RESEARCH ON ROUTE PLANNING METHOD FOR UAV SWARM AREA COVERAGE MISSIONS BASED ON COMPLEX NETWORKS

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Abstract

Unmanned aerial vehicle (UAV) swarm has high flexibility, low economic cost, and diversified mission capabilities, among which area coverage reconnaissance is an important task that embodies its unique advantages. Route planning is a key problem in area coverage reconnaissance. Self-organized route planning is an important route planning method because of its strong adaptability to dynamic environment. In this paper, the model of the UAV swarm area coverage reconnaissance is built, including the environment model, the UAV dynamics model and the communication model. Then, a collaborative search method based on genetic algorithm is proposed, and the chromosome coding method and optimal action sequence search process are given. Finally, combined with agent modeling and complex network, UAV swarm self-organized route planning are carried out according to typical ground reconnaissance mission scenarios. The results show that the self-organizing route planning method, which combines agent modeling and complex network modeling, can dynamically plan the route in real time according to the information of the search graph. At the same time, they coordinate with each other under certain mechanisms to reduce repeated visits and optimize the overall coverage of the swarm to the region.

Keywords: unmanned aerial vehicle swarm; area coverage reconnaissance; self-organization; route planning; complex network

1. Introduction

Unmanned Aerial Vehicle (UAV) swarm refers to a distributed system that integrates a large number of UAVs in an open system architecture. Based on collaborative control among platforms, its primary objective is to enhance collaborative mission capabilities. UAV swarms typically consist of small UAVs with limited capabilities, achieving collective behavior through interactions at the individual level. They operate without relying on a central controlling entity, demonstrating features of autonomy, self-governance, and decentralization.

For area-coverage reconnaissance missions, the main goal of route planning is to make a swarm of UAVs cover a designated area to find as many targets as possible in short time. The core is to eliminate route conflicts, reduce repeated visits, achieve the optimal coverage of the region, and improve the efficiency of target discovery. According to the way of solving the problem, it can be divided into random method, top-down method and bottom-up method. Nurzaman et al. studied a mobile robot target search method based on Levy migration and bacteria chemotaxis algorithm[1]. Wosniack et al. studied the foraging algorithm based on Levy wandering motion[2]. Garcia et al. compared the effectiveness of several different random methods in UAV search tasks[3]. The top-down method breaks down the problem layer by layer and carries out centralized planning through the central decision link. The typical representative is the area segmentation scanning method (scanning method for short). The scanning method divides the task area into several zones, and each UAV is assigned a zone to conduct reconnaissance along the scanning route in the zone. Different from random method and top-down method, bottom-up method realizes swarm reconnaissance spontaneously by self-organizing principle. Self-organization refers to the spontaneous transformation of the system from a disordered and chaotic state to an orderly state in time, space or function when the external changes reach certain conditions through continuous interaction with external matter and energy[4].

Modeling and simulation technology is an economical and efficient method, which has important guiding significance for expanding the application range of UAV swarm, improving the task capability of UAV swarm and coping with the development bottleneck of high cost of information warfare. The modeling methods of swarm can be divided into two types: modeling based on complex network and modeling based on multi-agent. The basic principle of complex network is to abstract a large number of components of the system into nodes, the interaction and relationship of nodes into edges, forming a network composed of nodes and edges. From the perspective of architecture, complex network organization can be divided into two categories: centralized and distributed. The centralized organizational structure is difficult to meet the dynamic and real-time requirements of UAV clusters. When the distributed organizational structure is adopted, each UAV has full autonomy and can share information and negotiate through the communication network to achieve independent decision-making[5]. Compared with the centralized organization structure, the decision-making does not need to wait for the control center to return the control instruction, and the system is better in real-time. Multi-agent based modeling focuses on individual objects[6]. By defining individual behaviors or attributes and placing them in a certain environment, the interaction between agents and agents, agents and environment, and emergent behaviors at the level of cluster system are analyzed[7].Wang et al. established a task model for UAV cluster to perform the task of observation and attack as a whole[8]. The cluster is composed of heterogeneous UAVs with different functions, and focused on the influence of the information interaction and fusion strategy proposed by Liao et al. on the UAV cluster task capability. Ilachinski et al. established a distributed UAV cluster that can perform reconnaissance, task assignment and tracking tasks, focused on designing the control logic algorithm of the UAV, set the UAV into four mission states: take-off mode, flight mode, reconnaissance mode and tracking mode, and optimized the flight path of the UAV[9].

