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Connectivity Maintenance Based on Multiple Relay UAVs Selection Scheme in Cooperative Surveillance

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Abstract: For the purpose of remote command and situation awareness, multiple unmanned aerial vehicles (UAVs) cooperative surveillance with a ground station via multihop communications is presented in this paper. Considering limited communication capacities, a reliable UAV-to-UAV communication relay chain is dynamically established for connectivity maintenance and real-time surveillance information transmission. Firstly, a multiple UAVs cooperative surveillance framework is constructed with history detection information and surveillance payoff estimation. Secondly, four attributes are proposed to characterize differences among UAV alternatives in communication network containing a ground station, and a novel multiple relay UAVs selection scheme based on fuzzy optimum selection is developed to achieve tradeoff between surveillance mission and connectivity maintenance. Furthermore, satisfied with collision avoidance, limited communication and UAV kinematic constraints, the optimal UAV motion plan is obtained by decentralized receding horizon control, which is solved by particle swarm optimization with elite mechanism. Simulations demonstrate the effectiveness of the proposed methods in multi UAVs cooperative surveillance.

Keywords: unmanned aerial vehicles; cooperative surveillance; multiple relay UAVs selection scheme; fuzzy optimum selection; particle swarm optimization with elite mechanism

1. Introduction

Due to the limited capacity of single UAV, in the future information and network centric environment, multiple UAVs have been widely employed in military and civil applications [1–5] due to the feasibility and scalability in complex tasks in recent years, such as target tracking, wildlife monitoring, disaster rescue and so on. Serving as communication relays for remote monitoring and situation awareness [6], multiple UAVs dynamically constructing a reliable peer-to-peer communication links chain has been studied in recent years [7–9].

Multiple UAVs cooperative surveillance attracts more attention in past years, which is realized by online motion planning according to real-time detection information. Generally, surveillance region is uniformly divided into grids with the same size, and the existence probabilities of unknown targets are associated with different search maps, such as probability map [10,11], pheromone map [12] and rate of return map [13,14]. Based on the latest detection information gained by multiple UAVs, search map is updated according to corresponding criteria, such as Bayesian rules, pheromone update rules and rate of return update rules. Similar to rate of return map, a multiple UAVs cooperative surveillance framework with a ground station is implemented connecting with history detection information and surveillance payoff estimation in this work.

While preserving connectivity, real-time surveillance information can be sent back to ground station for remote command and situation awareness, which widely exists in target monitoring, disaster rescue and remote surveillance. In [15], a novel role management concept is proposed for UAV motion control, which is realized by communication aware potential fields (CAPF) to maintain connectivity between spatial exploration agent and ground station. *K*-hop connectivity is a common indicator representing network topology in multi agents. The connectivity constraints are described as the gradients of *k*-connectivity matrix representing the network topology property of a graph, and agent motion control vectors are solved by quadratic program [16]. In [17], connectivity maintenance between a stationary agent and a remote exploring agent in a walled environment is developed, and the agent motion control is solved by bound linear programming with the derivative of Fiedler value and *k*-connectivity matrix constraints. However, these researches cannot effectively deal with UAV kinematic constraints, such as the minimum velocity.

Detection scope expansion and effective information collection is the primary task in multiple UAVs cooperative surveillance, but network connectivity is essential for real-time data transmission and remote command. For balancing surveillance payoff and network connectivity, a dynamic communication links chain is established by UAVs with different roles, and appropriate relay UAVs selection scheme is crucial to improve the performance of communication networks. Due to different factors for characterizing the differences among UAV alternatives for preserving connectivity, the optimal relay UAV selection [18] can be considered as a multi-attributes decision making problem, which is utilized to make an optimal choice with the highest degree of satisfaction from a set of UAV alternatives. As an important aspect of decision science, there are many researches on multi-attributes decision making problems [19–21]. Considering the feature of network topology comprised of ground station and multi UAVs, four special attributes are proposed to represent UAV alternatives differences in relay communication systems, and relay UAV alternatives sequence can be obtained by fuzzy optimum selection [22–24].

In this work, multiple UAVs cooperative surveillance with a ground station for remote command and situation awareness is presented. For the purpose of achieving tradeoff between surveillance mission and connectivity maintenance, a novel multiple relay UAVs selection scheme is developed based on fuzzy evaluation and fuzzy optimization, and UAVs are appropriately allocated different roles over time while detection scope extending. With corresponding constraints, each UAV plans its optimal motion plan based on decentralized receding horizon control, and the elite mechanism [25] is integrated into particle swarm optimization (PSO) to calculate the optimal control command sequence.

The main contributions of this paper are described as follows. Firstly, a multiple UAVs cooperative surveillance framework with ground station is constructed according to history detection information and surveillance payoff estimation. Secondly, four attributes are proposed to represent the differences among UAV alternatives in communication network containing ground station, and a multiple relay UAVs selection scheme based on fuzzy evaluation and fuzzy optimization is developed for dynamically adjusting communication links. Finally, decentralized receding horizon control is employed to optimize each UAV's control command sequence according to local information, which is solved by PSO with elite mechanism.

The structure of this paper is organized as follows: Section 2 mainly introduces sensor model, and a multiple UAVs cooperative surveillance framework is constructed. In Section 3, relevant attributes representing the differences among UAV alternatives are discussed, and multiple relay UAVs selection scheme is implemented by fuzzy optimum selection. UAVs optimal motion plan based on decentralized receding horizon control is developed, and PSO with elite mechanism is employed to solve the optimal control sequence in Section 4. Subsequently, Section 5 provides some simulation results analysis, and some conclusions and future directions are described in Section 6.

2. Problem Definition

2.1. Multiple UAVs Cooperative Surveillance with Ground Station

Communication is the basis of cooperation and collaboration between UAVs, which is crucial and essential [7]. Due to the limitations of the carrier processor capacity, UAVs communication range is restricted. When all UAVs are in the communication range of an infrastructure, such as a ground station or a satellite, the UAVs can directly communicate with the center. Considering limited communication capacity, real-time information collected from the environment can be transmitted to command center by peer-to-peer connections. Thus, it is essential to establish reliable relay communication links between ground station and remote UAVs swarm, which is beneficial for remote and large area surveillance scenario. A specific scenario consisting of remote surveillance UAVs and ground station is depicted in Figure 1. Remote surveillance UAVs search unknown region and monitor some hotspots for gathering surveillance information, which is sent back to ground station for remote command and situation awareness via multihop communications constructed by some relay UAVs. Serving as a communication bridge, relay UAVs guarantee connection between remote surveillance UAVs and ground station for information transmission.

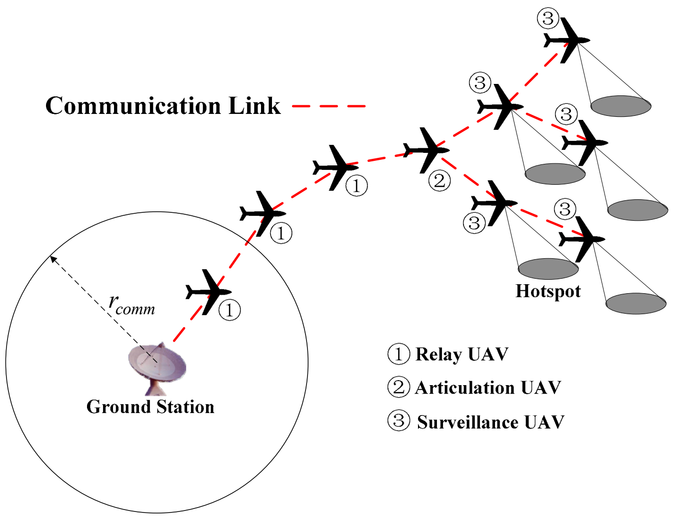

Figure 1. Multiple unmanned aerial vehicles (UAVs) cooperative surveillance with ground station.

