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Multiple UAV Formations for Cooperative Source Seeking and Contour Mapping of a Radiative Signal Field

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Abstract In this paper, four scenarios are presented for cooperative source seeking and contour mapping of a radiative signal field by multiple UAV formations. A source seeking strategy is adopted with saturation, and then it is modified to achieve contour mapping of the signal field with the moving source situation considered. A formation controller used for consensus problem is simplified and applied in the scenarios to stabilize the multiple UAV formation flight during source detection. The contour mapping strategy and the formation control algorithm are combined to guarantee stable source seeking and contour mapping in both circular flight path and square flight path via multiple UAV formations.

Keywords Multiple UAV formation · Cooperative · Source seeking · Contour mapping · Decentralized formation · Radiative signal field

1 Introduction

The radiative signal can be a spatially distributed source, for example, thermal energy spread, acoustic signal transmissions, light propagation, chemicals dissemination, electromagnetic radiation, and even radiation leakage. As an interesting research topic, source seeking has attracted increasing attentions. In [1], extremum seeking method is used to tune the forward velocity for source seeking without position measurements. Cochran et al. [2] analyzes the stability of source seeking scheme by tuning only the angular velocity while keeping the forward velocity constant, and the continuing paper [3] talks about the application of this source seeking method. In [4], a sliding mode controller is designed for gradient climbing and source seeking. In [5], groups of vehicles are considered as a sensor network, and a control strategy is presented to guarantee the mobile sensor network to achieve gradient climbing in an unknown environment. In practical situations, the radiative signal sources may be moving instead of being stationary, and the moving source cases are also studied in some publications. Daniel

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et al. [6] analyzes and evaluates the costs and benefits to detect a moving radioactive source by using a network, and the source is constricted to move along a single path. Demetriou [7] proposes a control scheme combined with state estimation and a moving source detection method by utilizing a sensor network. Brennan et al. [8] implements the Bayesian methods for sensor networks by detecting the moving point source with constant speed, and compares the consequences with different radiation levels. In [9], the model for biochemical dispersion from a moving source is derived with two possible situations considered, and then a statistical signal processing algorithm is developed to detect the moving source, and estimate the diffusion parameters. Cochran et al. [10] introduces a control strategy to tune the angular velocities of a nonholonomic vehicle for the moving scalar signal source, and it proves the local exponential convergence of the scheme. In [11], the extremum seeking method is used to navigate a modeled underwater vehicle for moving source seeking. In [12], controllers are designed to drive the mobile robots for randomly switching source seeking by extending the simultaneous-perturbation stochastic approximation (SPSA) algorithm. The convergence of the controllers is guaranteed for the stochastic source field.

Because of the rapid development of unmanned aerial vehicle (UAV) technologies, stable flight control for a single UAV has been strengthened [13, 14]. Based on single UAV stable flights, experimental multiple UAV formation flights are also achieved [15]. Cooperative multiple UAV formations could extend the capabilities of a single UAV, and accomplish the task in less time with higher efficiency and more robustness. Using multiple UAV formations for source seeking has been investigated in many papers. In [16], cooperative UAV formation is demonstrated to track the moving targets by using the developed guidance algorithms with both software simulation and hardware for application provided. In [17], two scenarios are presented for nuclear radiation detection by multiple UAV formation flights: one simulated contour mapping of the radiation field, and the other one studied nuclear radiation level detection on pre-defined waypoints. In [18], a method is introduced to estimate the gradient by a leader UAV based on the detected data from all the UAVs in formation, and then both the guidance law and the heading rate controller are designed for the leader UAV. Afterwards heading rate controllers are applied to each follower UAV to circle around the leader UAV for the cooperative source seeking. Zhang and Leonard [19] introduces a cooperative Kalman Filter to combine measurements from mobile sensor platforms for the unknown gradient estimation. The UAV formation is driven by a steering control algorithm to track the level curves of the scalar area. In [20], under the fractional order potential fields, the UAV formations are used to track the radio transmitters which are implanted to the fish, and the Kalman Filter is utilized to estimate the location of the transmitters. Zhu et al. [21] presents a leader-followers formation to seek a moving source with a least-square scheme, and it generates the guidance law for the leader UAV based on the estimations of both the source gradient and source moving velocity. The preliminary work of this paper is presented in [22], in which we shows the control strategies for source seeking and contour mapping of a stationary diffusive signal field and provides the simulation results for validation.