At present, the commonly used UAV swarm modeling methods mainly include agent-based modeling and complex network modeling[10]. The modeling method based on complex network is conducive to the analysis of UAV swarm from the global perspective, but it is difficult to reflect the behavior characteristics of UAV individual, which is not conducive to the characterization of its task attributes. Agent-based modeling focuses on describing the swarm from the individual and from the bottom up. Local interaction rules and individual behavior attributes are the main factors affecting the task capability of the cluster, and it is difficult to design the UAV cluster system from the macro level. Addressing these challenges, this paper combines agent-based modeling and complex network modeling, proposing a self-organizing route planning method based on complex networks. It uses complex networks to describe information distribution, sharing, and integration among UAV swarms, forming a generalized information relation network. This network encompasses various factors such as command, control, and coordination. In the self-organizing route planning method, UAVs use a search graph to depict changes in the environment and dynamically plan routes based on the information from the search graph. Simultaneously, they coordinate with each other, reducing redundant visits and optimizing the overall coverage of the swarm in the region. The method involves constructing the search graph, using genetic algorithm to make local route decisions, and coordinating inter-UAV routes.

2. Modeling of UAV Swarm Area Coverage Reconnaissance Mission

2.1 Problem Description

The flight control system is composed of task layer, decision-making layer and execution layer when UAV swarm performs reconnaissance task. The task layer is controlled by the ground station, which issues control commands to the swarm for the reconnaissance task and transmits them to the decision layer. After the decision layer receives the control instruction, the airborne computer makes a decision by combining the environmental information obtained by the local sensor, the status information of the UAV and the information transmitted by communication network, and transmits the generated decision instruction to the execution layer. After receiving the instruction, the execution layer adjusts the aircraft to achieve the desired flight state, searches the target area, and finally returns the updated UAV information and search results to the decision-making layer and the ground station. The execution layer is realized by the airborne flight controller of the UAV.

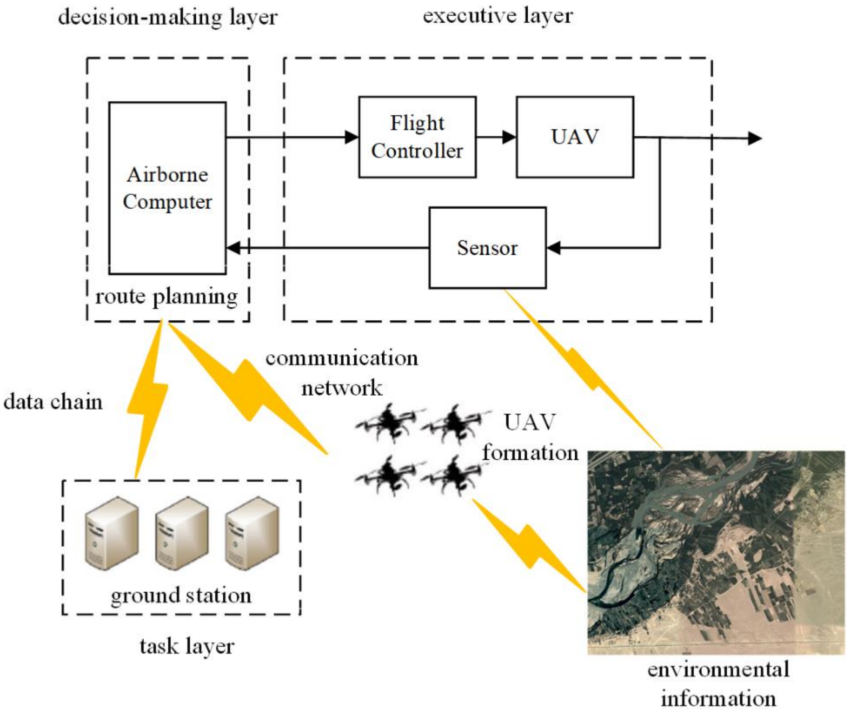


Figure 1 – Construction of UAV swarm area coverage reconnaissance mission.

