Cooperative Search of UAV Swarm Based on Improved Ant Colony Algorithm in Uncertain Environment

Fan Yang, Xiuling Ji, Chengwei Yang*, Jie Li, and Bing Li

Abstract—**Considering the situation that the regional environment is completely unknown and is dynamically changing, a novel method for multi-UAV (Unmanned Aerial Vehicle) conducting cooperative area search based on Ant Colony (AC) Theory is proposed. Firstly, the regional environment model and the UAV dynamic model were established. Secondly, the transfer rules of the waypoints were determined for UAVs by improving the behavior criterion of the ant colony algorithm and the updating principle of the pheromone map. Finally, Compared with the conventional search methods, the simulation results with higher coverage rate and search efficiency demonstrated the improved ant colony algorithm was rationality and validity.**

Index Terms—**cooperative area search; unmanned aerial vehicle (UAV); swarm; improved ant colony algorithm; pheromone map**

I. Introduction

UNDER the conditions of modern warfare, UAV is increasingly playing an important role in military and civilian fields with advantages of low casualties and high cost-benefit ratio, and widely applied to perform tasks such as search, rescue, traffic control and communication relay [1]. Recently, influenced by the constraints of single unmanned aerial vehicle's performance and load, it has become a trend that multi-UAV perform tasks cooperatively.

UAV swarm is used in cooperative regional search tasks. The regional search method is mainly divided into two types: Flying in Formation and Free Flight. The Flying in Formation requires multi-UAV forming a certain formation to perform search task, such as parallel search, internal spiral search, mainly applied to the situation where the regional environment is relatively simple [2], [3]. The Free Flight achieve cooperative area search task based on the dynamic control for UAV swarms, mainly applied to the situation where the regional environment dynamically changes [4], such as the dynamic search based on probability map or pheromone map.

Reference [5] proposed a cooperative area search algorithm for multi-UAVs in Free Flight mode based on predictive control, studying the influence of the regional probability map by the communication constraints. A new decentralized model was proposed for target search in [6], and the coordination mechanism was used to guide the UAV to search the potential area. UAV swarms communicated with each other according to coordination mechanism, selectively explored the critical locations in unknown areas [7]. Reference [8] represented a collaborative search method for multi-target based on multi ant colony algorithm, achieving cooperative search of multi UAVs effectively.

The key of the Free Flight based on pheromone map is the virtual digital pheromone, the concept of digital pheromone is developed by the evolution of chemical pheromone in ant colony theory [9]. Multiple references [10], [11] showed pheromone map was essentially considered as a potential function map. Compared to the traditional potential function map, the advantage of pheromone map was changing dynamically with time, and reflecting some information of the search area partially. Reference [12] pointed out that the difference between virtual digital pheromone and chemical pheromone was whether the UAV swarms could be embedded into the distributed computing grid environment, and achieve cooperative behavior of swarms through simple and equal communication. The concept of pheromone potential field was introduced in [13], [14], [15], it summarized three basic rules of pheromone: release, evaporation and diffusion, and in order to discuss the effectiveness of pheromone in monitoring, target searching and tracking, a method of UAV swarms control was proposed based on pheromone map. Reference [16] analyzed the limitation of environmental factors and task requirements, and described the concept of distributed pheromone map on the basis of Ad-Hoc wireless network, named each unit in swarms maintain lonely its own pheromone map, only when the distance between units is smaller than the communication distance, the unit exchanges its own information with each other, absolutely, distributed pheromone map is greater robustness and scalability.

Analyzing the current situation of cooperative area search for multi-UAV, we discover that most studies are based on the hypothesis which the environmental information is known. Actually, before performing search task, the UAV swarms have little information of the search area. Reference [5], [17] established the model of the searching probability

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map to solve the influence caused by the uncertain environment, but it was difficult to describe the dynamic environment with an accurate method for the searching probability map. A decentralized search algorithm was proposed in accordance with the probability map to describe the dynamic environment in [18], whereas, the method had some defects that each grid could only contain a target, which was contrary to the actual situation.

