Chapter 1
Multi-objective Dynamic Optimization Scheme for Unmanned Aerial Vehicles

Bao-Qiang Zhuang and Ya-Jun Wang

Abstract In this paper, we analyzed the effective location of unmanned aerial vehicle (UAV) transmitting signal and the position adjustment of UAV in different formation, and established the mathematical model of multi-objective dynamic programming under the shortest path. The corresponding model is solved by using optimization algorithm and simulated annealing algorithm. The precise azimuth of a passive UAV is calculated from known polar coordinates and angles. Based on the three-target bearings-only triangulation method, the target triangle is obtained and the UAV position is determined by heart. The UAV with better position on the circumference is selected as the launch source.

1.1 Introduction

When the UAV is flying in formation, it is necessary to keep electromagnetic silence to prevent external interference, to reduce the electromagnetic wave signal sent out, and to avoid causing sparse sensor nodes and uneven distribution of anchor nodes [1]. Aiming at the problem of low localization rate and large localization error caused by the random distribution of anchor nodes, Huang [2] proposed a wireless transmission and localization algorithm based on the connectivity of anchor nodes. MDS-MAP algorithm [3] is used to reduce the positioning error. So it is common to adjust the UAV's position, maintain formation based on bearings-only passive positioning. The formation of UAV has a fixed number, and other UAVs relative position does not change. Chen et al. [4] divided the network into many hexagons and proposed a path planning algorithm for auxiliary beacon nodes, which reduced the location time and the average location error. Wang et al. [5] proposed a static anchor node

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R. Kountchev et al. (eds.), *Proceedings of International Conference on Artificial Intelligence and Communication Technologies (ICAICT 2023)*, Smart Innovation, Systems and Technologies 368, https://doi.org/10.1007/978-981-99-6641-7_1

layout optimization method based on geometric precision and degree factor, but the positioning precision is constrained by the size of anchor nodes and the geometric area of points. Huang et al. [6] proposed a breadth-first search (BFS) algorithm to select virtual anchor nodes, reducing the number of virtual anchor nodes and the length of the moving path of the nodes. Cheng et al. [7] proposed to use the grid method to model the known land, map, introduce vectors to guide the path direction in the algorithm, through multiple rewards and punishment measures to carry out the path planning. The angle between the receiving UAV and any two transmitting UAV is direction information.

A common model is exhibited in Fig. 1.1: FY01, FY02, and FY03 send signals, FY04 receives the signal angle θ_1, θ_2, and θ_3. In Fig. 1.1, FY00 is a signal transmitter under the same height circle formation, and it transmits signal through the two UAVs in the formation and the UAV in the center of the circle. For the model in Fig. 1.1, we established the location model to receiving UAV, and studied the minimum number of UAV transmitting signals to ensure the precise UAV location in Sect. 1.2. Meanwhile, we designed UAV position adjustment program by the initial data in Fig. 1.2. In Sect. 1.2, we also discussed corresponding UAV position adjustment scheme in a cone bearing-only formation (Fig. 1.3).