Collaborative search by UAV swarm involves UAVs working together to accomplish a search mission. The task status of UAV swarm and information pheromone map consists of three components, as illustrated in the Figure 2. In terms of UAV behavior, it includes search, information interaction, and decision-making. Regarding digital information pheromones, it involves updating and merging the digital information pheromone map and selecting routes based on information pheromones. When a UAV obtains its current state at the current time, it makes optimal path decisions based on the information pheromone map obtained at that moment, determining the target position of the UAV in the next moment. As the UAV's position is updated, the UAV needs to update its own information pheromone map in real-time. Simultaneously, once communication conditions are met, the UAV must send its own information pheromone map to the communication network and receive the information pheromone maps of other UAVs. This completes the fusion of information pheromone maps, achieves multi-UAV collaboration, and uses it as a new information pheromone map to initiate the next search process, continuing until the search mission is completed.

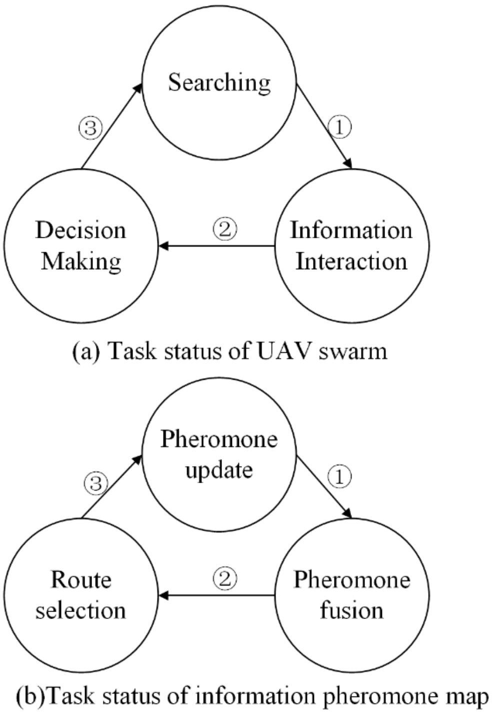


Figure 2 – Task status of UAV swarm and information pheromone map

2.2 Environmental Model

Adopting a sampling statistical method to quantitatively measure coverage, the movement of the operational unit assumes the 'flat Earth' hypothesis, neglecting the curvature of the Earth and variations in ground height, as well as disregarding the influence of wind. The origin is the center of the mission area, with the x and y axes pointing towards the east and south directions, respectively. The parameters of the battlefield environment mainly include the area of the battlefield and the number of enemy targets. The battlefield area is uniformly divided into M equally-sized cells, each with an area of 50*50 units. The central coordinates of the grid cells are denoted in the x and y directions as i and j ($-\infty<i<+\infty$, $-\infty<j<+\infty$).

$$x_{cell}(i,j)=i\cdot w_{cell} \tag{1}$$

$$y_{cell}(i,j)=j\cdot w_{cell} \tag{2}$$

2.3 UAV Dynamics Model

Describing the aircraft's dynamics, the 3-Degree-Of-Freedom (DOF) centroid kinematic equation is employed within the flight-path coordinate system as shown in Figure 3, and is defined as

$$\begin{cases} n_x = \dfrac{\dot{v}}{g} + \sin\gamma \\ n_y = \dfrac{v\cos\gamma\dot{\chi}}{g} \\ n_z = \dfrac{v\dot{\gamma}}{g} + \cos\gamma \end{cases} \tag{3}$$

Where v represents the speed of the aircraft and $\dot{v}$ represents the acceleration. χ represents the track azimuth angle, $\dot{\chi}$ represents the angular acceleration, γ represents the climb angle, and $\dot{\gamma}$ represents the angular acceleration. The execution of level flight, acceleration, and turning maneuvers is achieved by controlling the aircraft agent's overload (n_x, n_y, n_z).