Therefore, by real-time updating the pheromone map, this paper proposes an ant colony algorithm, guiding the dynamic selection of the waypoint for UAV, to solve the problem of the dynamically changing environment information for multi UAV performing cooperative search tasks. Meanwhile, through discretizing the search area into waypoints, we establish the environmental model to address the problem of the number of targets which limited in each grid. Within a certain distance, UAVs can communicate with each other to exchange and update their respective pheromone maps. According to the dynamic change of the pheromone concentration, the pheromone maps control the collaborative search behavior for multi UAV, and improve the overall search performance.

II. RELATED WORKS

A. Environmental model

As depicted in Fig. 1, assuming that the search area is rectangular, there are m UAVs on this area for collaborative search. The search area is evenly discretized into $N(N = N_x \times N_y)$ waypoints, and the set of all waypoints $E = \{1, 2, ..., N_i \times N_j \mid i = 1, 2, ..., N_x; j = 1, 2, ..., N_y\}$ is the search area.

$$\Delta = \sqrt{2} / 2 \times r \quad (1)$$

$$\begin{cases} N_x = X / \Delta \\ N_y = Y / \Delta \end{cases} \quad (2)$$

Where, X, Y represent the length and width of the rectangle to be searched, respectively, r expresses the image sensor detection radius for UAV.

(v, h) represents the waypoint of the v-th row and h-th column in the discrete area, and the coordinates corresponding to the waypoint is (x, y):

$$\begin{cases} x = v \times \Delta \\ y = h \times \Delta \end{cases} \quad (3)$$

Fig. 1. Environmental model for discretization of search area into the uniformly distributed waypoints

B. UAV movement model

Assuming that all unmanned aerial vehicles fly at the same altitude, the UAV is considered as a particle on the two-dimensional plane, and can move between adjacent waypoints, it detect the surrounding environment information of the current location through the airborne sensor. Due to the constraints of maneuverability and other factors, the k+1 step of UAV's heading is influenced by the k step. There are up to five optional destinations for the UAV, as shown in Fig. 2, flying straight, turning left (right) 45 degrees, or turning (left) right 90° degrees before flying. As for the difference of rotation angle for five directions, the UAV will pay different costs steering. The greater the angle of rotation, the greater the price paid, and the UAV has smaller probability to select the destination.

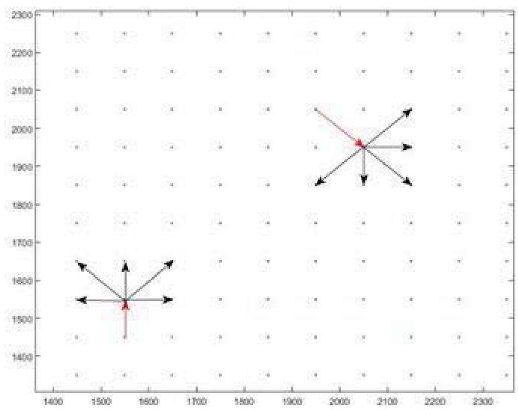


Fig. 2. Optional heading diagram for UAV

III. OVERVIEW OF THE PROPOSED SOLUTION

A. Cooperative search based on the improved ant colony theory

In this algorithm, each UAV corresponds to an ant in ant colony theory. Fig. 3 shows the brief steps of the improved ant colony algorithm proposed in this paper as follows: Firstly, setting the appropriate initial value for the pheromone map corresponding to all destinations in the area; Secondly, the m UAVs are randomly placed on different waypoints, and determine whether some targets were found, at the same time, each UAV flies to the appropriate feasible waypoint that has been selected according to the rules of waypoint transfer; Thirdly, after finishing waypoint transfer, each UAV will have an impact on its adjacent waypoints, and complete a real-time updating for its pheromone map. Finally, UAVs repeatedly perform the rules of waypoints transfer and pheromone updating, until all of the targets were found, or the number of cycles for the algorithm is maximal.