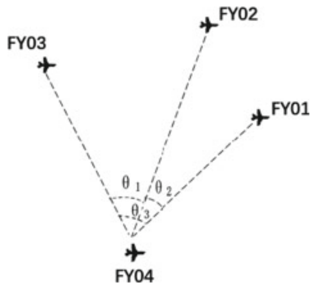


Fig. 1.1 Direction information of UAVs

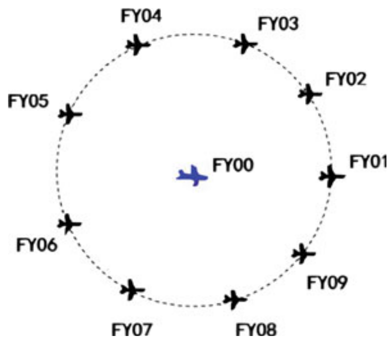


Fig. 1.2 Sketch of the formation of the circular UAVs

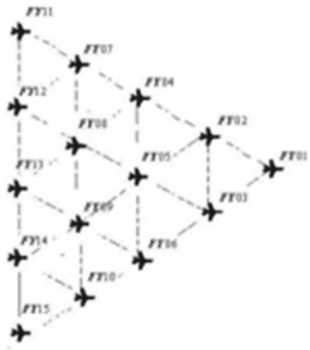


Fig. 1.3 Cone-shaped formation of UVAs

1.2 Analysis of UAV Position

1.2.1 Triangulation Method on UAV Positioning

The triangulation [8] method can detect the target position in different directions based on two or more UAVs, and can locate the target UAV position using the principle of plane triangle geometry. When the UAV transmits or receives a signal passively, its azimuth is the core parameter in target locating. The location model of passive received signal is established in this part. The azimuth angle of UAV can locate the target UAV, so that the target UAV can be located effectively. The position of the UAV is presented in Fig. 1.4.

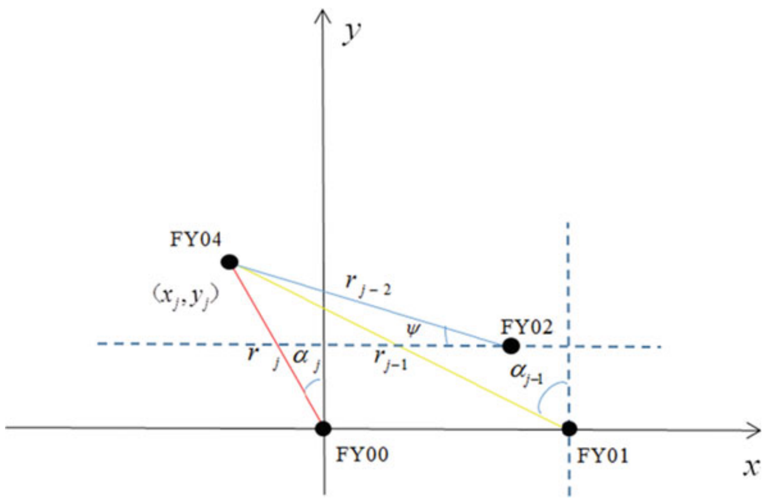


Fig. 1.4 Position of UAVs

Firstly, for special cases, we select special points FY01 and FY02 to send signals to FY04 to get the distance and angle, then establish the equation through the distance and angle, which can locate the position of FY04 effectively. From the position relation of the four UAVs in Fig. 1.4, we obtained:

$$\tan\alpha_j = \frac{x_j}{y_j} \tag{1.1}$$

$$\tan\alpha_{j-1} = \frac{r_j(\sin\alpha_j + 1)}{r_{j-1}\cos\alpha_{j-1}} \tag{1.2}$$

$$\begin{cases} x_{\mathrm{FY02}} = r_{j-2}\cos\psi - r_j\sin\alpha_j \\ y_{\mathrm{FY02}} = r_j\cos\alpha_j - r_{j-2}\sin\psi \end{cases} \tag{1.3}$$

Combining (1.1) to (1.3), three position relation equations of UAV can be obtained:

$$\begin{cases} x_1 = r_1\sin\alpha_1 \\ y_1 = \frac{r_0^2\sin 2\alpha_0}{2r_1(\sin\alpha_1+1)} \end{cases} \tag{1.4}$$

$$\begin{cases} x_2 = r_2\sin\alpha_2 \\ y_2 = \frac{r_1^2\sin 2\alpha_1}{2r_2(\sin\alpha_2+1)} \end{cases} \tag{1.5}$$

$$\begin{cases} x_3 = r_3\sin\alpha_3 \\ y_3 = \frac{r_2^2\sin 2\alpha_2}{2r_3(\sin\alpha_3+1)} \end{cases} \tag{1.6}$$

$\alpha_j (j = 1, 2, 3)$ is the azimuth angle of the target position (x_j, y_j), where the azimuth angle rotates clockwise from the positive half axis of the y axis, and the range is $[0, 2\pi]$.