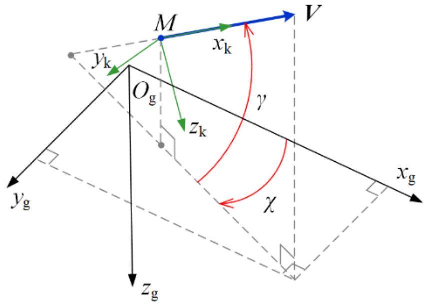


Figure 3 – Coordinate system and variable in motion model

2.4 Communication Model

When designing the network topology of a drone swarm based on a complex network model, the agents are represented as nodes in the complex network, and the interconnections between the swarm are represented by edges in the complex network. In the complex network model, two classical network topologies are considered: scale-free networks and random networks. This paper primarily utilizes these two network topologies for the networking of the UAV swarm. The networking process is described as follows.

(1) Scale-Free Network Formation

When forming a UAV swarm network based on a scale-free network, the cluster starts with m_0 fully connected drones. Each time a new drone agent i joins the swarm, agent i connects with m ($m \le m_0$) existing drones. The probability $P(k_{i,j})$ of agent i being connected to any existing drone agent j is defined as follows:

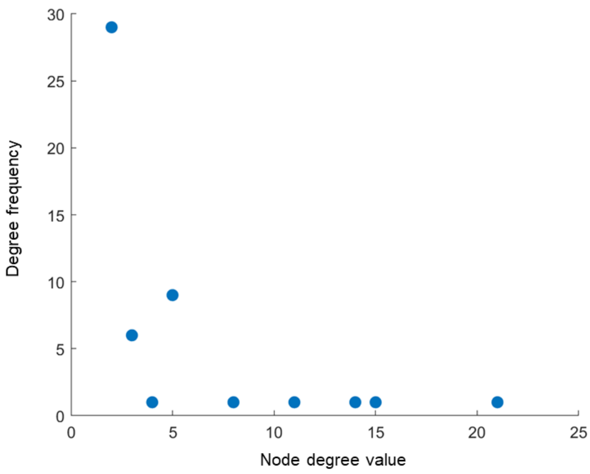
$$P\left(k_{i,j}\right) = \frac{k_i}{\sum_{j=1}^{N(t)} k_j} \tag{4}$$

(2) Random Network Formation

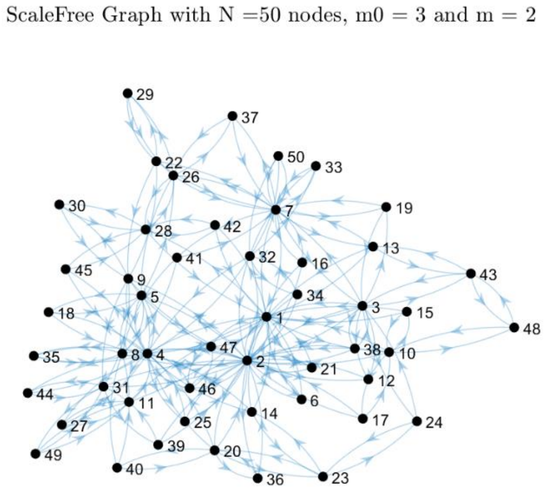
The process of forming a drone swarm network based on a random network is similar to that of forming a scale-free network. The cluster starts with m_0 fully connected drones. Each time a new drone agent i joins the cluster, agent i connects with m ($m \le m_0$) existing drones. The probability $P(k_{i,j})$ of agent i being connected to any existing drone agent j is uniform for all connections, defined as:

$$P\left(k_{i,j}\right) = 1 / N_t \tag{5}$$

Taking a UAV cluster composed of 50 UAVs as an example, the networking based on scale-free model and random network model is shown in the Figure 4 and Figure 5. The UAV cluster starts with two UAVs for networking, and new UAVs continue to join the cluster and connect with other UAVs according to the scale-free or random network networking rules until the cluster reaches 50 to complete networking. After the networking is completed, the network topology of the cluster will remain fixed during the task execution, providing stable and reliable information interaction technology support for the task execution of the UAV cluster.