2.2. UAV Dynamic Model

Suppose that each UAV has a reliable flight control system, which effectively controls the aerodynamic surfaces to accurately track velocity and turn rate commands. Considering no wind disturbance, all UAVs fly at a constant altitude to perform tasks. Correspondingly, the UAV kinematic model in two dimensions can be expressed as follow:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\psi} \\ \dot{v} \\ \dot{\omega} \end{bmatrix} = f(\boldsymbol{x}, \boldsymbol{u}) = \begin{pmatrix} v \cos \psi \\ v \sin \psi \\ \omega \\ -\frac{1}{\tau_v} v + \frac{1}{\tau_v} u_v \\ -\frac{1}{\tau_\omega} \omega + \frac{1}{\tau_\omega} u_\omega \end{pmatrix} \tag{1}$$

where $\boldsymbol{x} = (x, y, \psi, v, \omega)^T$ is UAV state vector; (x, y) denote the inertial coordinates of UAVs; and ψ, v, and ω are the heading angle, velocity, and turn rate of UAV, respectively. $\boldsymbol{u} = (u_v, u_\omega)^T$ is velocity and turn rate control command constrained by fixed-wing UAV dynamic model [26] in Equation (2). (τ_v, τ_ω) represent the time constants of actuator delay.

$$|u_v - v_0| \leq v_{\max} \; |u_\omega| \leq \omega_{\max} \tag{2}$$

where v_0 is UAV cruise velocity. Respectively, $v_{\max}$ and $\omega_{\max}$ are UAV velocity and turn rate maximal variation ranges.

2.3. Sensor Model

The surveillance region is assumed to be a ground plane as depicted in Figure 2. Minimizing the effect of UAV's state, the detection range of gimbaled sensor can be adjusted by a universal joint, which is a three degree rotation system. The maximum angle between two rotation axes of the universal joint is denoted as θ, and the posture change of UAV in flight is not considered. In Figure 2, μ_i is the projection of UAV i on ground plane, and h is the altitude of UAV. Accordingly, $R_s = h \tan \theta$ is the sensing radius of UAV, and the sensing regions can be expressed as $z = \{\boldsymbol{x} | \|\boldsymbol{x} - \mu_i\| \leq R_s\}$, which are depicted as the shaded parts in Figure 2. It is assumed that each UAV independently takes measurements over the grids completely within its sensing region, and a grid is assumed to be detected if it is wholly within the sensing region z. As the gray ones, the grids detected with UAV motions are depicted in Figure 3, and the red circles represent the sensing range of UAV.

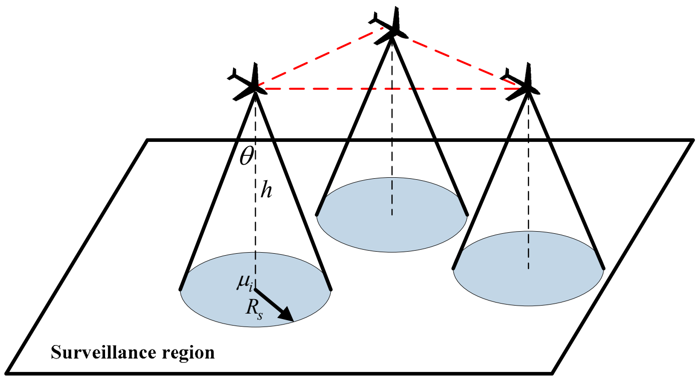

Figure 2. Sensor model in multiple UAVs cooperative surveillance.

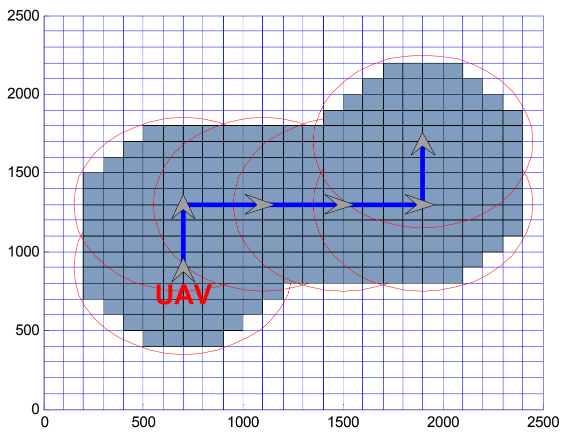

Figure 3. Schematic of coverage grids with UAV motions.

2.4. Multiple UAVs Cooperative Surveillance Problem Formulation

In this work, a remote and large area surveillance mission is designed, and there are some important and unknown targets scattering in this region. Real-time surveillance information can be gathered and sent back to ground station via multihop communications, which widely exists in disaster rescue, area monitoring and situation awareness. Combined with history detection information and surveillance payoff estimation, a multiple UAVs cooperative surveillance framework is constructed in this section.

Considering that there are N_U homogeneous UAVs performing cooperative surveillance tasks, and the set of UAVs is defined as $U = \{U_1, U_2, \ldots, U_{N_U}\}$. There are N_T targets randomly scattering in surveillance region. Similarly, the set of targets is defined as $T = \{T_1, T_2, \ldots, T_{N_T}\}$, and the target existence probability is normally distributed without loss of generality. Surveillance region is assumed to be a $L_X \times L_Y$ rectangle region on a ground plane, which is uniformly divided into $N_X \times N_Y$ grids of the same size, and it is assumed that each grid is identified with its center for simplicity.

In remote surveillance scenario, since some UAVs are gradually away from ground station for searching and detecting unknown regions, it is essential to establish UAV-to-UAV communication links for information transmission. Thus, some UAVs need to change roles and serve as relays to guarantee communication connection, and a dynamic communication links chain is constructed to balance surveillance payoff and network connectivity, which is specifically described in next section.

According to [13], the probability that UAV m detects target j with one look in a grid where the target j exists is defined as a_j^m, and $l^m(q, t_k)$ is the number of looks on grid q performed by UAV m at t_k time instant. Hence, the history detection numbers on grid q performed by UAV m can be recorded as:

$$h^m(q, t_k) = \{l^m(q, t_1), l^m(q, t_2), \ldots, l^m(q, t_k)\} \tag{3}$$

Consequently, $L^m(q, t_k) = \sum_{i=1}^{k} l^m(q, t_i)$ is the corresponding total number of looks on grid q. As communication network is connected, and all detection history information over grids can be shared between UAVs via single or multiple hops communications. It is assumed that each UAV independently looks over the same grid at different surveillance moments, and the detection process for the same grid by different UAVs is independent. Thus, history detection information reflects the entire surveillance process, and the uncertainty of target existence in the grid gradually reduces with more looks. As UAVs share surveillance information via multiple hops communications, UAVs receive the latest detection history information from its neighbors and perform relative surveillance motion. Considering the communication delay, UAV m receives the detection history number that UAV n has searched on grid q can be expressed as $h^{m,n}(q, t_k - \tau^{n,m})$ at t_k time instant, where $\tau^{n,m}$ is the arbitrary and finite communication delay, and $L^{m,n}(q, t_k - \tau^{n,m})$ is the received corresponding total number of looks on grid q of UAV n. Hence, detection history information of the group stored by UAV m at t_k time instant can be recorded as $\hat{h}^m(q, t_k) = \{h^{m,n}(q, t_k - \tau^{n,m}), n \in U\}$.

According to one look detection probability and history detection information, the detection probability of target j in grid q can be estimated [13] as:

$$b_j^m(\hat{h}^m(q, t_k)) = 1 - \prod_{n=1}^{N_U} (1 - a_j^n)^{L^{m,n}(q, t_k - \tau^{n,m})} \tag{4}$$

Based on the latest surveillance information, UAV m plans its motion and decides whether taking one more look to search grid q based on the estimation detection payoff. If UAV m decides to take one more look on grid q, the corresponding estimated total detection number on grid q by UAV m will be modified as $\hat{L}^m(q, t_k) = L^m(q, t_k) + 1$.