In this paper, multiple UAV formations are used to achieve cooperative source seeking and contour mapping of a radiative signal field. Source seeking and contour mapping can help people to recognize the radiative signal field. The decision-makers could evaluate the situation based on the acquired contour mapping, and then deploy the appropriate salvage or corresponding actions within least amount of time. The four scenarios which are the main contributions of this paper are illustrated step by step to detect, locate the radiative signal field and perform contour mapping. First, an existing controller is adopted with saturation considering the practical flight speed limit, and it is applied to a linear UAV model simplified from the nonholonomic model for source seeking and locating. Then the controller is modified to steer the specified signal level contour mapping with the moving source situation covered. Next, a method used for multi-vehicle consensus is simplified and utilized to stabilize the formation flights for detecting the radiative field. At last, these two methods in above two steps are combined to realize the cooperative contour mapping of the radiative signal field by multiple UAV formations.

This paper is organized as follows: Section 2 presents the radiative signal source seeking and locating driven by the improved controller. Section 3 illustrates the signal level contour mapping for both stationary and moving source using the modified controller. Section 4 applies a control strategy once used in multi-agent consensus problem to stabilize the multiple UAV formations for the radiative signal field detection. In Section 5, the contour mapping controller and formation controller cooperatively control the multiple UAV formation to achieve the contour mapping. Section 6 concludes this paper.

2 Source Seeking, and Locating of a Radiative Signal Field

The source seeking problem usually considers the nonholonomic model [23], which is shown as

$$\begin{cases} \dot{x} = v\cos\theta, \\ \dot{y} = v\sin\theta, \\ \dot{\theta} = \omega, \end{cases} \tag{1}$$

