehicle (UAV) formation, it is required to complete the combat tasks such as covering reconnaissance, processing battlefield information and striking targets. A cooperative combat model is proposed to assign combat tasks and plan flight paths for Unmanned Aerial Vehicles (UAVs) in scenarios that need to perform differentiated missions. In view of the UAV function's failure and fail to complete the assigned task, a dynamic task adjustment algorithm is proposed to distinguish the mission stages. Based on the task allocation scheme, the hierarchical adjustment strategy is developed, which take the adjustment time, communication cost and adjustment load into consideration respectively, so as to reduce the adjustment cost and improve the combat capability of the UAV formation on the basis of ensuring the completion of the combat task. Taking the combat formation of UAV as the simulation model, the results show that the proposed algorithm can reduce the adjustment cost and improve the combat capability of the formation on the premise that the formation can complete the combat task.

Keywords: Unmanned Aerial Vehicle (UAV) · Path planning · Cooperative task assignment · Dynamic task adjustment

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1 Introduction

In modern war, UAV has been applied in various aspects, which has great research significance and development space. The research model of UAV formation is of great significance. The UAV formation does not carry out a single type of mission, but a variety of tasks at the same time. Therefore, in this paper, the UAV formation is taken as the research model. UAV formation of needs to have strong cooperative combat capability. The cooperative combat of UAV formation has an important influence on winning the war.

The formation combat mode of cooperative reconnaissance, rapid decision-making and precise strike can improve the success rate of combat in the process of combat, and the assignment of combat tasks and the planning of the flight track of each UAV are key issues in the study of formation combat. According to specific combat tasks, task assignment is carried out for the formation [1–5]. Literature [6] proposed a task allocation strategy based on the Hungarian algorithm. In recent years, scholars at home and abroad have carried out a large number of studies on UAV cluster path planning, including the spatial representation of UAV track, planning objectives and constraints [7–10]. At present, the research on combat formation is relatively simple and does not involve the task allocation that needs to perform multiple tasks. To sum up, this paper puts forward a cooperative combat model, which realizes the cooperation and coordination among UAVs by using task allocation and flight path planning methods.

The rest of this paper is arranged as follows. Section 2 establishes the cooperative combat model of UAV formation. Section 3 introduces dynamic task adjustment. Section 4 provides the simulation results and analysis. Finally, Sect. 5 concludes the paper.

2 Cooperative Combat Modeling

2.1 UAV Formation Scene Research

In the process of combat, according to the needs of the task, the UAV has a variety of functional modules, which form a comprehensive formation with a variety of capabilities, and carry out combat operations to the target in the combat area, in order to meet the strategic needs. By referring to the idea of the circular process of observation, positioning, decision and action (OODA) in modern combat theory, each function of UAV is modeled into corresponding function nodes, that is, reconnaissance node S, decision node D and strike node I. The reconnaissance node S can detect and collect battlefield information in the target area. Decision node D can process the reconnaissance information and command the attack node. Strike node I accepts the instruction of the decision node to strike the target.

In the course of combat, the combat mission is described as follows: in a bounded area A, m heterogeneous UAVs are performing tasks, which require full coverage reconnaissance of A, and they can quickly process reconnaissance information and carry out fire strike tasks.

2.2 Cooperative Task Assignment

Decision-Making Stage. First of all, the division of combat area should be solved in the cooperative task assignment of UAV formation. The decision UAV is responsible for information processing of corresponding region, which is the basis of cooperative operation. The problem of region division can be transformed into the problem of responsible regions of decision nodes. The number of sub-regions can be divided according to the number of decision nodes, i.e. $N_a = N_D$. During region division, D nodes are assigned to each sub-region to obtain N_a subtask sets, and each subtask set contains a D node, that is, $\{T\} = \{T_1, T_2, ..., T_{N_a}\} = \{\{D_1\}, \{D_2\}, ..., \{D_{N_D}\}\}$.

The Reconnaissance Stage. For the reconnaissance stage, it is the purpose of task allocation to minimize the time required to fully cover the reconnaissance combat area. Parallel search is a commonly used cover reconnaissance strategy. The distance between the two parallel lines is defined as the width of the region [12]. In order to ensure the minimum number of turns in the covering reconnaissance process, the reconnaissance node moves along the vertical direction of the minimum width of the region.