Integrating the modified total number $\hat{L}^m(q, t_k)$ into Equation (4), the estimated detection probability of target j in grid q with one more look can be given as:

$$\hat{b}_j^m(\hat{h}^m(q, t_k)) = 1 - (1 - a_j^m)^{\hat{L}^m(q, t_k)} \prod_{n=1, n \neq m}^{N_U} (1 - a_j^n)^{L^{m,n}(q, t_k - \tau^{n,m})} \tag{5}$$

Equation (4) reflects the estimated detection probability of target j in grid q at current instant t_k, and Equation (5) represents the estimated detection probability of taking one more look by UAV m for target j. Subsequently, the estimated improvement of detection probability for target j if UAV m performs one more look over grid q can be calculated as follow:

$$\hat{\beta}_j^m(\hat{h}^m(q,t_k)) = \hat{b}_j^m(\hat{h}^m(q,t_k)) - b_j^m(\hat{h}^m(q,t_k)) \tag{6}$$

Considering the a priori probability of target existence $p_j^m(q)$ in grid q, where $p_j^m(q) = p_j(q)$ is satisfied for each UAV by gathering same initial information, the estimated additional surveillance payoff of UAV m performing one more look on grid q can be defined as $\hat{c}_d^m(q,t_k) = \sum_{j\in T} p_j(q)\hat{\beta}_j^m(\hat{h}^m(q,t_k))$. Hence, the surveillance payoff of UAVs group at t_k time instant in cooperative surveillance tasks can be defined as:

$$p(t_k) = \omega \sum_{q\in Q}\sum_{j\in T} p_j(q)\cdot(1-\prod_{m=1}^{N_U}(1-a_j^m)^{L^m(q,t_k)}) \tag{7}$$

Actually, the surveillance payoff is defined as the product of detection probability and target existence probability. ω is a weighting parameter as 10^6 in this work, and $(1-\prod_{m=1}^{N_U}(1-a_j^m)^{L^m(q,t_k)})$ is the overall detection probability of target j in grid q at t_k time instant, which is modified by Equation (4) without communication delay. T is the set of targets randomly scattering in surveillance region, and Q is the set of grids detected in surveillance region.

In each time instant, neighbor UAVs only need to share total detection number on grid q to separately update stored history detection information of group. Therefore, when UAV m decides to take one more look over grid q, the surveillance payoff improvement with single step motion can be estimated. Considering the detection history information of group, the a priori probability of target existence and communication delay, the total surveillance payoff estimation with one more look can be calculated as:

$$c_d^m(t_k) = \omega\sum_{q\in Q^m}\hat{c}_d^m(q,t_k) = \omega\sum_{q\in Q^m}\sum_{j\in T} p_j(q)\hat{\beta}_j^m(\hat{h}^m(q,t_k)) \tag{8}$$

If just one step motion plan is considered, the optimal control command of UAV m can be described as:

$$\boldsymbol{u}_m^*(t_k) = \mathrm{argmax} c_d^m(t_k) \tag{9}$$

In [27], single UAV's search motion in a certain sequence of steps is optimized by a greedy strategy. Similar to the highest search effectiveness mentioned, the purpose of UAVs motion plan with corresponding constraints is maximizing surveillance payoff, which is optimized by decentralized receding horizon control described in detail in next section.

3. Multiple Relay UAVs Selection Scheme Based on Fuzzy Optimum Selection

In multi UAVs cooperative surveillance, since some UAVs are gradually away from ground station for detection scope expansion, it is essential to construct UAV-to-UAV communication links for preserving connectivity. With surveillance range expansion, UAVs are appropriately allocated three proposed roles to balance surveillance payoff and network connectivity, and a multiple relay UAVs selection scheme consisting of two consecutive stages is developed. Multiple relay UAVs are chosen according to membership degrees to the optimum alternative, which are assessed based on fuzzy optimum selection with four relevant attributes representing the feature of network topology with ground station. Besides, according to relationship among UAVs, role conversion stage is designed to dynamically adjust communication links with the surveillance scope change.

3.1. Three UAV Roles in Cooperative Surveillance with Ground Station

Three roles, Relay UAV (RUAV), Articulation UAV (AUAV), and Surveillance UAV (SUAV), are designed to perform different tasks to gather more real-time surveillance information and maintain network connectivity, and the details are described in Table 1. The primary task of RUAVs is providing peer-to-peer communication links, namely maintaining network connectivity among SUAVs, AUAV and ground station. SUAVs cooperatively perform surveillance tasks and search unknown regions to gather real-time information with limited communication. Serving as a joint, AUAV is a critical role to connect surveillance UAVs swarm and RUAVs, and the goal of AUAV is achieving tradeoff between surveillance payoff and network connectivity. Due to the minimum cruise velocity constraint, fixed-wing UAVs serving as relay have to circle around specified points while providing UAV-to-UAV communication links, and it is emphasized that RUAVs perform auxiliary surveillance task around circling points to improve the UAVs cooperative surveillance utility.

Table 1. Three UAV roles in cooperative surveillance with ground station.

Role	Task	Role Description
RUAV	preserving communication connection	constructing relay communication links
AUAV	connecting RUAV and SUAVs swarm	balancing surveillance mission and network connectivity
SUAV	searching and detecting unknown region	maximizing surveillance payoff

3.2. Membership Degree of UAV Alternatives Assessment Based on Fuzzy Optimum Selection

With motion of UAVs, it is obvious that UAV importance changes dynamically in communication network. As a multi-attributed decision making problem, the membership degree to the ideal optimum alternative of multiples UAV is considered as an evaluation indicator for relay selection, which is assessed by fuzzy optimum selection. Correspondingly, multiple relay UAVs are chosen based on the descending membership degree sequence for connectivity maintenance.

Combined with the feature of network connectivity in cooperative surveillance, four modified attributes representing differences among UAV alternatives are proposed in this work. It is obvious that the closer UAV to ground station is more critical to maintain connectivity, and vice versa. Firstly, frequent role conversion is not benefit for the continuity of surveillance tasks, therefore maintaining appropriate roles by different role values (RV) are essential for cooperative surveillance tasks. Similar to the shortest path in graph, minimum hops to ground station (MH) corresponds to the shortest end-to-end communication channel, which effectively reduce surveillance information delay and improve the reliability [28]. The ratio of minimum hops channels via current UAV between all UAVs and ground station (RMH) is similar to all shortest paths that travel through the same one node in graph, which reflects the influence of current UAV on others' communication with ground station. In some extreme situations, it is not explicit to distinguish UAV alternatives with the same role. For the purpose of overcoming the shortage, actual distance to ground station (AD) is a complementary factor. Thus, four attributes comprised of role values, minimum hops to ground station, the ratio of minimum hops channels via current UAV between all UAVs and ground station, and actual distance to ground station, namely RV, MH, RMH and AD, are employed to assessing UAV alternatives in cooperative surveillance. The attributes are described as follows:

$$RV(i) = \begin{cases} 1, \ UAV \ i \text{ is a SUAV} \\ 2, \ UAV \ i \text{ is a AUAV} \\ 3, \ UAV \ i \text{ is a RUAV} \end{cases} \tag{10}$$

$$MH(i) = \min_{x_i \in \Omega_i} H(x_i) \tag{11}$$

$$RMH(i) = \sum_{i \neq j, j \in U} \frac{H_{ji}}{H_j} \tag{12}$$

$$AD(i) = \sqrt{(x_i - x_b)^2 + (y_i - y_b)^2} \tag{13}$$

In Equations (10)–(13), i is the UAV identification. Equation (10) reflects different UAV role values in cooperative surveillance, and the minimum hops to ground station of UAV i is described as Equation (11), where Ω_i is the set of all communication channels between UAV i and ground station. $\boldsymbol{x}_i$ is the communication channel between UAV i and ground station, and $H(\boldsymbol{x}_i)$ is the hop counts of $\boldsymbol{x}_i$. The ratio of minimum hops channels via current UAV between all UAVs and ground station is denoted as Equation (12), where H_j is the number of communication channels between UAV j and ground station with minimum hops, and H_{ji} is the number of minimum hops channels via UAV i.