1.2.2 Three-Target Bearings-Only Triangulation on UAV Positioning

Three-target bearings-only triangulation are a method of transmitting signals from UAV at different positions to the same target. If the UAV position is unbiased, three azimuth lines intersect at one point, the position coordinates of the passive receiving UAV can be obtained. However, the UAV is affected by the noise in the atmosphere caused by an electromagnetic wave signal it sends. So there are some position deviations in the actual circumstances, causing that three lines cannot meet at a point, but form a target triangle.

In Fig. 1.5, the selecting UAVs randomly FY0M, FY0N, and FY00 send signals to FY0K at the same time. After the target triangle is determined, we determine the

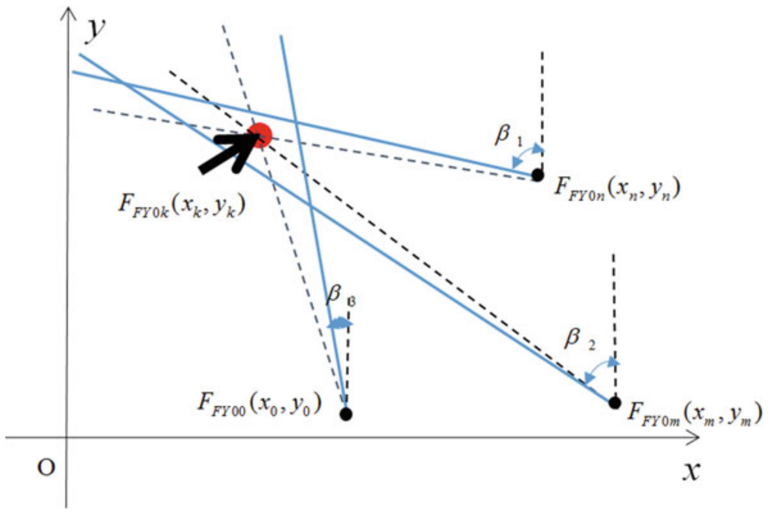
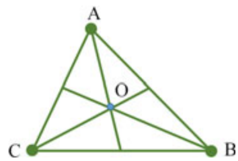


Fig. 1.5 Three-target cross-localization of geometric sketch

Fig. 1.6 Triangle heart with angle bisector



position of the UAV (Fig. 1.6) using the center method, where we take the intersection of the triangle's three bisectors as the target point.

As shown in Cartesian coordinate system in Fig. 1.6, we assume that the three transmitting targets are $F_{nm}(x_{nm}, y_{nm})$, $F_{n0}(x_{n0}, y_{n0})$, and $F_{m0}(x_{m0}, y_{m0})$, and the passive receiving target is FY0k(x_0, y_0). In this situation, the angles between receiving target and three transmitting targets are β_1,β_2, and β_3, respectively. According to the method of double-target triangulation, the intersection coordinates (x_{nm}, y_{nm}) of FY0n and FY0m are:

$$\begin{cases} x_{nm} = \frac{x_m \sin\beta_n \cos\beta_m - x_n \cos\beta_n \sin\beta_m + (y_n - y_m)\sin\beta_n \cos\beta_m}{\sin(\beta_n - \beta_m)} \\ y_{nm} = \frac{y_n \sin\beta_n \cos\beta_m - y_m \cos\beta_n \sin\beta_m + (x_m - x_n)\sin\beta_n \cos\beta_m}{\sin(\beta_n - \beta_m)} \end{cases} \tag{1.7}$$

The intersection coordinates (x_{n0}, y_{n0}) of FY0n and FY00 are:

$$\begin{cases} x_{n0} = \frac{x_0 \sin\beta_n \cos\beta_0 - x_n \cos\beta_n \sin\beta_0 + (y_n - y_0)\sin\beta_n \cos\beta_0}{\sin(\beta_n - \beta_m)} \\ y_{n0} = \frac{y_n \sin\beta_n \cos\beta_0 - y_0 \cos\beta_n \sin\beta_0 + (x_0 - x_n)\sin\beta_n \cos\beta_0}{\sin(\beta_n - \beta_0)} \end{cases} \tag{1.8}$$