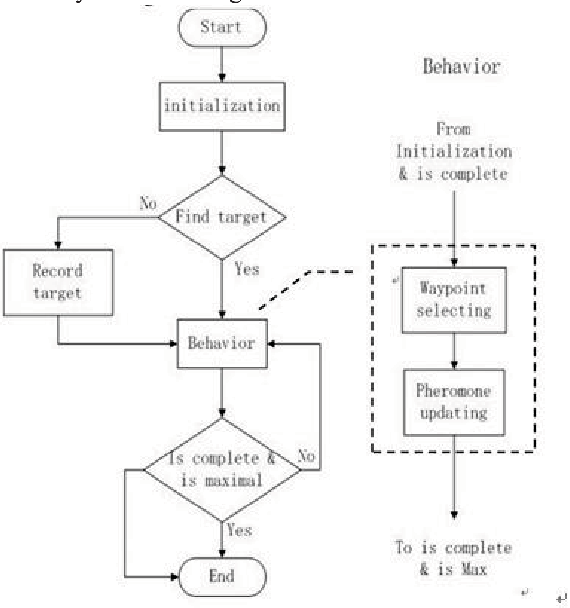


Fig. 3. Overview of the improved ant colony algorithm for cooperative search. The module of Behavior contain two sub-modules: the module of Waypoint selecting and Pheromone updating.

B. Waypoint transfer

Initially, UAVs are put on randomly chosen waypoints. At each step, UAV_k applies a probabilistic action choice rule, called waypoint transfer, to decide which waypoint to visit next. In particular, the probability of which UAV_k, currently at waypoint i, choosing to visit waypoint j is

$$P_{ij}^{k} = \frac{\tau_j^{\alpha} \cdot \eta_{ijk}^{\beta}}{\sum_{j \in J_k} \tau_j^{\alpha} \cdot \eta_{ijk}^{\beta}}, j \in J_i^k \tag{4}$$

Where J_i^k is the feasible neighborhood of UAV_k when being at waypoint i; τ_j expresses pheromone concentration of waypoint j; η_{ijk} is a heuristic value that is transcendental knowable, indicating the difficulty of flying from waypoint i to j for UAV_k; α and β are two parameters that determine the influence of the pheromone concentration and the heuristic information [9].

In addition, the heuristic factor η_{ijk} is determined by two factors: heading angle and waypoint distance.

Heading angle:

$$\eta_{ijk} = \begin{cases} 1/4 \times \eta_{ij}, \theta = 0^{\circ} \\ 5/24 \times \eta_{ij}, \theta = 45^{\circ} \\ 1/6 \times \eta_{ij}, \theta = 90^{\circ} \\ 0, others \end{cases} \tag{5}$$

Where, θ represents the angles of the heading changed.

Waypoint distance:

$$\eta_{ij}(t) = \begin{cases} 1.4, D(i,j) = 100 \\ 1, D(i,j) = 100\sqrt{2} \\ 0, others \end{cases} \tag{6}$$

Where $D(i,j)$ represents the distances between the waypoint of i and j.

C. Pheromone updating

Pheromones are merely distributed at the waypoints in the area. At the initial moment, the concentration of pheromone at each waypoint is maximal value $\tau_0 (\tau_0 \neq 0)$. After all the UAVs have finished their tours, the concentration of pheromone within a certain range will be reduced. The updating of pheromone is implemented by

$$\tau_j(t+1) = \tau_j(t) - \Delta\tau_j(t) \tag{7}$$

Where $\tau_j(t)$ and $\tau_j(t+1)$ are the concentration of pheromone before and after the updating of pheromone for waypoint j; $\Delta\tau_j(t)$ represents the reductive amount of the concentration causing by all UAVs at the current time for waypoint j, it is defined as follows:

$$\Delta\tau_j(t) = \sum_{k=1}^{m} \Delta\tau_{ij}^{k}(t) \tag{8}$$

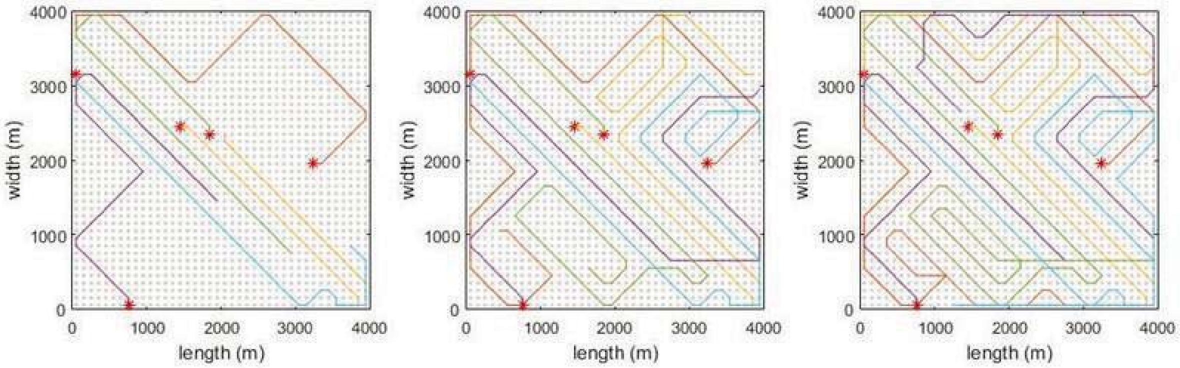
Where $\Delta\tau_{ij}^{k}(t)$ is the variable amount of pheromone, UAV_k influences the waypoints within a certain range it has visited. It is defined as follows:

$$\Delta\tau_{ij}^{k}(t) = \begin{cases} \frac{1}{2\sqrt{2\pi}} \exp\left(-\frac{\left(\frac{Q}{D(i,j)}\right)^2}{2}\right), D(i,j) < 500 \\ 0.9, D(i,j) = 0 \end{cases} \tag{9}$$

Where Q represents the attenuation coefficient of pheromone.

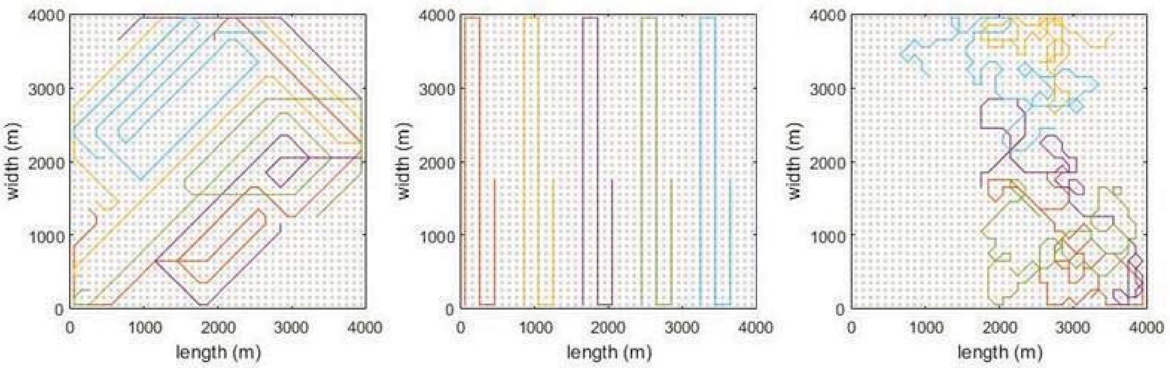
In general, waypoints that pheromones have been decreased by all UAVs are therefore less likely to be chosen by UAV in future influenced by the improved ant colony algorithm.