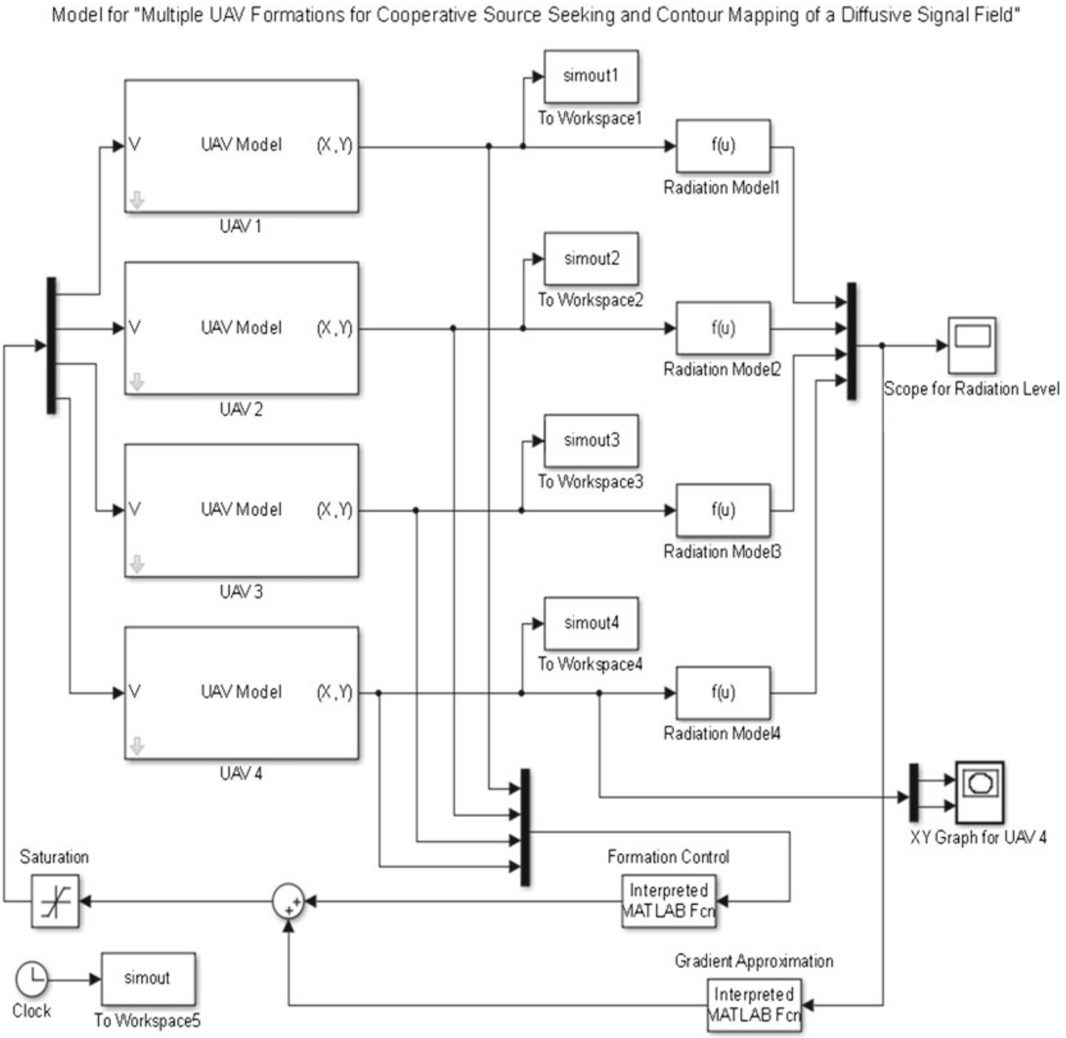

Fig. 1 Simulation model: multiple UAV formation for cooperative source seeking and contour mapping of a radiative signal field

where (x, y) denotes the position, v represents the linear velocity, θ means the orientation, and ω is the angular velocity. In order to get rid of the nonholonomic constraint, feedback linearization could be used to simplify the model.

$$\begin{cases} x_i = x + L\cos\theta, \\ y_i = y + L\sin\theta. \end{cases} \tag{2}$$

Suppose that there is a point at position (x_i, y_i) which is off the center of the vehicle (x, y) with distance L and orientation θ. If v and ω in Eq. 1 are defined as functions of v_{ix}, v_{iy}, L, and θ properly, the kinematic model for (x_i, y_i) in Eq. 2 could be linearized as

$$\begin{cases} \dot{x}_i = v_{ix}, \\ \dot{y}_i = v_{iy}, \end{cases} \tag{3}$$

where (x_i, y_i) is the position of the ith UAV, and (v_{ix}, v_{iy}) is the velocity of the ith UAV which is considered as control input in this paper with restriction within (−20 m/s, +20 m/s).

All the UAVs are assumed to fly at constant altitudes denoted as $\dot{z}_i = 0$, where z_i is the altitude of the ith UAV, and in order to avoid the collision, each UAV should stay at different altitude.

In this paper, the radiative signal model is defined as

$$D(x, y) = 10e^{-\frac{(x-100)^2+(y-90)^2}{80,000}}, \tag{4}$$

which is a Gaussian signal. The range of the field is restricted within a square from −400 to 600 m in X axis and from −400 to 600 m in Y axis in simulation.

The simulation model is given in Fig. 1, which could be used for all of the four scenarios in this paper by only adjusting some parameters.

The developed controller in [23] is adopted to the linearized model (3) with saturation and defines as

$$u = \mathrm{Sat}\left[k\sum_{i=1}^{N} D_i(x, y)\, e\left(\theta_0 + \frac{2\pi}{N}(i-1)\right)\right], \quad N \geq 3, \tag{5}$$

where $\begin{bmatrix} v_{ix} \\ v_{iy} \end{bmatrix} = u$, $Sat[]$ is the saturation to restrict the velocity considering the practical situation, k is the gain which is set to 30 in this scenario, $D_i(x, y)$ is the detected radiative signal level by the sensor installed on the ith UAV, $e(\phi) = \begin{bmatrix} \cos\phi \\ \sin\phi \end{bmatrix}$, θ_0 is the initial deflection angle which is set to 0 degrees, and N is the number of multiple UAVs in formation, which is set to 4 in this paper.

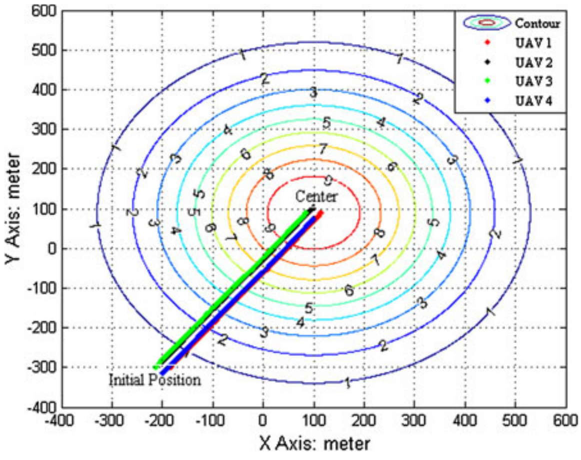

Fig. 2 4 UAV formation for radiative signal source seeking and locating

This controller guarantees the 4 UAV formation to detect the gradient of the radiative signal, and achieve source seeking and locating with process shown in Fig. 2.