The intersection coordinates (x_{m0}, y_{m0}) of FY0m and FY00 are:

$$\begin{cases} x_{m0} = \frac{x_m \sin\beta_m \cos\beta_0 - x_0 \cos\beta_m \sin\beta_0 + (y_m - y_0)\sin\beta_m \cos\beta_0}{\sin(\beta_\mathrm{n} - \beta_\mathrm{m})} \\ y_{m0} = \frac{y_0 \sin\beta_m \cos\beta_0 - y_m \cos\beta_m \sin\beta_0 + (x_0 - x_m)\sin\beta_m \cos\beta_0}{\sin(\beta_m - \beta_0)} \end{cases} \tag{1.9}$$

The vertex coordinates of the target triangle can be determined by (1.10). The inner coordinates of the triangle are

$$x_{is} = \frac{Ax_{nm} + Bx_{n0} + Cx_{m0}}{A + B + C} \tag{1.10}$$

$$y_{is} = \frac{Ay_{nm} + By_{n0} + Cy_{m0}}{A + B + C} \tag{1.11}$$

The length of the triangles is

$$\begin{aligned} l_1 &= \sqrt{(x_{n0} - x_{m0})^2 + (y_{n0} - y_{m0})^2} \\ l_2 &= \sqrt{(x_{nm} - x_{m0})^2 + (y_{nm} - y_{m0})^2} \\ l_3 &= \sqrt{(x_{nm} - x_{n0})^2 + (y_{nm} - y_{n0})^2} \end{aligned} \tag{1.12}$$

In conclusion, we discussed the situation of UAV transmitting and receiving signals under special circumstances, and we calculated the precise positioning of UAV by establishing polar coordinate equations. Due to the existence of errors, the azimuth lines form a target triangle, and the intersection points formed by the two azimuth lines of the UAV are calculated, finally, the intersection point formed by the triangle bisector of the target is obtained, which is the precise positioning of the UAV.

1.3 The Establishment and Solution of Model

Assuming that FY00 and FY01 send a signal to a misplaced UAV (x_u, y_u), the angle is β_u, we establish the model equations:

$$\begin{cases} x_{01} = \frac{x_1 \sin\beta_0 \cos\beta_1 - x_0 \cos\beta_0 \sin\beta_1 + (y_0 - y_1)\sin\beta_0 \cos\beta_1}{\sin(\beta_0 - \beta_1)} \\ y_{01} = \frac{y_0 \sin\beta_0 \cos\beta_1 - y_1 \cos\beta_0 \sin\beta_1 + (x_1 - x_0)\sin\beta_0 \cos\beta_1}{\sin(\beta_0 - \beta_1)} \end{cases}$$
$$\begin{cases} x_{0u} = \frac{x_u \sin\beta_0 \cos\beta_u - x_0 \cos\beta_0 \sin\beta_u + (y_0 - y_u)\sin\beta_0 \cos\beta_u}{\sin(\beta_0 - \beta_1)} \\ y_{0u} = \frac{y_0 \sin\beta_0 \cos\beta_u - y_u \cos\beta_0 \sin\beta_u + (x_u - x_0)\sin\beta_0 \cos\beta_u}{\sin(\beta_0 - \beta_u)} \end{cases}$$
$$\begin{cases} x_{1u} = \frac{x_u \sin\beta_1 \cos\beta_u - x_1 \cos\beta_u \sin\beta_1 + (y_1 - y_u)\sin\beta_1 \cos\beta_u}{\sin(\beta_0 - \beta_1)} \\ y_{1u} = \frac{y_1 \sin\beta_1 \cos\beta_u - y_u \cos\beta_1 \sin\beta_u + (x_u - x_1)\sin\beta_1 \cos\beta_u}{\sin(\beta_1 - \beta_u)} \end{cases} \tag{1.13}$$

$$\begin{cases} x_{01} = x_{0u} = x_{1u} \\ y_{01} = y_{0u} = y_{1u} \end{cases}$$