For connectivity maintenance, some UAVs should serve as relays to dynamically establish communication links, and relevant relay UAVs are chosen by fuzzy optimum selection according to four attributes mentioned above, which can be considered as the objectives to identify an optimum alternative from N_U UAVs. The set of attributes can be expressed as $\left\{ RV(i) \quad MH(i) \quad RMH(i) \quad AD\ (i) \right\}$ for UAV i, and the values of four attributes in N_U UAV alternatives can form an objective value matrix as follows:

$$\boldsymbol{X} = (x_{ij})_{4 \times N_U} = \begin{bmatrix} RV(i) \\ MH(i) \\ RMH(i) \\ AD(i) \end{bmatrix}_{4 \times N_U} = \begin{bmatrix} x_{11} & \cdots & x_{1i} & \cdots & x_{1N_U} \\ x_{21} & \cdots & x_{2i} & \cdots & x_{2N_U} \\ x_{31} & \cdots & x_{3i} & \cdots & x_{3N_U} \\ x_{41} & \cdots & x_{4i} & \cdots & x_{4N_U} \end{bmatrix}_{4 \times N_U} \tag{14}$$

where x_{ij} is the value of attribute i for the j UAV alternative. Due to the different units among four attributes in above matrix, and the optimum value is decided according to the positive and negative correlation for the attributes. Hence, the normalized matrix of $\boldsymbol{X}$ can be obtained according to following criteria.

If the attribute value is bigger, the membership degree to the optimum alternative is larger. The values of optimum and attribute are positive correlation, such as RV and RMH, and the normalizing formula is denoted as:

$$r_{ij} = \frac{x_{ij} - x_{i\min}}{x_{i\max} - x_{i\min}}$$

In contrast, the optimum and attribute values are negative correlation: when the attribute value is smaller, the membership degree to the optimum alternative is larger, such as MH and AD. Correspondingly, the normalizing formula can be expressed as:

$$r_{ij} = \frac{x_{i\max} - x_{ij}}{x_{i\max} - x_{i\min}}$$

where $x_{i\min}$, $x_{i\max}$ are, respectively, the corresponding minimum and maximum values for all alternatives of attribute i, and the normalized matrix can be denoted as follow:

$$\boldsymbol{R} = (r_{ij}) = \begin{bmatrix} r_{11} & \cdots & r_{1i} & \cdots & r_{1N_U} \\ r_{21} & \cdots & r_{2i} & \cdots & r_{2N_U} \\ r_{31} & \cdots & r_{3i} & \cdots & r_{3N_U} \\ r_{41} & \cdots & r_{4i} & \cdots & r_{4N_U} \end{bmatrix} \tag{15}$$

In above matrix, the entry r_{ij} is the relative value to optimum alternative in the interval [0,1]. $r_{ij} = 1$ represents that the UAV alternative j is the optimum alternative just according to the attribute i, otherwise $r_{ij} = 0$ is the worst alternative. Correspondingly, the ideal optimum alternative can be calculated as $\boldsymbol{g}^T = (g_1, \ldots, g_4) = (\max\limits_{j=1,\ldots,N_U}(r_{1j}), \ldots, \max\limits_{j=1,\ldots,N_U}(r_{4j}))$, and the ideal worst alternative can be expressed as $\boldsymbol{b}^T = (b_1, \ldots, b_4) = (\min_{j=1,\ldots,N_U}(r_{1j}), \ldots, \min_{j=1,\ldots,N_U}(r_{4j}))$. Hence, the membership degree matrix to the optimum and worst alternatives are defined as follows:

$$\boldsymbol{U}_{2\times N_U} = \begin{bmatrix} u_{11} & u_{12} & \ldots & u_{1N_U} \\ u_{21} & u_{22} & \ldots & u_{2N_U} \end{bmatrix} \tag{16}$$

Correspondingly, the following constraints should be satisfied.

$$0 \leq u_{kj} \leq 1(k = 1, 2; j = 1, \ldots, N_U),\ \sum_{k=1}^{2} u_{kj} = 1(j = 1, \ldots, N_U),\ \sum_{j=1}^{N_U} u_{kj} > 0(k = 1, 2)$$

where u_{1j} is the membership degree to the ideal optimum alternative and u_{2j} is the one to the ideal worst alternative.

Considering the four assessment attributes, role values is employed to prevent frequently role converting in cooperative surveillance, thus role values is considered as the most important attribute. Similar to shortest paths, the importance of the minimum hops to ground station is same as the ratio of minimum hops channels via current UAV between all UAVs and ground station, so they are more important criteria. In addition, actual distance to ground station is an auxiliary attribute for UAV alternatives assessment and reflects less information of communication network. In this work, the relevant assessment attributes are ordered as RV, MH, RMH, AD. Considering the feature of UAV alternatives in communication network, the weighed vector reflecting different influence of the four attributes can be calculated by analytic hierarchy process. Correspondingly, the judgment matrix can be denoted as follow:

$$\mathrm{A} = \begin{bmatrix} & \mathrm{RV} & \mathrm{MH} & \mathrm{RMH} & \mathrm{AD} \\ \mathrm{RV} & 1 & 3 & 3 & 5 \\ \mathrm{MH} & \frac{1}{3} & 1 & 1 & 3 \\ \mathrm{RMH} & \frac{1}{3} & 1 & 1 & 3 \\ \mathrm{AD} & \frac{1}{5} & \frac{1}{3} & \frac{1}{3} & 1 \end{bmatrix} \tag{17}$$

The judgment matrix is satisfied with the complete consistency. Correspondingly, the weighed vector is calculated as $\boldsymbol{\omega} = (0.5205, 0.2010, 0.2010, 0.0775)$, and the evaluation vector of UAV alternative j can be expressed as

$$\boldsymbol{r}_j = \left(r_{1,j}, r_{2,j}, r_{3,j}, r_{4,j}\right)^T$$

In space $\mathbf{R}^4$, the generalized superior distance of UAV alternative j to the ideal optimum alternative can be defined as:

$$\|\boldsymbol{\omega} \cdot (\boldsymbol{r}_j - \boldsymbol{g})\| = \left\{\sum_{k=1}^{4} \left[\omega_k \cdot (r_{kj} - g_k)\right]^P\right\}^{\frac{1}{P}} \tag{18}$$

In contrast, the generalized inferior distance can be denoted as:

$$\| \boldsymbol{\omega} \cdot (\boldsymbol{r}_j - \boldsymbol{b}) \| = \left\{\sum_{k=1}^{4} \left[\omega_k \cdot (r_{kj} - b_k)\right]^P\right\}^{\frac{1}{P}} \tag{19}$$

When $p = 2$, the distance between the ideal optimum alternative and UAV alternative j is represented by Euclidean distance. Hence, the weighted generalized superior and inferior distances can be expressed as:

$$\begin{aligned} D(\boldsymbol{r}_j, \boldsymbol{g}) &= u_{1j} \cdot \|\boldsymbol{\omega} \cdot (\boldsymbol{r}_j - \boldsymbol{g})\| \\ D(\boldsymbol{r}_j, \boldsymbol{b}) &= u_{2j} \cdot \|\boldsymbol{\omega} \cdot (\boldsymbol{r}_j - \boldsymbol{b})\| \end{aligned} \tag{20}$$

In order to solve optimal membership degree u_{1j}, an objective function can be designed as:

$$Min\left\{F(u_{1j}) = \sum_{i=1}^{N_U}\left[D^2(\boldsymbol{r}_i,\boldsymbol{g}) + D^2(\boldsymbol{r}_i,\boldsymbol{b})\right] = \sum_{i=1}^{N_U}\left[{u_{1i}}^2 \cdot \|\boldsymbol{\omega}\cdot(\boldsymbol{r}_i-\boldsymbol{g})\|^2 + (1-u_{1i})^2 \cdot \|\boldsymbol{\omega}\cdot(\boldsymbol{r}_i-\boldsymbol{b})\|^2\right]\right\}, j = 1,2,\ldots,N_U \quad (21)$$

Define that $\frac{dF(u_{1j})}{du_{1j}} = 0$, the following result can be obtained.