The actions of each UAV during source seeking are plotted in X axis, and Y axis, which are demonstrated in Figs. 3 and 4 separately.

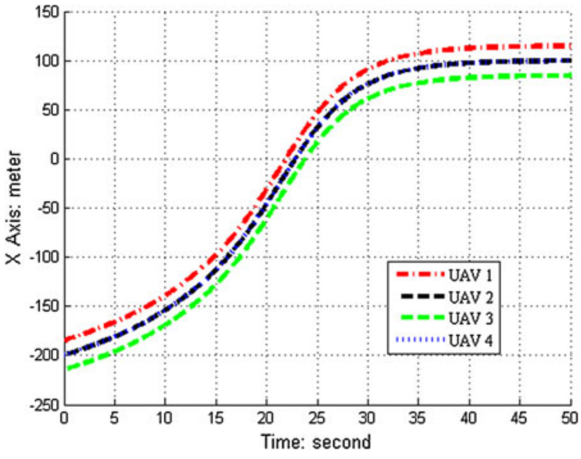

Fig. 3 X axis plot for each UAV action in source seeking

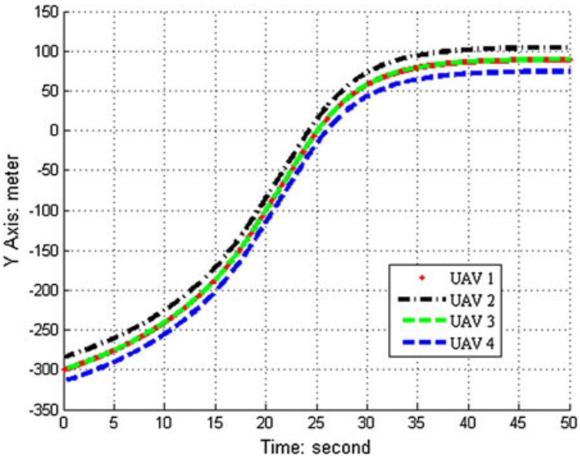

Fig. 4 Y axis plot for each UAV action in source seeking

According to the X axis plot, and Y axis plot, it can be seen that the 4 UAVs fly towards the gradient direction of the source signal in a circular formation. The center of the 4 UAV formation is set at (-200 m, -300 m) originally. After 50 s, the 4 UAV formation achieves the source seeking, and locates the radiative signal source at position (100 m, 90 m).

k is an important factor for the controller, which should be properly adjusted. Because when k is set to a bigger value, the output of u will reach the saturation limit at 20 m/s, and affect the path of the formation while shortening the time to locate the source. Figure 5 demonstrates the UAVs reach the saturation limit during source seeking and locating process with $k = 80$.

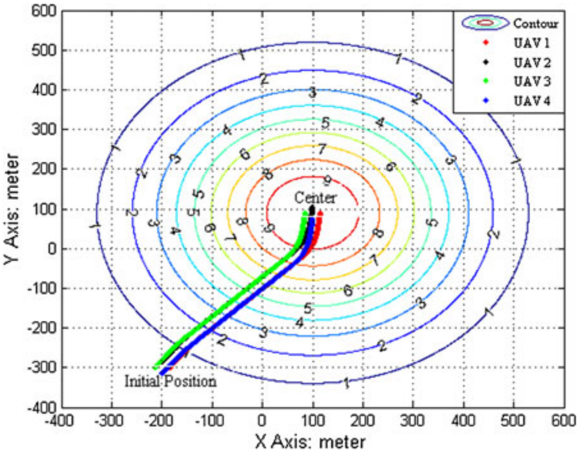

Fig. 5 4 UAV formation for source seeking when k is 80

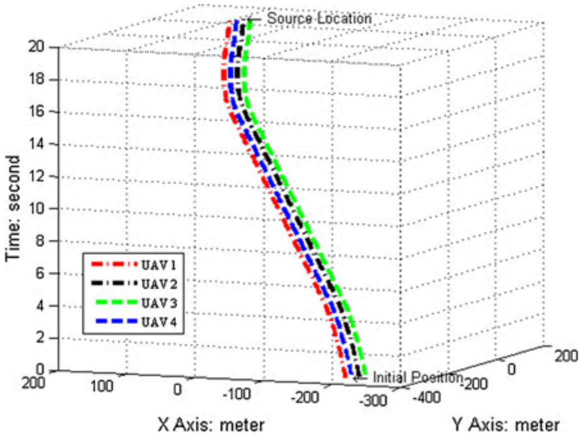

Fig. 6 3D plot of 4 UAV formation for source seeking when k is 80

From Fig. 6, it can be seen that, the 4 UAV formation locates the radiative signal source after 20 s.