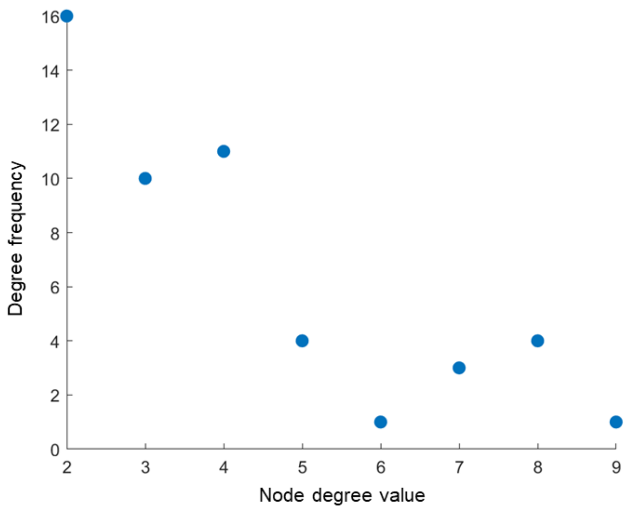


(a) node degree value of scale-free network

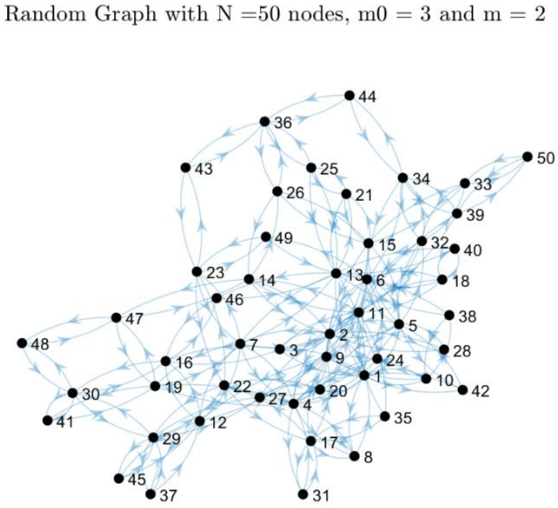


(b) node connection of scale-free network

Figure 4 – Scale-Free network model



(a) node degree value of random network



(b) node connection of random network

Figure 5 – Random network model

3. Self-organizing route collaborative search algorithm

In this paper, genetic algorithm is used to search for the optimal action sequence satisfying the optimization objective. In this problem, each individual represents an action sequence, and the fitness of the individual is the cumulative benefit of the action sequence. The crossover operator adopts the classical roulette parent selection method and the uniform crossover operator. The following is mainly to explain the chromosome coding mode and the search process of the optimal action sequence.

3.1 Chromosome coding mode

Genetic algorithms, inspired by biological evolution, offer advantages such as good convergence, high computational accuracy, low time requirements, and strong robustness. This method is a population-based optimization approach that assumes the existence of a population representing the potential solution set for the problem. The population consists of a certain number of individuals with different chromosomes, where chromosomes serve as the primary carriers of genetic material in the form of a particular gene combination. This combination determines the external manifestation (fitness) of an individual's traits. After the initial population is generated, suitable individuals are selected based on the rule of fitness size. Using genetic operators inspired by natural genetics, such as crossover and mutation, new individuals are produced. By replacing the worst-performing individuals in the offspring, the overall fitness of the offspring is improved. This process is repeated, continuously generating better offspring, ultimately leading to the optimal population for the problem.

Each action of the drone can access 8 Moore neighbors of the current grid, that is, there are 8 possible actions, which are represented by a 3-bit binary code for one action. Note that the number of adjacent grid units along the direction of the current track deflection angle is 0, and then along the clockwise direction, the number of grid units is 1, 2, 3, 4, 5, 6, 7, then the corresponding code is shown in Figure 6.

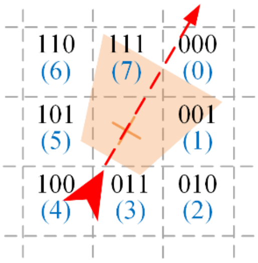


Figure 6 – Chromosome coding mode

3.2 Optimal action sequence search process

The process of using genetic algorithm to search the optimal action sequence is as follows.