$$u_{1j} \cdot \|\boldsymbol{\omega}\cdot(\boldsymbol{r}_j-\boldsymbol{g})\|^2 - (1-u_{1j}) \cdot \|\boldsymbol{\omega}\cdot(\boldsymbol{r}_j-\boldsymbol{b})\|^2 = 0 \quad (22)$$

Then for all UAV alternatives, namely $j = 1,\ldots,N_U$, the optimal matched membership degree of alternative j can be calculated as follow:

$$u_{1j}^* = \frac{1}{1+\frac{\|\boldsymbol{\omega}\cdot(\boldsymbol{r}_j-\boldsymbol{g})\|^2}{\|\boldsymbol{\omega}\cdot(\boldsymbol{r}_j-\boldsymbol{b})\|^2}} = \frac{1}{1+\frac{\sum_{k=1}^{4}\left[\omega_k\cdot(r_{kj}-g_k)\right]^2}{\sum_{k=1}^{4}\left[\omega_k\cdot(r_{kj}-b_k)\right]^2}} \quad (23)$$

As final reference indicator, the membership degree of UAV alternative j, reflects distances to the ideal optimum and worst alternatives. Obviously, greater u_{1j} corresponds to the more important UAV alternative j, and vice versa. Thus, if u_{1j} is bigger, UAV alternative j is easily chosen as a relay UAV to construct communication links for connectivity maintenance.

In multiple UAVs cooperative surveillance, each UAV can be chosen as a relay to establish communication network. According to the proposed four assessment attributes, multiple relay UAVs selection sequence is obtained by sorting the membership degrees in descending. According to the alternatives sequence, UAVs are appropriately allocated three different roles to balance surveillance payoff and network connectivity based on multiple relay UAVs selection scheme.

3.3. Multiple Relay UAVs Selection Scheme in Cooperative Surveillance

Based on the four proposed attributes mentioned above, the membership degree to optimal alternative of multiple UAVs can be calculated by fuzzy optimum selection. As final assessment indicator, relay UAVs are correspondingly chosen and communication links are dynamically adjusted by the relationship among UAVs. Then UAVs are appropriately allocated three different roles to guarantee the performance of cooperative surveillance. It is assumed that just only one UAV switches its role at the same time for simplicity. For balancing surveillance payoff and connectivity maintenance, multiple relay UAVs selection stage is performed according to the relevant relay UAVs number N_R ranging from 0 to $N_U - 2$. Subsequently, a role conversion stage is developed to dynamically modify the relay UAVs number with surveillance scope adjustment. The relay UAV alternatives sequence is defined as $\boldsymbol{V}_{Seq}$, and the one with the nth highest membership degree to optimum alternative in $\boldsymbol{V}_{Seq}$ is defined as the nth UAV, which not corresponds to its real ID.

3.3.1. Multiple Relay UAVs Selection Stage

It is emphasized that different UAV roles are appropriately allocated according to relay UAV alternatives sequence $\boldsymbol{V}_{Seq}$. Firstly, the membership degrees of UAV alternatives are assessed according to four proposed attributes representing network connectivity. Then, 1st~N_Rth UAVs are selected as RUAVs to establish communication links, and $(N_R + 1)$th UAV serves as AUAV connecting with remote SUAVs swarm and RUAVs. As SUAV, the remaining UAVs continue performing surveillance tasks and expanding searching scope. For the purpose of surveillance scope expansion, it is assumed that supplying relay UAV is more important than removing relay UAV at the same instant. After multiple relay UAVs are selected based on $\boldsymbol{V}_{Seq}$, the role conversion stage is designed to dynamically revise relay UAVs number for detection scope adjustment.

3.3.2. Role Conversion Stage

Role conversion state is developed to dynamically adjust communication links by revising the relay UAVs number, and it is assumed that just only one UAV changes its role at the same time for simplicity. As network is connected, all UAVs can exchange information with each other via single and multiple hops, and r_{comm} is the communication range. The role conversion stage is implemented according to the relationship among SUAVs swarm, AUAV and the N_Rth RUAV, which is depicted in Figure 4, and the relay UAVs number and communication links are dynamically adjusted in cooperative surveillance.

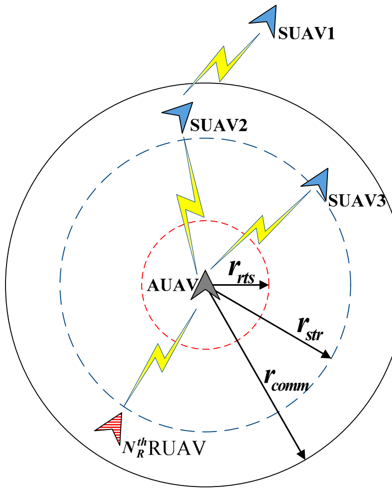

Figure 4. Geometry relationship among RUAV, AUAV and SUAVs in role conversion stage.

r_{rts} is the threshold distance for AUAV converting role to continue to perform surveillance task, and the blue dotted circle with radius r_{str} reflects the threshold distance for AUAV changing role to serve as RUAV. According to the relationship among the $N_R th$ RUAV, AUAV and SUAVs swarm, the role conversion stage is realized as follows.

If there is no SUAV in the circle zone $z_1 = \{\boldsymbol{x} : \|\boldsymbol{x} - \boldsymbol{x}_u\| \leq r_{str}\}$ of AUAV, it represents that SUAVs swarm is away from ground station, and the network connectivity will be broken if AUAV does not change its roles to serve as RUAV. At this time, it is essential that supplying a RUAV to prevent communication interruption. Correspondingly, the relay UAVs number should be revised as $N_R + 1$, and a new AUAV is selected to connect SUAVs swarm and RUAVs.

It is obvious that supplying RUAV can effectively extend surveillance scope, which is considered more important than removing RUAV for surveillance range contraction. If no relay UAV supplement, it is concerned that whether there are some UAVs in the circle zone $z_2 = \{\boldsymbol{x} : \|\boldsymbol{x} - \boldsymbol{x}_u\| \leq r_{rts}\}$ of the $N_R th$ RUAV. If there is at least one UAV in this zone, it represents network is effectively connected and the AUAV can change role to perform surveillance task again. Accordingly, relay UAVs number should be revised as $N_R - 1$, and the most remote RUAV adjusts its role to serve as a new AUAV.

In Figure 4, the ring domain $z_{buffer} = \{\boldsymbol{x} : r_{\rm rts} \leq \|\boldsymbol{x} - \boldsymbol{x}_u\| \leq r_{str}\}$ can be seen as a buffer zone to prevent UAVs role converting frequently, which is beneficial for effectively achieving tradeoff between surveillance payoff and network connectivity. For some special cases, it is emphasized that relay UAV supplement is ineffective when $N_R = N_U - 2$, and relay UAV removal should not be triggered when $N_R = 0$ in contrast.

3.3.3. Multiple Relay UAVs Selection Scheme

The multiple relay UAVs selection scheme is a centralized approach to obtain the membership degree sequence of UAV alternatives to the optimum alternative, and the detail algorithm process is described in Algorithm 1.