To solve the equations, we analyze coefficient matrix

$$A = \begin{bmatrix} \frac{\sin\beta_0\cos\beta_u}{\sin(\beta_0-\beta_1)} & \frac{-\sin\beta_0\cos\beta_u}{\sin(\beta_0-\beta_1)} \\ \frac{-\cos\beta_u\sin\beta_1}{\sin(\beta_0-\beta_1)} & \frac{-\sin\beta_1\cos\beta_u}{\sin(\beta_0-\beta_1)} \end{bmatrix}$$

The matrix determinant $|A| \neq 0$. If the solution of linear equations exists, the UAV can locate target UAV effectively. According to the law of exhaustion, we suppose that there are two position deviations of UAVs in transmitting signal, so the position deviation subjected to the same point of constraint:

$$\text{s.t.}\begin{cases} x_{01} = x_{0u1} = x_{1u1} = x_{0u2} = x_{1u2} \\ y_{01} = y_{0u1} = y_{1u1} = y_{0u2} = y_{1u2} \end{cases} \tag{1.14}$$

We obtained a nonlinear equation describing the position relationship between UAVs:

$$\begin{cases} x_{01} = \frac{x_1\sin\beta_0\cos\beta_1 - x_0\cos\beta_0\sin\beta_1 + (y_0-y_1)\sin\beta_0\cos\beta_1}{\sin(\beta_0-\beta_1)} \\ y_{01} = \frac{y_0\sin\beta_0\cos\beta_1 - y_1\cos\beta_0\sin\beta_1 + (x_1-x_0)\sin\beta_0\cos\beta_1}{\sin(\beta_0-\beta_1)} \end{cases}$$
$$\begin{cases} x_{0\mathrm{u}1} = \frac{x_{u1}\sin\beta_0\cos\beta_{u1} - x_0\cos\beta_0\sin\beta_{u1} + (y_0-y_{u1})\sin\beta_0\cos\beta_{u1}}{\sin(\beta_0-\beta_1)} \\ y_{0u1} = \frac{y_0\sin\beta_0\cos\beta_{u1} - y_{u1}\cos\beta_0\sin\beta_{u1} + (x_{u1}-x_0)\sin\beta_0\cos\beta_{u1}}{\sin(\beta_0-\beta_{u1})} \end{cases}$$
$$\begin{cases} x_{1u1} = \frac{x_{u1}\sin\beta_1\cos\beta_{u1} - x_1\cos\beta_{u1}\sin\beta_1 + (y_1-y_{u1})\sin\beta_1\cos\beta_{u1}}{\sin(\beta_0-\beta_1)} \\ y_{1u1} = \frac{y_1\sin\beta_1\cos\beta_{u1} - y_{u1}\cos\beta_{u1}\sin\beta_1 + (x_{u1}-x_1)\sin\beta_1\cos\beta_{u1}}{\sin(\beta_1-\beta_{u1})} \end{cases}$$
$$\begin{cases} x_{0u2} = \frac{x_{u2}\sin\beta_0\cos\beta_{u2} - x_0\cos\beta_0\sin\beta_{u2} + (y_0-y_{u2})\sin\beta_0\cos\beta_{u2}}{\sin(\beta_0-\beta_1)} \\ y_{0u2} = \frac{y_0\sin\beta_0\cos\beta_{u2} - y_{u2}\cos\beta_0\sin\beta_{u2} + (x_{u2}-x_0)\sin\beta_0\cos\beta_{u2}}{\sin(\beta_0-\beta_{u2})} \end{cases}$$
$$\begin{cases} x_{1u2} = \frac{x_{u2}\sin\beta_1\cos\beta_{u2} - x_1\cos\beta_{u2}\sin\beta_1 + (y_1-y_{u2})\sin\beta_1\cos\beta_{u2}}{\sin(\beta_0-\beta_1)} \\ y_{1u2} = \frac{y_1\sin\beta_1\cos\beta_{u2} - y_{u2}\cos\beta_{u2}\sin\beta_1 + (x_{u2}-x_1)\sin\beta_1\cos\beta_{u2}}{\sin(\beta_1-\beta_{u2})} \end{cases} \tag{1.15}$$