3 Contour Mapping Scenario

3.1 Stationary Source Contour Mapping

In this scenario, the controller introduced in [23] is modified for contour mapping of specified radiative signal field. The modified controller could detect the gradient level of the radiative source, and when the 4 UAV formation reaches the desired radiative level, the direction of the formation will be rotated to the orthogonal direction. Consequently, the 4 UAV formation is able to track the specified radiative signal level, and achieves the contour mapping. The radiation level at the center of the N UAV formation is denoted as $D_{\text{mean}}(x, y)$, which is calculated by Eq. 6,

$$D_{\text{mean}}(x, y) = \frac{\sum_{i=1}^{N} D_i(x, y)}{N}, \quad N \geq 3. \tag{6}$$

The radiative signal level $D_s(x, y)$ could be pre-specified in the modified controller before executing the contour mapping, and when $D_s(x, y) \geq$

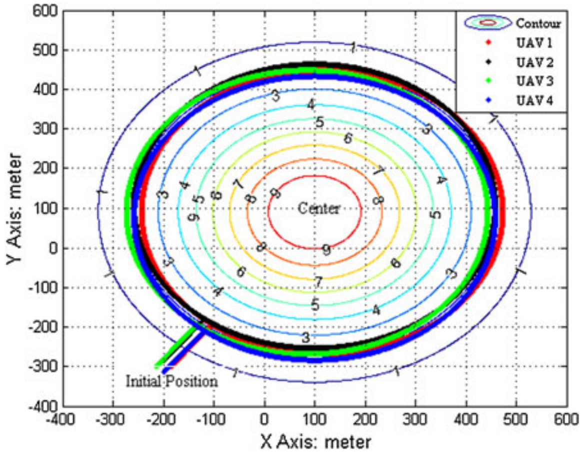

Fig. 7 4 UAV formation for contour mapping of specified radiative level

$D_{\text{mean}}(x, y)$, the formation will rotate the flight heading to the orthogonal direction with process shown in Eq. 7

$$u = \left(\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} u^{\mathrm{T}} \right)^{\mathrm{T}} . \tag{7}$$

u is already defined in Eq. 5, and u^{T} is the transpose of u. In the simulation for this scenario, the center of the 4 UAV formation is also set at (−200 m, −300 m) initially, the $D_s(x, y)$ is pre-specified to level 2, and $k = 30$. The contour mapping progress is shown in Fig. 7.

The results show that, the radiative signal with pre-specified level 2 is tracked properly by the stabilized 4 UAV formation, and the contour mapping is realized successfully.

In more realistic situation, there is some noise for the sensors installed on every UAV which are used to detect the radiation level. Therefore, a Gaussian noise is added for each sensor which is set as $\frac{1\ \text{dBW}}{9}$ in the simulation, and the process is shown in Fig. 8.

3.2 Moving Source Contour Mapping

The model for the moving source is assumed as

$$\begin{cases} x_s = 100 - 0.8t, \\ y_s = 90 - 0.6t, \end{cases} \tag{8}$$

where (x_s, y_s) is the position of the source related with both initial position (100 m, 90 m) and t, t is the simulation time which is set to 980 s in this simulation, and all the other parameters are set the same as stationary source situation. The process of the moving source contour mapping is shown in Fig. 9.

The plotted result shows that the radiative signal source moves from (100 m, 90 m) to (−684 m, −498 m) after 980 s, and the 4 UAV formation properly achieves level 2 contour mapping of the moving radiative signal source during the process.