Algorithm 1. Multiple Relay UAVs Selection Scheme

Input: UAVs state information (positions P_i and roles R_i) for $i = 1, \ldots, N_U$, the relay UAVs number N_R
Output: updated information (roles R_i and circling points $P_{i,C}$) for $i = 1, \ldots, N_U$.
// multiple relay UAVs selection stage:
1. Calculate $RV(i), MH(i), RMH(i), AD(i), i = 1, \ldots, N_U$ (Equations (10)–(13))
2. Membership degree of UAV alternatives assessment based on fuzzy optimum selection (Equations (14)–(23))
3. $R_1 \sim R_{N_R} \rightarrow$ RUAV, $R_{N_R+1} \rightarrow$ AUAV, $R_{N_R+2} \sim R_{N_U} \rightarrow$ SUAV // $\rightarrow$ *represents role allocation operation* R_i
// role conversion stage: is the role of the ith UAV
4. if there is no SUAV in z_1 of AUAV
5. $R_{N_R+1} \rightarrow$ RUAV, $R_{N_R+2} \rightarrow$ AUAV, $N_R = N_R + 1$ // *relay UAV supplement*
6. else
7. if there is at least one UAV in z_2 of the $N_R th$ RUAV
8. $R_{N_R} \rightarrow$ AUAV, $R_{N_R+1} \rightarrow$ SUAV, $N_R = N_R - 1$ // *relay UAV removal*
9. endif
10. endif
11. Calculate the circling points $P_{i,C}$ for $i = 1, \ldots, N_R$

In cooperative surveillance, all UAVs send state information to ground station to evaluate the membership degrees to ideal optimal alternative among the group via single or multi hops communications, and the multiple relay UAVs selection scheme carries out in ground station. According to relationship among UAVs depicted in Figure 4, role conversion is correspondingly performed. Subsequently, the ground station sends relevant role information to each UAV, which consists of UAV role, circling point and other messages, and relevant UAVs update roles and perform new tasks in cooperative surveillance respectively.

Based on the multiple relay UAVs selection scheme in Algorithm 1, each UAV is allocated appropriate role over time for balancing surveillance payoff and network connectivity. It is noted that the circling points are uniformly distributed between ground station and the central of SUAVs swarm, and the interval is set as r_{str}.

4. Multiple UAVs Motion Plan in Cooperative Surveillance

As network is connected, UAVs exchange information via single or multi hops communications in cooperative surveillance. Each UAV plans its optimal motion based on local neighbor UAV information. At each instant, each UAV's optimal control command sequence is calculated by decentralized receding horizon control, and the optimization metrics are different for three proposed UAV roles. Considering connection with other UAVs, the primary goal of RUAV is constructing dynamic and reliable peer-to-peer communication links between remote UAVs swarm and ground station. For the purpose of maximizing surveillance payoff, SUAVs try to gather more surveillance information and explore more unknown regions, but it is necessary that connecting with at least one UAV in its communication range. As an essential role, AUAV, which can be considered as a special SUAV, serves as a communication joint to connect remote SUAVs and RUAV, and its task is achieving tradeoff between surveillance mission and connectivity maintenance.

4.1. Receding Horizon Motion Plan Based on UAV Roles

As the communication network is connected, all UAVs can share surveillance and state information while performing tasks. Considering UAV kinematic constraints, collision avoidance and connectivity preservation in multiple UAVs cooperative surveillance, each UAV can optimize its motion plan by decentralized receding horizon control according to relevant different UAV roles. According to Equation (1), the continuous UAV model can be discretized as follow:

$$\boldsymbol{x}_{k+1} = f_d(\boldsymbol{x}_k, \boldsymbol{u}_k) = \boldsymbol{x}_k + T_S f(\boldsymbol{x}_k, \boldsymbol{u}_k) \tag{24}$$

where $\boldsymbol{x}_k$ is UAV current state vector, and $\boldsymbol{u}_k$ is control command vector. At each sample instant, each UAV next instant state can be propagated by above equation. In next sample period, each UAV optimize its control sequence based on updated local neighbor information in the same manner.

The given planning horizon length can be expressed as N, and the control command sequence of UAV m can be denoted as $\boldsymbol{u}_{m,k} = [\boldsymbol{u}_{m,k}^0, \boldsymbol{u}_{m,k}^1, \ldots, \boldsymbol{u}_{m,k}^{N-1}]$. For relevant UAV roles, the optimization metrics are different. The primary purpose of RUAV is maintaining connectivity by constructing communication links, which is realized by circling over predefined points, and the optimization metric is described as follow:

$$J^m(k) = -\sum_{i=1}^{N} \left(\frac{\|\boldsymbol{x}_{m,(k+i)} - \boldsymbol{x}_{m,i}^c\| - r_l}{r_l} \right)^2 \tag{25}$$

where $\boldsymbol{x}_{m,i}^c$ is the assigned circling point, and r_l is the circling radius calculated by UAV kinematic constraints. For AUAV, its primary task is maintaining balance between surveillance payoff and network connectivity, hence AUAV is a particular type of SUAV with additional connection tasks. Correspondingly, the performance of estimated surveillance payoff can be expressed as follow:

$$J^m(k) = \sum_{i=1}^{N} c_d^m(t_{k+i}) = \sum_{i=1}^{N} \sum_{q \in Q_{k+i,N}^m} \hat{c}_d^m(q, t_{k+i}) \tag{26}$$

where $Q_{k+i,N}^m$ is the set of grids can be searched by UAV m in the ith horizon at time instant t_k.

In order to satisfy the collision avoidance and connectivity preservation constraints, a simple penalty function is designed to penalize the movement that may cause collision or network disruption, and the penalty function can be expressed below:

$$P^m(k) = \sum_{i=1}^{N} \left(\sum_{j \in N_{Comm}^m} \mathrm{sgn}(\|x_{m,(k+i)} - x_{j,(k+i)}\| - R_{comm}) \cdot \left(\frac{R_{comm} - \|x_{m,(k+i)} - x_{j,(k+i)}\|}{R_{comm}} \right)^2 + \sum_{n \in U} \mathrm{sgn}(R_c - \|x_{m,(k+i)} - x_{n,(k+i)}\|) \left(\frac{\|x_{m,(k+i)} - x_{n,(k+i)}\| - R_c}{R_c} \right)^2 \right) \tag{27}$$

where N_{comm}^m is set of necessarily connected UAVs with UAV m for connectivity preservation, and $\mathrm{sgn}(\cdot)$ is sign function.

Considering the collision avoidance, network connectivity and UAV kinematic constraints, the following constraints should be satisfied for each UAV $m \in U$, and $\forall i = 1, \ldots, N$ in the receding horizon.

$$\begin{cases} \|\boldsymbol{x}_{m,(k+i)} - \boldsymbol{x}_{n,(k+i)}\| > r_{safe},\ n \neq m,\ n \in U \\ \|\boldsymbol{x}_{m,(k+i)} - \boldsymbol{x}_{r,(k+i)}\| < r_{comm},\ r \in N_{comm}^m \\ \left| u_{m,v}^{k+i-1} - v_0 \right| \leq v_{\max} \left| u_{m,\omega}^{k+i-1} \right| \leq \omega_{\max} \end{cases} \tag{28}$$

Integrating penalty value into performance criteria, the performance function can be modified as:

$$J_m(k) = J^m(k) - P^m(k) \tag{29}$$

In each sample instant, each UAV can optimize its control command sequence by decentralized receding horizon control just based on the local neighbor information, and the corresponding constraints mentioned above should be satisfied in each horizon. Accordingly, the performance and penalty function are dynamically adjusted by the role of UAV m, and the optimal control command sequence can be written as:

$$\boldsymbol{u}_m^* = [\boldsymbol{u}_{m,0}^*, \boldsymbol{u}_{m,1}^*, \ldots, \boldsymbol{u}_{m,(N-1)}^*] = \text{argmax} J_m(k) \tag{30}$$

where $\boldsymbol{u}_m^*$ is current optimization control command sequence, and $\boldsymbol{u}_{m,0}^*$ is selected as current control command for UAV m.

Due to the complexity of multiple UAVs cooperative surveillance problem, evolutionary algorithms should be employed to optimize each UAV's motion plan, such as immune algorithm, genetic algorithm, particle swarm optimization, etc. Considering the flexibility, robustness and global optimization capacity, the UAV control command sequence can be solved by PSO with elite mechanism in this work.