For region i, the mission area is divided into $n_{sc,i}$ scan lines along the reconnaissance direction, and S moves along the scan lines. The number of reconnaissance nodes in region i, $n_{Ts,i}$, is determined according to the size of the minimum width L^i_{min}.

$$n_{sc,i} = L^i_{\min}/2R_s \tag{1}$$

$$n_{Ts,i} = N_s \times L^i_{\min}/\sum_{i=1}^{N_a} L^i_{\min} \tag{2}$$

$$N_S = \sum_{i=1}^{N_a} n_{Ts,i} \tag{3}$$

Considering the multi-functional properties of UAVs, when assigning S nodes to each task set, S nodes belonging to the same UAV as D are first assigned to the sub-task set where the UAVs belong to, and then the remaining S nodes are assigned to each sub-task set according to $n_T s$. When you update the task set, you get the task set with the node number: $\{T\} = \{\{D_1, S_1, ..., S_{n_{Ts,1}}\}, \{D_2, S_2, ..., S_{n_{Ts,2}}\}, ..., \{D_{N_D}, S_1, ..., S_{n_{Ts,N_D}}\}\}$.

The Striking Stage. Attacking node I^T_i in each sub-region executes the attack mission in its region. For targets that appear randomly in space, according to the area of the sub-region, the task assignment in the attacking stage assign nodes to each subtask set. The number of nodes in region i is:

$$n_{Ti,i} = N_I \times S_{ar,i}/S_{ar} \tag{4}$$

where, N_I is the total number of strike nodes in the formation, S_{ar} is the total area of the combat region, and $S_{ar,i}$ is the area of sub-region i.

Node I belonging to the same UAV as D or S is also assigned to the corresponding task set when node D or node S is assigned, while the remaining I

nodes are assigned to each task set according to Eq. (4). The task assignment results of the three types of functional nodes are as follows:

$$\{T\} = \{\{D_1, S_1, ..., S_{n_{Ts,1}}, I_1, ..., I_{n_{TI,1}}\}, ..., \{D_{N_D}, S_1, ..., S_{n_{Ts,N_D}}, I_1, ..., I_{n_{TI,N_D}}\}\} \tag{5}$$

2.3 Path Planning Methods

The Track of Node S. According to Eq. (5), the track of UAV in each task set is planned. Firstly, the track of the reconnaissance UAV is planned, that is, the scan line of the mission area responsible for each S node is determined. The goal of track planning of node S is to minimize the time t_{cover} required to complete a single coverage of reconnaissance area A. The communication probability between the two closest UAVs U_n and U_m in the adjacent area should always be greater than the communication probability threshold P_{tv}. The path planning problem of reconnaissance UAV can be described as follows:

$$\begin{aligned}
&mint_{\text{cover}} = \min(\max(t_{AS,1}, t_{AS,2}, ..., t_{AS,N_a})),\\
&t_{AS,i} = \max(t_{S,1}, t_{S,2}, ..., t_{S,n_{Ts,i}}), i \in \{1, ..., N_a\}\\
&t_{S,j} = \sum_{k=1}^{n_{sc,ij}} l_{ijk}/v + (n_{sc,ij} - 1) \times t_{sw}, j \in \{1, ..., n_{Ts,i}\}\\
&s.t. \begin{cases} n_{sc,i} = \sum_{j=1}^{n_{Ts,i}} n_{sc,ij} \\ P_{U_n,U_m,t} \geq P_{tv} \end{cases}
\end{aligned} \tag{6}$$

where, t_{cover} is equal to the maximum of the time taken for each sub-region to complete coverage reconnaissance; $t_{AS,i}$ represents the time required for sub-region i to complete a coverage reconnaissance, which is equal to the maximum $t_{s,j}$ of the time taken by each UAV in this region to complete the mission. $t_{s,j}$ includes reconnaissance mission area scan line time and turn time; $n_{Ts,i}$ is the number of reconnaissance nodes in region i; $n_{sc,ij}$ is the number of scan lines in the area in which UAV j is responsible in region i; l_{ij} is the length of scan lines in the task area k of UAV j; v is the speed of UAV movement; t_{SW} is the time required for UAV to turn.

The Track of Node D. In combat, node D moves along with node S in the region in order to process reconnaissance information. D node belongs to the same UAV as S node, and its flight path is the same as the corresponding S node. The other D nodes are determined by the track of S node in the region.