Meanwhile, to avoid the fluctuation range of pheromone for some waypoints, the concentration of pheromone in the search



(a) (b) (c)

Fig. 4. Under the guidance of the improved ant colony algorithm, the tracks of UAVs at different times. UAVs perform coordinated exploration, and 5 stars represent the starting waypoints for each UAV. (a) When the improved ant colony algorithm runs to 50 steps, the tracks of UAVs are shown; (b) When the improved ant colony algorithm runs to 100 steps, the tracks of UAVs are shown; (c) When the improved ant colony algorithm runs to 150 steps, the tracks of UAVs are shown.



(a) (b) (c)

Fig. 5. Under the guidance of the different algorithms, the tracks of UAVs when the algorithm runs to 100 steps. (a) The tracks of UAVs guided by the improved ant colony algorithm is shown; (b) The tracks of UAVs guided by the parallel search method is shown; (c) The tracks of UAVs guided by the random search method is shown.

certain range $[\tau_{\min}, \tau_{\max}]$, preventing the algorithm converges prematurely, and results in search stagnation.

$$\tau_j = \begin{cases} \tau_{\min}, \tau_j < \tau_{\min} \\ \tau_{\max}, \tau_j > \tau_{\max} \\ \tau_j, others \end{cases} \tag{10}$$

IV. SIMULATION

In this paper, as shown in Fig. 4, UAVs explored an uncertain environmental area, and the area was 4km×4km. The number of iterations was 150 steps, the parameters of the pheromone and the heuristic information were respectively 0.5 and 0.1, the initial concentration of pheromone was 1, the fluctuation range of pheromone was [0.1 1], and the attenuation coefficient of pheromone was 100. 5 UAVs started search from different locations in the area.

The task of UAV swarms collaborative area search is divided into two types: one is the maximal coverage of the area search through the control of the unmanned aerial vehicles in the swarms; the other one is searching as much as possible the number of targets at the lowest cost (e.g. the shortest time) through the control of the unmanned aerial vehicles in the swarms. In order to verify the validity of the improved ant colony algorithm in this paper, we choose the other two search methods were chosen to compare as follows: a. parallel search method, selecting the next waypoint with a certain rule, each UAV flies parallel; b. random search method, selecting the next waypoint randomly.

As shown in Fig. 5, the 5 UAVs are compared with the area search coverage obtained by the different algorithm when algorithms run to 100 steps.

Fig. 5(a) shows that waypoints which 5 UAVs have visited according to the method presented in this paper when the algorithm iterates 100 steps. Waypoints that UAVs have visited have less overlap by the guidance of the improved ant colony algorithm proposed in this paper, therefore, UAVs cover the search area more effectively.

Fig. 5(b) shows that waypoints which 5 UAVs have visited according to the parallel search method when the algorithm iterates 100 steps. We find that there is no problem of overlapping waypoints for parallel search method, but its flaws are obvious, it is necessary to plan waypoints which UAVs will visit in advance, the position of starting and ending are fixed. Therefore, the reliability of parallel search method is poor. Fig. 5(c) shows that waypoints which 5 UAVs have visited according to the random search method when the algorithm iterates 100 steps. It can be seen that the method of search for waypoints is decentralized, and highly random. Because there is no influencing factor, the method is a blind search, the problem of overlapping waypoints is more serious.