4.2. UAV Control Command Optimization Based on PSO with Elite Mechanism

In a basic particle swarm optimization system, a population of individuals is randomly initialized in the search space. Each individual is considered as a particle, and each particle is a potential solution. The position and velocity of the ith particle can be respectively described as $\boldsymbol{X}_i = (x_{i,1}, x_{i,2}, \ldots, x_{i,d})$ and $\boldsymbol{V}_i = (v_{i,1}, v_{i,2}, \ldots, v_{i,d})$ in the d-dimensional space. The personal best position $\boldsymbol{P}_i = (p_{i,1}, p_{i,2}, \ldots, p_{i,d})$ represents the best fitness value obtained so far, namely pbest, and the global particle gbest is denoted by $\boldsymbol{P}_g$, which represents the best particle found so far [29]. In each iteration cycle, the velocity and position of particle can be updated as follow:

$$\begin{aligned} \boldsymbol{v}_i^{k+1} &= \omega \cdot \boldsymbol{v}_{id}^k + c_1 r_1 (\boldsymbol{p}_i - \boldsymbol{z}_i^k) + c_2 r_2 (\boldsymbol{p}_g - \boldsymbol{z}_i^k) \\ \boldsymbol{z}_i^{k+1} &= \boldsymbol{z}_i^k + \boldsymbol{v}_i^{k+1} \end{aligned} \tag{31}$$

where r_1, r_2 are random parameters ranging from $[0, 1]$, and c_1, c_2 are acceleration coefficients. Besides, ω is an inertia factor.

In this work, inspired by [25], elite mechanism is employed to improve the effectiveness of PSO. It is obvious that some high ranking particles will produce more diversity particles than just one single particle, which is useful to improve optimization performance. Correspondingly, the elite mechanism consists of the elite group of each individual and elite group of the global best particle, which increases the diversity of particles and effectively overcomes the problem of premature convergence associated with conventional PSO. Moreover, it is noted that the introduced elite mechanism should not increase the complexity in relevant calculation process. Accordingly, the modified velocity can be expressed as follow:

$$\boldsymbol{v}_i^{k+1} = \omega \cdot \boldsymbol{v}_{id}^k + \sum_{m=1}^{E_p} c_{1,m} r_1 (Pbest_{i,m}^k - \boldsymbol{z}_i^k) + \sum_{n=1}^{E_g} c_{2,m} r_2 (Gbest_n^k - \boldsymbol{z}_i^k) \tag{32}$$

where E_p, E_g are the numbers of personal elite group and global elite group respectively. $Pbest_i$ is the elite group set of ith particle so far, and $Gbest$ is the elite group set of the global swarm.

In multi UAV cooperative surveillance, each UAV can optimize its control command sequence just according local information, namely the motion plan of each UAV can be implemented in parallel. Therefore, each particle represents one possible control sequence of UAV, and the corresponding UAV motion plan optimization can be solved by PSO with elite mechanism.

5. Numerical Results

In this section, the numerical simulation results are presented to demonstrate the effectiveness of multi UAVs cooperative surveillance framework consisting of ground station for remote command and situation awareness. Particularly, the effects of proposed multiple relay UAVs selection scheme based on fuzzy optimum selection are discussed. The multi UAV cooperative surveillance consists of a ground station and six UAVs, and there are ten potential targets randomly scattering in a surveillance region. While surveillance scope expansion, relay UAVs alternatives sequence is obtained by sorting the membership degrees of UAV alternatives to optimum alternative, which is solved by a multi-attributes decision making method, namely fuzzy optimum selection. Subsequently, the relay UAVs number and communication links are dynamically adjusted based on instantaneous relationship among UAVs with surveillance scope change.

According to three proposed roles in cooperative surveillance, six UAVs are allocated appropriate roles to cooperatively perform search and monitor tasks over a 4000 m $\times$ 4000 m rectangle region, which is uniformly divided into 40 $\times$ 40 grids with the same size. Real-time surveillance information is gathered and transmitted to ground station for remote command and situation awareness. The primary purpose of cooperative surveillance is maximizing surveillance payoff meanwhile the network connectivity should be guaranteed. According to different roles in cooperative surveillance, each UAV decides its motion plan by decentralized receding horizon control in parallel, and the optimal control sequence is solved by PSO with elite mechanism. The total simulation steps size is 300, and the receding horizon steps size is 4. UAV performance parameters v_0, $v_{\max}$, $\omega_{\max}$, r_{comm}, r_{safe}, and R_s are 80 m/s, 20 m/s, 0.8 rad/s, 1000 m, 50 m, 500 m, respectively, and the role conversion threshold distances r_{str}, r_{rts} are 700 m, 400 m. It is assumed that target existence probability is normal distribution without loss of generality, and the standard deviation is set as 250 m. Besides, the detection probability by one single look is defined as $a_j^m = 0.5$ for each target, $\forall m \in U$. For communication preservation, penalty distances R_{Sur}, R_{Rel} for SUAV and RUAV are set as 900 m, 650 m, and the penalty distance for collision avoidance R_C is 200 m. The UAVs optimal control sequence can be calculated by PSO with elite mechanism, and the corresponding parameters c_1, c_2 are 0.7, 0.6. Besides, the particle numbers of personal and global elite groups are 3, 2.

Figures 5–8 represent the simulation results of multiple UAVs cooperative surveillance. For remote command and situation awareness, a ground station located at the bottom left corner of surveillance region is employed to remote command and six homogeneous UAVs cooperatively perform search and detection tasks, which are uniformly deployed at the below edge of surveillance region with 200 m interval.

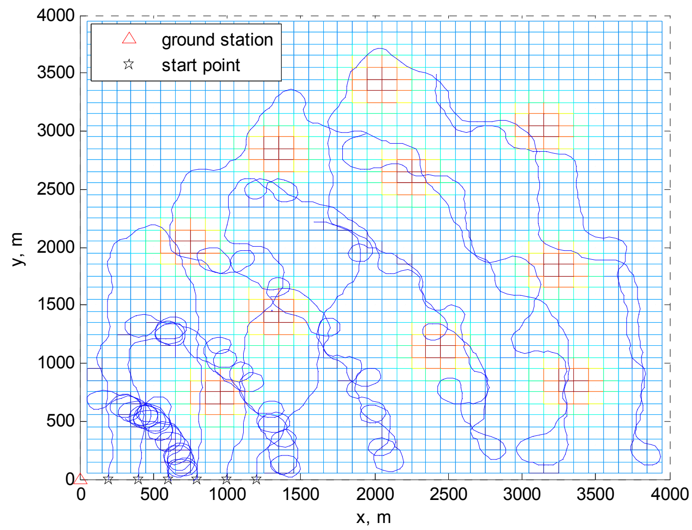

Figure 5. UAVs cooperative surveillance trajectories.

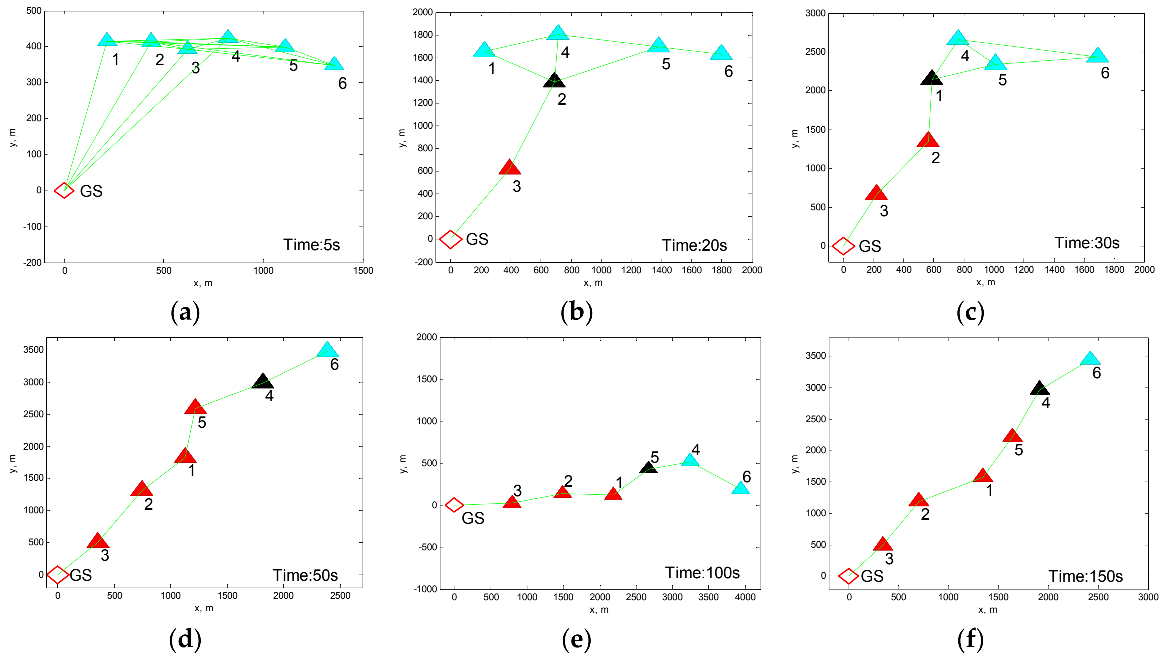

Figure 6. Network topologies in multiple UAVs cooperative surveillance at different instants: (**a**) 5 s; (**b**) 20 s; (**c**) 30 s; (**d**) 50 s; (**e**) 100 s; (**f**) 150 s. The red triangle means RUAV and the blank represents AUAV, and the remaining cyan one is SUAV.