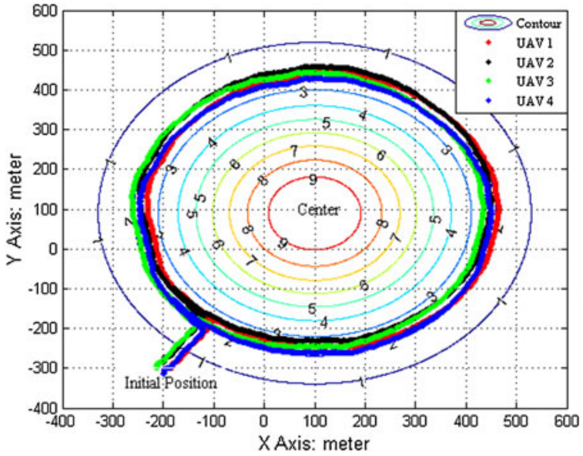

Fig. 8 Contour mapping of specified level with sensor noise

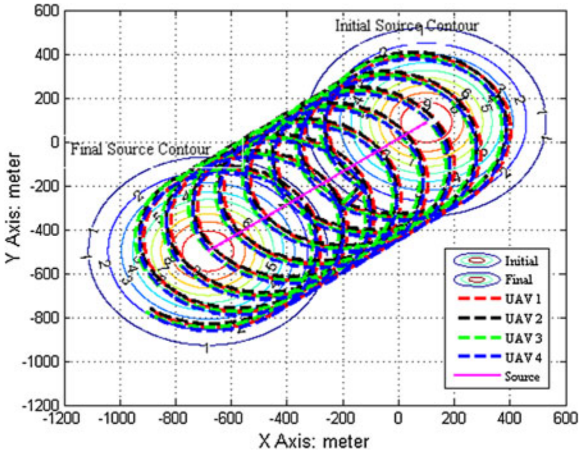

Fig. 9 4 UAV formation for contour mapping of a moving radiative signal field

4 Decentralized Multiple UAV Formation for Radiative Signal Detection

In this scenario, the multiple UAVs (also use 4 UAVs as an example) are steered in decentralized formation to detect the radiative signal field. Each UAV in decentralized formation could share information with other UAVs during flight. Consequently, this greatly enhances the robustness of the formation flight. In case the communication between the ground control station (GCS) and one of the 4 UAVs is in bad status or even totally lost, the 4 UAVs could still stabilize the formation to detect the radiative level along the desired path.

The topology for the decentralized 4 UAV formation is shown in Fig. 10.

A controller used for multi-UAV consensus problem [24] is simplified and then implemented to the model given in Eq. 3 for stabilizing the decentralized formations during the detection. The simplified controller is defined as

$$\begin{cases} v_{xi} = Sat\Big[-l\left(x_i - x_i^d\right) \\ \qquad - \sum_{j=1}^{N} k_{ij}\left[\left(x_i - x_i^d\right) - \left(x_j - x_j^d\right)\right]\Big], \\ v_{yi} = Sat\Big[-l\left(y_i - y_i^d\right) \\ \qquad - \sum_{j=1}^{N} k_{ij}\left[\left(y_i - y_i^d\right) - \left(y_j - y_j^d\right)\right]\Big], \end{cases} \tag{9}$$

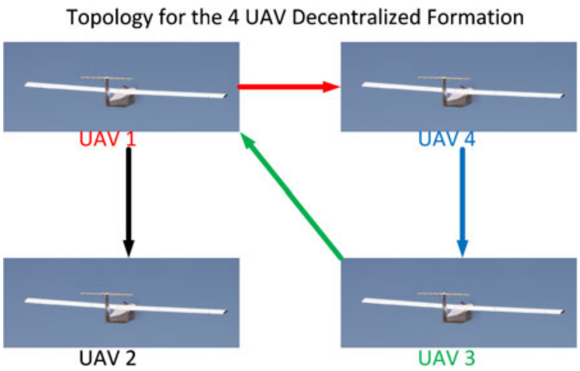

Fig. 10 Topology for 4 UAV (AggieAir) decentralized formation

where Sat[] is the saturation, $l > 0$, (x_i, y_i) is the position of the ith UAV, (x_i^d, y_i^d) is the desired destination of the ith UAV, (x_j, y_j) and (x_j^d, y_j^d) follow the same definitions, and N is the number of UAVs set to 4. $k_{ij} > 0$ if the ith UAV can receive information from the jth UAV, otherwise $k_{ij} = 0$. According to the communication topology demonstrated in Fig. 10, It can be found that only $k_{13} > 0$, $k_{21} > 0$, $k_{34} > 0$, $k_{41} > 0$, all the other k_{ij} are all equal to 0.

This scenario is designed to detect the radiative source level along certain path, like between a certain specified position and the source position. In this scenario, $l = 0.05$, $k_{ij} = 1$ for the k_{ij} which are not 0, the initial position for the center of 4 UAV formation is also set at (−200 m, −300 m), and the source position is still at (100 m, 90 m). In the simulation, the initial positions for UAV 1–UAV 4 are set at (−185 m, −300 m), (−200 m, −285 m), (−215 m, −300 m), (−200 m, −315 m) respectively, and the positions for according destination are set at (115 m, 90 m), (100 m, 105 m), (85 m, 90 m), (100 m, 75 m). The gains l, and k_{ij} should be properly adjusted to achieve a stabilized formation. The detecting process is shown in Fig. 11, which could not be a straight line if the l and k_{ij} are not set within certain range.