The communication topology between S nodes can be represented by a weighted directed graph, and the communication distance is represented as the weight of the edge. The communication between UAVs is related to the distance. In region i, the information interaction topology in the directed graph at time t can be represented as a directed minimum spanning tree $T_{Si,t}$ with minimum sum of edge weights $w_{T_S,i}$.

$$w_{T_S,i} = \min \sum_{(u,v)\in T_{Si,t}} w(u,v) \tag{7}$$

According to the minimum spanning tree $T_{Si,t}$, the two S nodes with the farthest distance among all nodes can be obtained. The central position of the connecting line of these two nodes is the position of node D at time t.

According to the track planning of S node, the position of S node at every moment can be obtained. In order to facilitate the study, the position of S node is extracted by taking Δt as the time interval to obtain the position of D node at the same time. Connect all the time positions of D node in time sequence, and finally get the track of D node.

The Track of Node I. The flight path planning of the attack UAV is carried out, and the flight path is the same as that of the corresponding S or D node, which belongs to the I node of an UAV. The rest of the I nodes move around the D nodes. In order to ensure that D and I can communicate with each other and quickly attack the target, the location of node I should be between node D and each node S, and the distance to D should be $d_{S-D}/2$. d_{S-D} is the distance between S node and D node. When the number of I nodes is less than S node, the position of I node is determined from far to near.

3 Dynamic Task Adjustment

3.1 Failure Analysis of Various Nodes

Reconnaissance Node S **has Failed.** In the dynamic task adjustment strategy, the S node satisfying the optimal adjustment is adjusted from the original task set $\{T_{S,N_P}\}$ to the task set $\{T_{S,P}\}$ with S failure. The ratio of the minimum width of the region to the number of reconnaissance nodes in the region is defined as reconnaissance load C_S, that is

$$C_S = L_{\min}/n_{Ts} \tag{8}$$

Let $C_{S,p}$ and C_{S,N_P} represent the reconnaissance load of $T_{S,P}$ and T_{S,N_P} after adjustment respectively, and the reconnaissance load of $T_{S,P}$ must be greater than or equal to the reconnaissance load of T_{S,N_P}, i.e.$C_{S,p} \geq C_{S,N_P}$. The S node satisfying the optimal adjustment should have the minimum task adjustment time t_p, that is to say, t_p is equal to the minimum task adjustment time required by each adjustment scheme, as shown in Eq. (9).

$$\begin{cases} t_P = \min\{t_{P,N_i}\}, \\ t_{P,N_i} = \max(t_{S,p_i} + \alpha t_{M_i}, t_{S,N_i}). \end{cases} \\ s.t. C_{S,p} \geq C_{S,N_P} \tag{9}$$

where, t_{P,N_i} represents the adjustment time required by the i adjustment scheme, t_{S,p_i} and t_{S,N_i} respectively represent the maximum time taken by $\{T_{S,P}\}$ and $\{T_{S,N_I}\}$ to complete the coverage task after adjustment. t_{M_i} represents the time taken for S node to move from $\{T_{S,N_I}\}$ to $\{T_{S,P}\}$; α is the weight coefficient, representing the influence degree of adjustment time in the combat mission.

When the optimal adjustment results are obtained, the task set is updated. $\{T_{S,P}\}$ and $\{T_{S,N_P}\}$. Track planning is carried out for S nodes of $\{T_{S,N_P}\}$ and $\{T_{S,P}\}$ according to the path planning method.

Strike Node I has Failed. After the failure of node I, the task adjustment strategy is the same as the S node failure strategy, which adjusts the I node satisfying the optimal adjustment from the original task set $\{T_{I,N_P}\}$ to the task set $\{T_{I,P}\}$ when the node fails. Strike load C_I is defined as the ratio of the area to the number of nodes I, that is:

$$C_I{=}S_{ar}/n_{TI} \tag{10}$$

The optimally adjusted I node should meet the following conditions:

$$\begin{cases} C_{Adj} = \min\{C_{I,P_i}\}, \\ C_{I,P_i} = C_{I,p} + \beta t_{p_i}. \end{cases} \\ s.t. C_{I,p} > C_{I,N_p} \tag{11}$$

The result of the optimal adjustment is to choose the scheme with the minimum C_{I,P_i} of the adjustment load. Where, C_{I,P_i} represents the adjustment load of adjustment scheme i, and t_{p_i} represents the time taken for node I to move from $\{T_{I,N_i}\}$ to $\{T_{I,P}\}$. β is the weight coefficient, which represents the influence of adjustment time on the task. After adjustment, the strike load $C_{I,P}$ of the I node failure task set $\{T_{I,P}\}$ should be larger than the strike load C_{I,N_P} of the original task set $\{T_{I,N_P}\}$.