Step 1: Initialize. The initial grid cells are calculated and parameters such as population size, variation rate and crossover rate are set.

Step 2: Generate initial population. The initial population is generated according to the random method, and the individual fitness in the population is calculated, that is, the cumulative benefit of the route.

Then, for each individual within the population, perform steps 3-6.

Step 3: Cross. Select another parental individual according to the roulette algorithm, and cross according to the method of uniform cross to generate a new individual.

Step 4: Mutate. Mutate the genes of progeny individuals according to the specified mutation rate.

Step 5: Route feasibility check. If the new progeny route is not feasible, go to step 3 and re-cross and mutate until the feasible route is generated.

Step 6: Calculate the fitness of individual offspring.

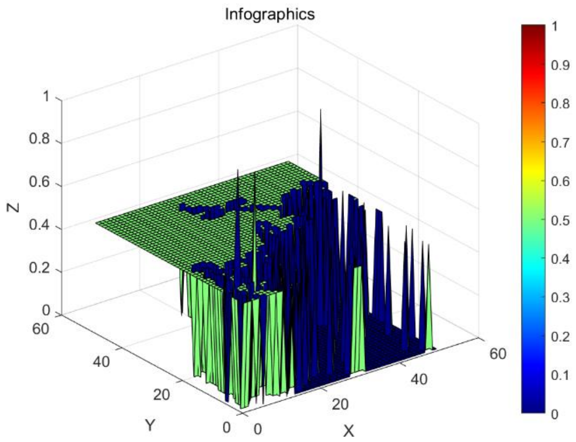
After performing Steps 3-6 for each individual, go to Step 7.

Step 7: Sort by fitness.

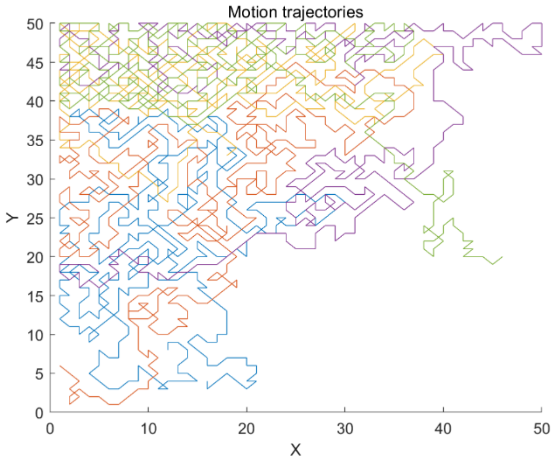
Step 8: Convergence decision. If the convergence condition is met, the optimization ends and all individuals in the offspring population are output. Otherwise, continue optimizing and go to Step 3.

4. Typical UAV swarm reconnaissance area coverage task

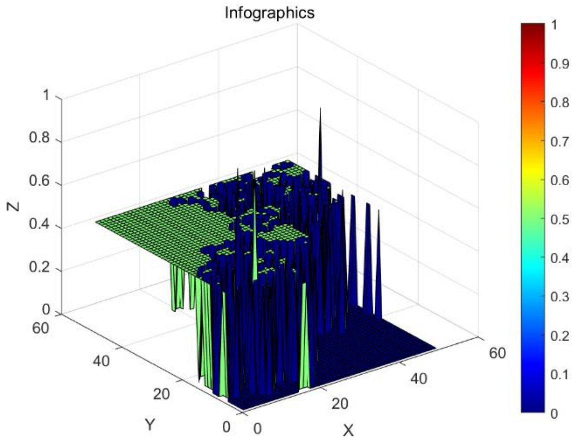
Each UAV calculates waypoints in the rolling time domain according to the local search map. When the drone reaches a waypoint, the route decision is updated. Each decision is made in the *k* step time domain, and a *k* step action sequence is calculated, that is, *k* grid units that need to be visited in sequence. Then, only the first action in the sequence of actions is performed, that is, moving towards the first waypoint, accessing the first grid cell. Once the waypoint is reached, repeat the above steps and calculate a new sequence of *κ* steps again, again performing only the first action, and so on. When *k* is 5, the infographics and motion trajectories of 5 UAVs running 500 steps with and without self-organized route planning based on complex networks are calculated respectively, as shown in the figure. It can be seen that the multi-step trajectory obtained by the self-organizing route planning method based on complex network can reduce the repeated visits of the region.