The result shows that the formation controller can steer the 4 UAVs from pre-defined positions to approach the destinations with stabilized formation.

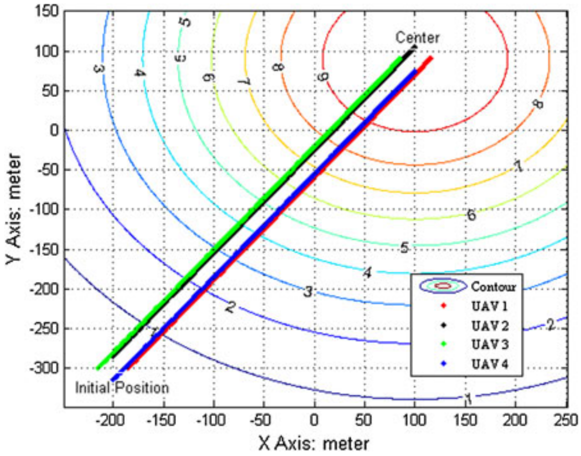

Fig. 11 4 UAV decentralized formation for radiative signal source detection

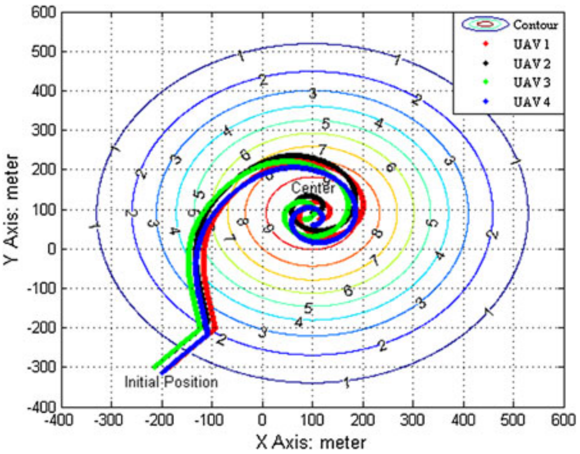

Fig. 12 4 UAV formation for cooperative source seeking and contour mapping

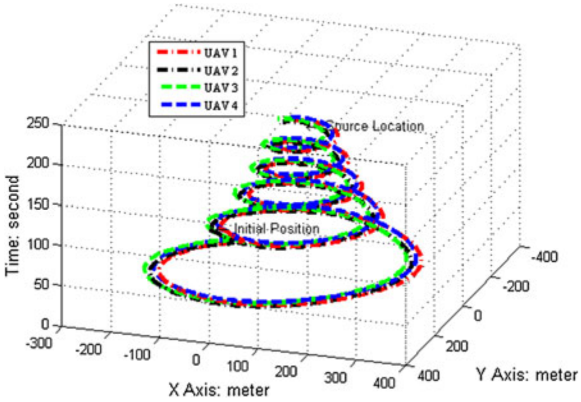

Fig. 14 Cooperative source seeking and contour mapping plot with time

5 Cooperative Contour Mapping of the Radiative Signal Field

In this scenario, the modified contour mapping control strategy in Section 3, and the decentralized formation controller illustrated in Section 4 are combined to steer the 4 UAV formation for cooperative contour mapping of the radiative signal field. The formation controller could guarantee stabilized formation flight while the contour mapping controller could detect the gradient of the radiative signal, and they cooperatively drive the 4 UAV formation to execute contour mapping. After the combination, the 4 UAV formation could accomplish the contour mapping of the radiative signal with decreasing radius circular loop or square loop until the radiative signal source is located and reached.