When the optimal adjustment results are obtained, the task sets $\{T_{I,P}\}$ and $\{T_{I,N_P}\}$ are updated. Then, the path planning is carried out for the I node of $\{T_{I,N_P}\}$ and $\{T_{I,P}\}$ according to the path planning method in this paper.

Decision Node D has Failed. In this paper, for the established network model, a method of network robustness analysis based on function chain is proposed [12]. The network robustness is evaluated by the comprehensive operational capability of all function chains. After the failure of node D, the ability to deal with reconnaissance information is reduced, and the robustness of the network is also reduced. In the dynamic task adjustment, other task sets $\{T_{D,N_i}\}$ are selected for S node and I node in $\{T_{D,P}\}$ with the aim of improving robustness, so that these nodes can maintain communication with the nodes in $\{T_{D,N_i}\}$. The communication cost of S node or I node to $\{T_{D,N_i}\}$ is calculated, and the $\{T_{D,N_i}\}$ with the lowest communication cost w_{k,T_i} is selected as the new task set of S or I. Communication cost w_{k,T_i} is measured by distance cost d_{k,T_i} and error cost f_{k,T_i} of the link. Distance cost of link d_{k,T_i} refers to the distance between U_{Ti} and U_k, which is closest to UAV U_k in task set $\{T_{D,N_i}\}$. Link error cost f_{k,T_i} refers to the length of the communication link between U_k and U_{Ti}, and UAV with decision-making function in $\{T_{D,N_i}\}$ after the establishment of communication.

Normalize d_{k,T_i} and f_{k,T_i}:

$$D_{k,T_i} = \frac{d_{k,T_i} - d_{T_{\min}}}{d_{T_{\max}} - d_{T_{\min}}} \tag{12}$$

$$F_{k,T} = \frac{f_{k,T_i}}{f_{T_{\max}}} \tag{13}$$

where, $d_{T_{\min}}$ and $d_{T_{\max}}$ respectively represent the minimum and maximum distance between UAVs in $\{T_{D,N_i}\}$ after U_k is added to $\{T_{D,N_i}\}$, and $f_{T_{\max}}$ represents the maximum length of communication link in $\{T_{D,N_i}\}$.

The communication cost w_{k,T_i} from UAV U_k to task set $\{T_{D,N_i}\}$ is denoted as:

$$w_{k,T_i} = \gamma D_{k,T_i} + \mu F_{k,T} \tag{14}$$

wherein, γ and μ are weight coefficients, satisfying $\gamma + \mu = 1$.

Traverse the S node in $\{T_{D,P}\}$ to get the adjustment result of each S node; Traverse the I node in $\{T_{D,P}\}$ to get the adjustment result of each I node. Update the task set.

3.2 Dynamic Task Adjustment Algorithm

The corresponding adjustment strategies are designed for the failure of three functional nodes. First, determine whether there is a failure of node S. If so, determine whether there is a failure of node I after adjustment. Finally, determine whether there is a failure of node D. The dynamic task adjustment algorithm is given as follows (Table 1):

Table 1. Dynamic task adjustment algorithm

Algorithm: Dynamic task adjustment algorithm
1. Judge whether there is S node failure. If yes, go to 2. If no, go to 5;
2. Calculate $C_{S,i}$ to determine whether it needs to be adjusted from other task sets. If yes, go to 4. If no, go to 3;
3. Re-plan the track of S node in $\{T_{S,P}\}$ and move to 5;
4. The subtask set $\{T_{S,N_i}\}$ satisfying $C_{S,P} \geq C_{S,N_i}$ was obtained, and t_{P,N_i} was calculated. Select the smallest S node of t_{P,N_i} and adjust it to $\{T_{S,P}\}$. Plan the track of S node in $\{T_{S,P}\}$ and $\{T_{S,N_P}\}$;
5. Judge whether there is an I node failure. If yes, go to 6. If no, go to 9;
6. Calculate $C_{I,i}$ to determine whether it needs to be adjusted from other task sets. If so, go to 8; if not, go to 7;
7. Re-plan the path of node I in $\{T_{I,P}\}$ and go to 9;
8. Where $\{T_{I,N_i}\}$ satisfies $C_{I,P} > C_{I,N_P}$, calculate C_{I,P_i}. Select the smallest I node in C_{I,P_i} and adjust it into $\{T_{I,P}\}$. The path of node I in planning $\{T_{I,P}\}$ and $\{T_{I,N_P}\}$;
9. Determine whether there is a D node failure. If so, go to 10; if not, go to 12;
10. Extract UAV coordinates with Δt as an interval, calculate w_{k,T_i}, and select the one withthe least communication cost $\{T_{D,N_i}\}$;
11. Repeat Step 10 to traverse node$S$ and node I in $\{T_{D,P}\}$. Get the adjustment result of each node and go to 12;
12. End.