In transmitting electromagnetic wave signal, we established linear equations matrix based on (1.15) between the UAVs

$$B = \begin{bmatrix} \frac{\sin\beta_0\cos\beta_{u1}}{\sin(\beta_0-\beta_1)} & \frac{-\sin\beta_0\cos\beta_{u1}}{\sin(\beta_0-\beta_1)} & \frac{-\sin\beta_{u1}\cos\beta_{u2}}{\sin(\beta_0-\beta_1)} \\ \frac{-\cos\beta_{u1}\sin\beta_1}{\sin(\beta_0-\beta_1)} & \frac{-\sin\beta_1\cos\beta_{u1}}{\sin(\beta_0-\beta_1)} & \frac{\sin\beta_{u2}\cos\beta_{u1}}{\sin(\beta_0-\beta_1)} \\ \frac{\sin\beta_0\cos\beta_{u2}}{\sin(\beta_0-\beta_1)} & \frac{-\sin\beta_0\cos\beta_{u2}}{\sin(\beta_0-\beta_1)} & \frac{-\sin\beta_{u2}\cos\beta_{u1}}{\sin(\beta_0-\beta_1)} \\ \frac{-\cos\beta_{u2}\sin\beta_1}{\sin(\beta_0-\beta_1)} & \frac{-\sin\beta_1\cos\beta_{u2}}{\sin(\beta_0-\beta_1)} & \frac{\sin\beta_{u1}\cos\beta_{u2}}{\sin(\beta_0-\beta_1)} \end{bmatrix}$$

The matrix determinant $|B| \neq 0$ implies that (1.15) are linear equations, and the coordinates of the targets can be obtained. It can be concluded that the two UAVs can be used as the signal transmitter to locate other UAVs effectively. Given the initial position parameters of UAV, we can solve the linear equations of system to get the accurate positioning of UAV by MATLAB. The function code is $x = f\text{solve}(\text{fun}, x0)$, where fun equation to be solved, $x0$ is the initial value of calculation and x is the solution.

1.3.1 Multi-objective Dynamic Scheduling Model

In multi-objective dynamic scheduling model, we take the times of unmanned scheduling and the shortest distance from the received signal UAV to the ideal position as the optimization objectives, and establish the multi-objective UAV scheduling optimization model.

Objective Function

In each UAV adjustment scheme, we set the objective function according to the optimal objective with the minimum distance between the adjusted UAV and the ideal position:

$$\min z = \min N_i^{(k)} \times S^{(k)} \tag{1.16}$$

where $N_i^{(k)}$ is the number of scheduled UAVs and $S^{(k)}$ is the scheduling distance.

Constraint Conditions

1. Each UAV receives a signal in a dispatch only

$$\sum_{i=1}^{9} N_{ni} = 1 \tag{1.17}$$

2. After receiving the signal, each UAV changes position to schedule

$$f_i^{(k+1)} = f_i^{(k)} + x_i^{(k)}(1 - f_i^{(k)}) \tag{1.18}$$

3. The dispatching distance of UAV cannot exceed its next dispatching distance

$$\sum_{k=1}^{k} \sum_{i=1}^{9} x_i^{(k)}(s_{\mathrm{i}}^{(k)} + s_{\mathrm{Ti}}^{(k)} \times f_i^{(k)}) \leq 9 \times S_T \tag{1.19}$$

4. The $k + 1$th scheduling point $p^{(k+1)}$ is the end of kth scheduling point $q^{(\mathrm{k})}$

$$q^{(k)} = p^{(k+1)} \tag{1.20}$$

5. The number of UAVs on the circle increased by 1

$$N_{ni}^{(k+1)} = N_{ni}^{(k)} + \sum_{i=1}^{9}\left(f_i^{(k)} + x_i^{(k)}\right) \tag{1.21}$$