The trajectories of multiple UAVs are depicted in Figure 5, and the black pentacles are the initial positions of UAVs. One can see that UAVs search and detect the grids with high probability of target existence, but surveillance scope expansion is moderately restricted by network maintenance with ground station. With some SUAVs away from ground station, UAV importance for communication maintenance is evaluated and relevant relay UAVs are selected to establish communication links based on fuzzy optimum selection, which circle around the predefined points corresponding to spiral trajectories near ground station in Figure 5. Correspondingly, other UAVs serve as AUAV and SUAV according to the multiple relay UAVs selection scheme. With the dynamic adjustment of communication links, the performance of cooperative surveillance mission is guaranteed.

The instantaneous UAVs network topologies are depicted in Figure 6, where the ground station is expressed by red diamond, and the triangles with different colors represent three relevant roles in cooperative surveillance. The Figure 6a represents that the most of UAVs can directly communicate with ground station at the beginning of simulation, and relay UAV is unnecessary. With some UAVs beyond effective communication range of ground station, some UAVs are chosen as relays to establish communication links at 20 s depicted in Figure 6b, and the relay UAV alternatives sequence V_{seq} is calculated by ground station as $\{3, 2, 1, 5, 4, 6\}$. Combined with the current relay UAVs number $N_R = 1$, UAV3 is selected as relay to provide communication linking service, and UAV2 serves as AUAV connecting remote SUAVs swarm and UAV3. While SUAVs swarm is away from ground station, UAV2 subsequently converts role to RUAV and UAV1 serves as AUAV for surveillance range expansion at 30 s as Figure 6c. With the surveillance scope expansion, the communication links gradually increase with multiple relay UAVs selection scheme, and more unknown regions can be detected at 50 s, which is described in Figure 6d. Comparing with the last two subfigures, the relay UAVs number is dynamically adjusted by the relationship among UAVs with surveillance scope change. According to the instantaneous network topologies, it is concluded that some UAVs gradually transform roles to stretch communication links and expand search scope based on multiple relay UAVs selection scheme, and all potential target existence regions are detected by UAVs over time. In cooperative surveillance, multiple relay UAVs are appropriately chosen by fuzzy optimum selection, and communication links are dynamically adjusted by relationship among UAVs with surveillance scope change. It is concluded that balance between surveillance payoff and network connectivity can be guaranteed by the proposed multiple relay UAVs selection scheme.

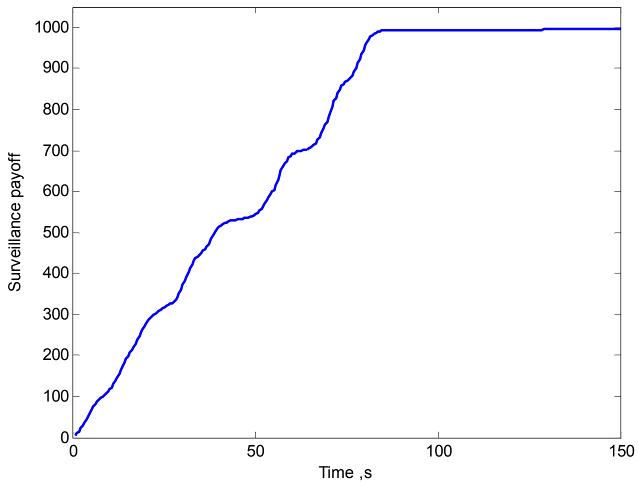

Figure 7. Surveillance payoff in multi UAVs cooperative surveillance.

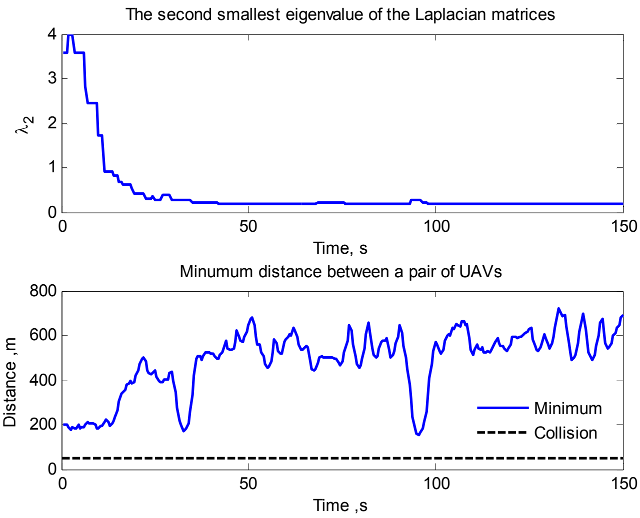

Figure 8. Topology connectivity and minimum distance between UAVs.

The cooperative surveillance payoff curve is depicted in Figure 7. One can see that the payoff curve is growing quickly with surveillance scope expansion over time. All unknown and potential target existence regions are searched and detected by multiple UAVs in a short time, and maximum surveillance payoff can be obtained, which represents that the effectiveness of the proposed method. Due to the dispersed target distributions and network connectivity with ground station, the payoff curve slowly grows in some periods.

Figure 8 shows the topology connectivity and minimum distance between UAVs. The network connectivity depicted in the above subfigure is described by the second smallest eigenvalue of the Laplacian matrices, namely λ_2 The value of λ_2 gradually decreases over time, which means that the communication links extension with the surveillance UAVs swarm is far away from ground station over time. Moreover, λ_2 is always larger than zero, and network connectivity is guaranteed in entire simulation based on multiple relay UAVs selection scheme, meanwhile multiple UAVs cooperative surveillance mission is commendably completed. The minimum distance between pair of UAVs is depicted in the bottom subfigure, which is always larger than the minimum safe distance. Figure 8 indicates the validity of penalty function for connectivity maintenance and collision avoidance.

6. Conclusions and Future Works

Multi UAVs cooperative surveillance comprised of ground station and multiple homogeneous UAVs for remote command and situation awareness is represented in this paper. Considering history detection information and surveillance payoff estimation, a multi UAVs cooperative surveillance framework is implemented. For achieving tradeoff between maximizing surveillance payoff and maintaining network connectivity, the membership degrees of UAV alternatives are evaluated by fuzzy optimum selection according to four proposed attributes, and then a multiple relay UAVs selection scheme, which consists of two successive stages, namely multiple relay UAVs selection and role conversion, is designed to dynamically adjust UAV roles and communication links with surveillance scope change. Besides, according to different UAV roles and local neighbor information, the UAV control command sequence is optimized by PSO with elite mechanism based on decentralized receding horizon control.

In this work, multiple relay UAVs selection scheme is performed in ground station, namely a centralized method, which depends on the entire necessary information of surveillance group. Obviously, a decentralized method based on local neighbor information is essential for improving the reliability and performance of cooperative surveillance. Moreover, complex sensing model and connectivity disruption caused by UAV failure will be considered in the future.

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