4 Simulation Results and Analysis

4.1 Simulation Scenario and Task Parameter Settings

Before task assignment, the functions of each UAV are determined and the function nodes are numbered. The corresponding relationship between UAV and function nodes is shown in Table 2. The 20 columns represent 20 UAVs, each with one or more functions. The UAV function is modeled into three types of nodes, and the three rows respectively represent the three functional nodes of reconnaissance, decision and attacking. Nodes are numbered, and 0 means that the UAV does not have this function. There are 40 nodes in total, and the number of S, D and I is 15, 6 and 19, respectively.

Table 2. Setting of UAV formation simulation parameters

Function	UAV number																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
S	1	2	0	3	4	5	0	0	6	7	8	9	10	11	0	12	0	13	14	15
D	0	16	0	0	0	0	17	18	0	0	19	0	0	0	20	0	21	0	0	0
I	22	23	24	25	26	27	28	0	29	30	31	32	33	34	35	36	37	38	39	40

The combat area A studied in this paper is A rectangular area of $40\,\text{km} \times 30\,\text{km}$, whose vertices are arranged counterclockwise as $\{v1, v2, v3, v4\}$, and the corresponding two-dimensional coordinates are $(0,0)$,$(40 \times 10^3, 0)$,$(40 \times 10^3, 30 \times 10^3)$,$(0, 30 \times 10^3)$. According to the number of D nodes, A is partitioned, and 6 sub-regions are obtained. Set the reconnaissance radius of UAV as R_s=1000 m, and calculate the minimum width of each sub-region as 13.3 km, 13.3 km, 13.4 km, 13.3 km, 13.3 km and 13.4 km respectively. According to Eq. (1) and Eq. (2), S nodes are assigned to each region. The number of I nodes in each sub-region is determined by calculating the area of each sub-region. The results of initialization task assignment are shown in Table 3.

Table 3. Result of task assignment

Set of tasks	S	D	I	UAV number
1	2,3,4	16	23,25,26	2,4,5
2	1,5	17	22,27,28	1,6,7
3	6,7,9	18	29,30,32	8,9,10,12
4	8,10	19	24,31,33	3,11,13
5	11,12	20	34,35,36	14,15,16
6	13,14,15	21	37,38,39,40	17,18,19,20

Track planning is carried out for node S. The 6 sub-areas divided by a black dotted line in Fig. 1(a) are arranged counterclockwise from the lower left corner to correspond to each task set. The reconnaissance area for each S node in each mission set is separated by a gray dotted line. In general, the cruising speed of small and medium-sized UAVs is between 16.7–33.3 m/s. Therefore, it is assumed that the speed of UAVs is set as $v = 20$ m/s, and the time taken for a single full coverage of S node is 3470 s.

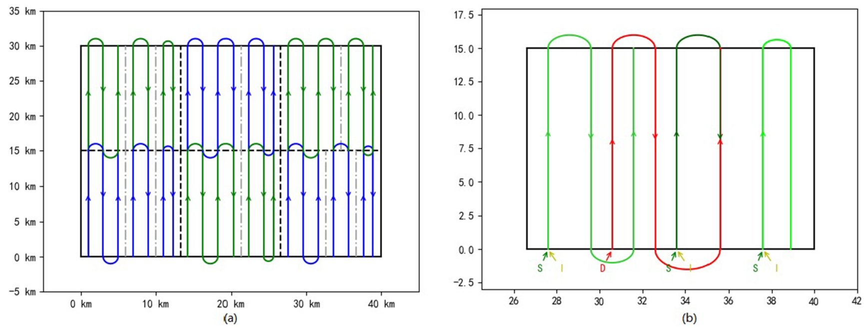

Fig. 1. (a) S node track planning diagram, (b) Node track planning diagram in subtask set $\{T_3\}$ (Color figure online)

Figure 1(b) depicts the path planning of all nodes in subtask set $\{T_3\}$. There are four UAVs in this sub-task set. The three S nodes and the three I nodes belong to the same UAV respectively, and the other UAV only has the decision-making function. Green, red and yellow represent the tracks of S node, D node and I node, respectively.