A. Area search coverage

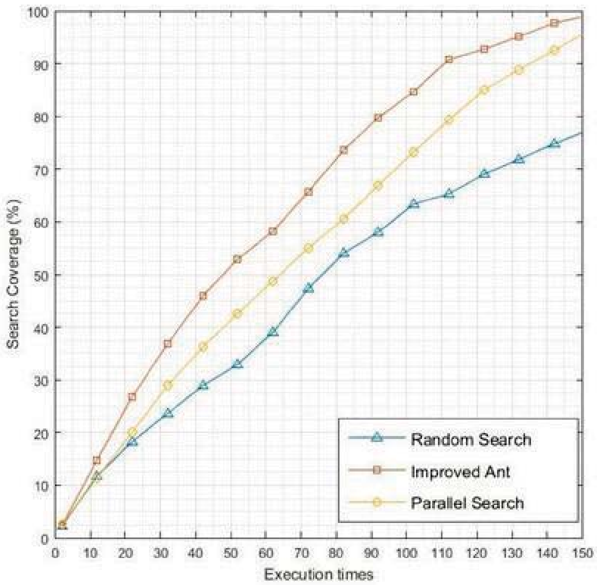


Fig. 6. The change of area search coverage with execution times under the guidance by the different algorithms.

Fig. 6 describes the trend of area search coverage over time for 5 UAVs in the 4km×4km area under different algorithms. We can find that the coverage of the parallel search and random search are almost the same at the beginning of the search, and the search coverage based on the improved ant colony algorithm is slightly higher than first two methods. With the increase of the time, when the algorithm runs to 100 steps, the rate of coverage for the improved ant colony algorithm proposed in this paper is 84.25%, and the numerical value are 1.16 times (72.5%) and 1.34 times (63.06%) of the parallel search method and the random search method respectively. The advantage of the improved ant colony algorithm is more obvious in this stage. The use of pheromone feedback mechanism enhances the collaborative search capability of UAVs, effectively avoiding the problem of overlapping waypoints.

B. Target search efficiency

Simulation of 5 UAVs for 10 random targets in the 4km× 4km area is performed under different search methods. Simulation were carried out 10 times to obtain the average number of targets searched at different steps under three search methods.

Table. I
The number of targets found

algorithm	steps				
	30	60	90	120	150
Random	2.8	4.9	6.2	7.2	7.5
Parallel	2.6	3.5	5.4	7.9	9.3
Improved-AC	3.5	6.2	7.8	9.0	9.4

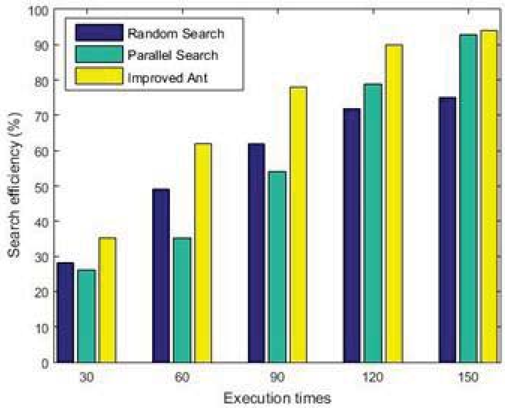


Fig. 7. Average search efficiency with execution times influenced by the different algorithms.

As shown in Fig. 7, 5 UAVs search for targets in the 4km ×4km area under the different search methods, and the average search efficiency varies with the time. It can be seen that the improved ant colony algorithm proposed in this paper is the highest all the time, but the trend of search efficiency slowed down in the later period. Whereas the efficiency of the parallel search method linearly increases with time, and finally the search efficiency is very close to the algorithm proposed in this paper. As for the random search method, the search efficiency is the lowest in the whole process, and there is no increasing trend in the later period.

V. Conclusions

In an uncertain environment, this paper analyzes the multi-UAV collaborative search problem, and proposes an improved ant colony algorithm for multi-UAV to solve the problem of cooperative search based on the feedback mechanism of pheromone. Compared with the other two non-cooperative search algorithms, the results of simulation show that the improved ant colony algorithm proposed in this paper can complete the task of search for unknown environments. Moreover, the algorithm proposed in this paper makes use of the feedback mechanism of pheromone to integrate the information among UAVs, avoids the overlap of waypoints, has a higher coverage and more effective than other traditional methods, providing a reference for multi UAV search problem.

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