In the scenario, the specified signal level for contour mapping is still set at 2, which is denoted as $D_s(x, y) = 2$. The initial positions of each UAV, the position of the source, and k, l, k_{ij} are all set to the same parameters as prior scenarios in this paper. Because the physical limitation of fixed wing UAVs, there is a minimum radius for the circling formation flight, so when the 4 UAVs in formation reach the minimum flight radius, they will maintain the circling formation flight with the

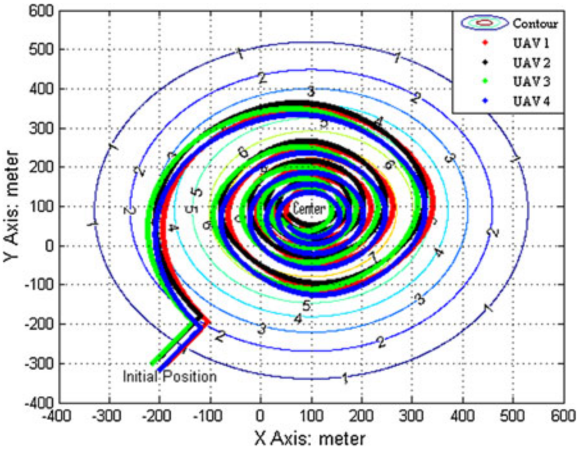

Fig. 13 Cooperative source seeking and contour mapping with $l = 0.01$

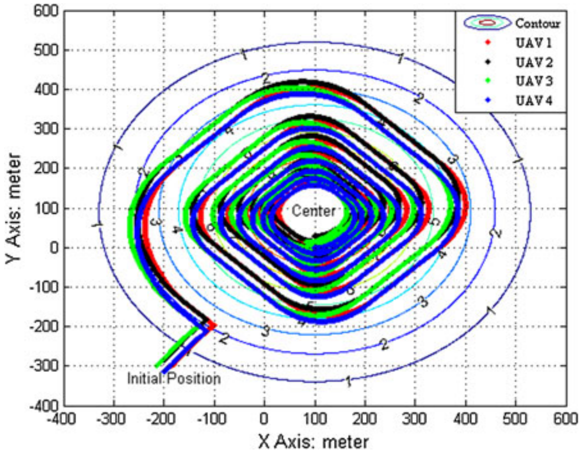

Fig. 15 Cooperative source seeking and contour mapping with $l = 0.01$ and $k = 60$

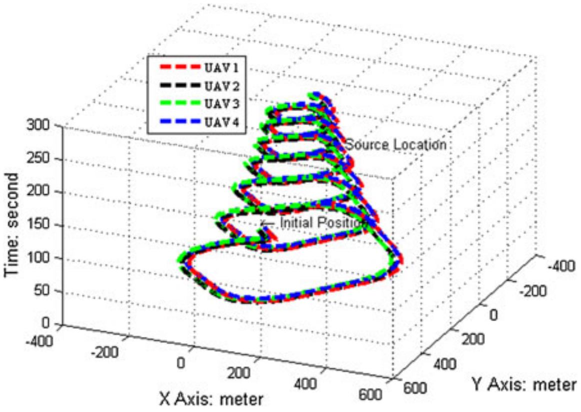

Fig. 16 Cooperative source seeking and contour mapping in square path plot with time

minimum radius for a while. The simulation result is demonstrated in Fig. 12.

l could be adjusted to a smaller parameter if more area of the radiative signal field is required to be covered with more accurate contour mapping provided. For example, if $l = 0.01$ instead of $l = 0.05$, the process is demonstrated in Fig. 13 with more area contour mapping provided.

The actions of the 4 UAV formation with time is demonstrated in Fig. 14.

It is more safe for the multiple UAV formation to fly in square path instead of circular path. Because for the square formation flight path, the multiple UAVs could slightly adjust their positions to keep better formation in the practical situation. While for the circular formation flight path, the UAVs keep turning which is more likely to overshoot, and difficult to keep desired formation. This situation is also considered in this paper, k could be adjusted to a bigger value if an approximate square flight path is needed for contour mapping. For example, if $k = 60$ instead of $k = 30$, the process is demonstrated in Fig. 15. From the shown results, the square formation flight path is executed instead of circular flight path in Fig. 13.

The process of the 4 UAV formation flight in square path with time is shown in Fig. 16.

6 Conclusions

This paper is focused on multiple UAV formations for cooperative source seeking and contour mapping of a radiative signal field. Four scenarios are provided: the first scenario is 4 UAV formation based source seeking and locating with an adopted controller. In second scenario, the controller is modified for contour mapping under stationary signal source and moving signal source conditions. The third scenario is the radiative signal level detection along certain path by 4 UAV decentralized formations. In the last scenario, the two control strategies illustrated in scenario 2 and 3 are combined to cooperatively control the multiple UAV formation for source seeking and contour mapping by flying in a decreasing radius circular or square loop. Those scenarios are simulated by considering practical flight situations, and verified by the simulation results.

Implementing the controllers in this paper to practical flight is the future work.

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