4.2 Dynamic Task Adjustment Simulation

Node I usually belongs to the same UAV as node S or node D. Therefore, in the simulation study, this paper only considers the failure of S nodes and D nodes.

Table 4. Dynamic task adjustment results

Set of task	1	2	3	4	5	6	Adjustment scheme
S node number	2,3,4	1,5	6,7,9	8,10	11,12	13,14	
	2,3	1,5	6,7,9	8,10	11,12	4,13	$S4 : \{T_1\} \rightarrow \{T_6\}$
	2,3	5,6	7,9	8,10	11,12	4,13	$S6 : \{T_3\} \rightarrow \{T_2\}$
	2,3	5,6	7,9	8,10	11	4,13	
	2,3	5,6	7,9	8	10	4,13	$S10 : \{T_4\} \rightarrow \{T_5\}$

S Node Failure. In the single full coverage of region A by node S, randomly attack five UAVs with node S, whose numbers are 20, 19, 1, 16, 14, and the corresponding nodes of node S are 15, 14, 1, 12, 11. For the convenience of the research, the time when all the UAVs start from the initial position at the same time is 0, then the corresponding failure time of the five UAVs is 234 s, 724 s, 1937 s, 2336 s and 3028 s respectively. If $\alpha = 0.2$, the adjustment result is shown in Table 4.

Figure 2(a) describes the real-time coverage of UAV formation to the combat area in a single coverage reconnaissance. The vertical axis is the covered area. Only the area covered for the first time is considered, and the area of repeated scanning is not calculated. In the random adjustment scheme, other S nodes in the same task set will complete the reconnaissance task of the subtask set after S node fails.

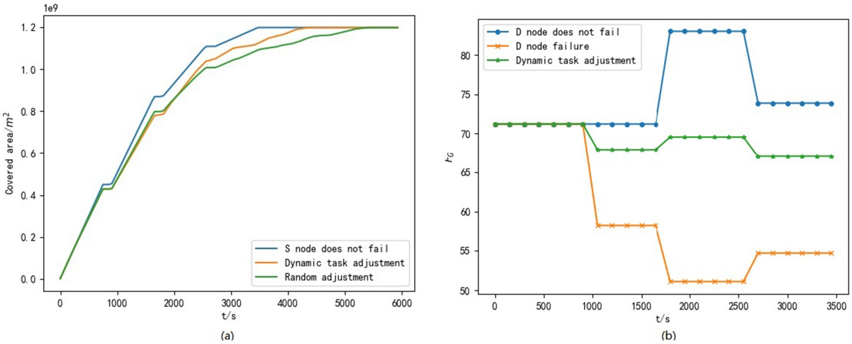

Fig. 2. (a) Real-time area coverage, (b) Real-time changes in network robustness

According to the simulation results, the time to complete a single full coverage scan in the three cases is 3470 s, 4362 s and 5421 s respectively. In the case of S node isn't failure, the time of full coverage scanning is the shortest. After the failure of S node, the formation is adjusted through the dynamic task adjustment scheme, which is compared with the random adjustment, so as to reduce the time that taken to complete the single full coverage.

D Node Failure. Randomly attack two UAVs with D nodes. The UAVs are numbered 2 and 15, and the corresponding D nodes are numbered 16 and 20. The failure times were 927 s and 1780 s. Let $\gamma = 0.3$ and $\mu = 0.7$. Take Δt= 150 s as the time interval to extract the position of each UAV at each moment, and the network robustness corresponding to each moment is shown in Fig. 2(b). After the failure of node D, the robustness of the damaged network is improved by 13.7103 on average through dynamic task adjustment, and the adjustment effect is obvious.

5 Conclusion

According to the operational requirements, a cooperative combat model is designed, including cooperative task assignment and path planning. The main work of collaborative task assignment is to divide the sub-task set, track planning is to plan the track of each UAV according to the sub-task set. In order to reduce the impact of function failure on the combat capability, a dynamic task adjustment algorithm is designed for the function failure in the battle process. After the UAV formation function failure, the mission adjustment can not only ensure the completion of the mission but also improve the combat capability. The simulation results demonstrate the effectiveness of the modeling for UAV formation combat.

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