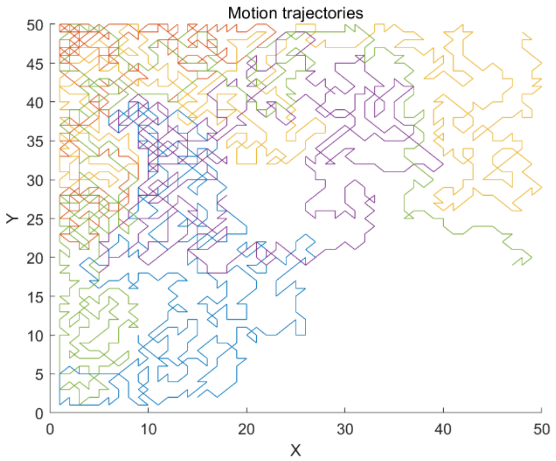
(a) Infographics of scale-free network



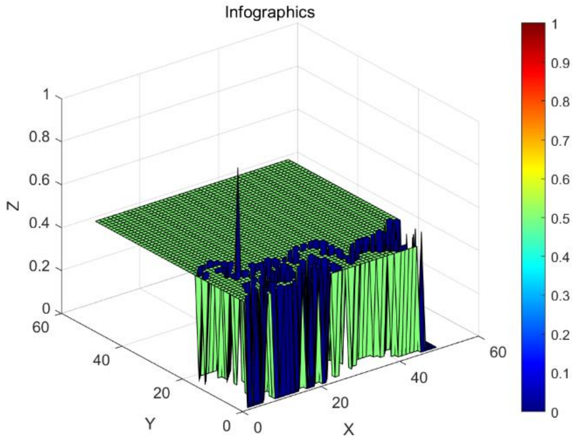
(b) Motion trajectories of scale-free network



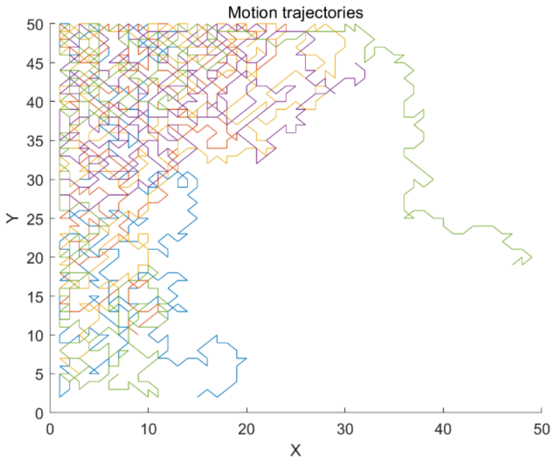
(c) Infographics of random network



(d) Motion trajectories of random network



(e) Infographics without self-organized route



(f) Motion trajectories without self-organized route

Figure 7 – Infographics and motion trajectories of 5 UAVs running 500 steps

5. Conclusions

(1) The paper proposes a collaborative search method based on genetic algorithm, along with detailed descriptions of chromosome encoding and optimal action sequence search processes. This method demonstrates its capability in planning reconnaissance routes for UAV swarms in dynamic environments, proving its effectiveness and adaptability for achieving area coverage reconnaissance tasks.

(2) By combining agent modeling and complex network modeling, the self-organizing route planning method presented in the paper can dynamically plan routes in real-time based on the information of the search graph. This approach ensures the flexibility and responsiveness of the UAV swarm in executing reconnaissance tasks in changing environments.

(3) The self-organizing route planning method enables the UAV swarm to coordinate under certain mechanisms, avoiding redundant visits to the same areas. This coordination optimizes the overall coverage of the swarm in the region, enhancing reconnaissance efficiency and reducing mission costs, further demonstrating the unique advantages of UAV swarms in area coverage reconnaissance tasks.

6. Acknowledge

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8. Copyright Statement

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