6. Before the first dispatch, there is one UAVs on circle

$$N_{n0} = 1 \tag{1.22}$$

Therefore, we established the scheduling model of UAVs based on the shortest deviation angle from the ideal distance

$$\min z = \min N_i^{(k)} \times S^{(k)}$$

$$\text{s.t.}\begin{cases} k = 1, 2, 3 \ldots, i = 1, 2, \ldots 9 \\ \max(N_m^{(k)}, T_i^{(k)}) = \min T_i^{(k)} \\ \sum_{i=1}^{9} N_{ni} = 1 \\ f_i^{(k+1)} = f_i^{(k)} + x_i^{(k)}(1 - f_i^{(k)}) \\ \sum_{k=1}^{k}\sum_{i=1}^{9} x_i^{(k)}(s_{\mathrm{i}}^{(k)} + s_{\mathrm{Ti}}^{(k)} \times f_i^{(k)}) \le 9 \times S_T \\ q^{(\mathrm{k})} = p^{(\mathrm{k+1})} \\ N_{ni}^{(k+1)} = N_{ni}^{(k)} + \sum_{i=1}^{9}(f_i^{(k)} + x_i^{(k)}) \\ N_{n0} = 1 \end{cases} \tag{1.23}$$

1.3.2 The Solution of Model

Considering the angle of the UAV to reach ideal position, we obtained the heuristic information of the distance of UAV to reach the ideal position, and designed the objective function of the deviation angle

$$S^{(k)} = \min(s_{p(k)q(k)}^{(k)} + s_i^{(k)} N_i^{(k)}) \tag{1.24}$$

In the dynamic optimization model of UAV formation, we establish the model taking optimal flying angle as the objective function.

(1) The UAV has completed the scheduled tasks

For the scheduled UAVs, taking the optimal deviation angle as the objective function, we establish the model:

$$\theta_1 = \min \sum_{m=1}^{M} \sum_{k=1}^{V} \sum_{z=1}^{i} F_{mk} Y_{kz} d_z \tag{1.25}$$

F_{mk} is the number of UAVs, Y_{kz} is the size of the circle, and d_z is the distance between adjacent UAVs.

(2) The UAVs have not completed scheduled tasks

If the UAV has not received the signal or moved to the target position, we take optimal flying angle as objective function, and the shortest flying distance as the constraint condition:

$$\theta_2 = \sum_{m=1}^{\mathrm{m}} \sum_{k=0}^{\mathrm{I}_{mk}} \sum_{z=0}^{\mathrm{I}_{mk}} F_{mk} Y_{kz} d_z L_{mk} + \sum_{n=1}^{M} \left(\sum_{k=l_{mk}}^{V} \sum_{z=l_{mn}}^{V} F_{mk} Y_{kz} d_z l_{mk} + d_m l_m \right) \tag{1.26}$$

where θ_1 is the angle that drone approaches the target and θ_2 is the angle which the drone approaches the target:

$$\theta = \theta_1 + \theta_2 \tag{1.27}$$

We take (1.26) pluses (1.27) as the function of the optimal flying angle in dynamic scheduling optimization model:

$$\text{s.t.} \sum_{k=0,z=0}^{V} \sum_{k \neq z}^{V} P_{mk} O_{mk} d_z \leq \theta \tag{1.28}$$

In this case, the objective function is a dynamic optimization model, so we can solve the model of adjustment scheme for UAV with step acceleration method. First, we select the UAVs in good position except FY00 and FY01 as the launch source according to the initial data, then use the signals from UAVs to determine the locations of other UAVs. The positions of UVAs are adjusted according to the position information obtained. After an adjustment of position, we compare the positions of the seven UAVs other than FY00 and FY01, and select the UAVs with better positions as the launch source again. Repeating the above steps, if the final distribution of the UAVs has no deviation, all UAVs on the circle move to the exact position.

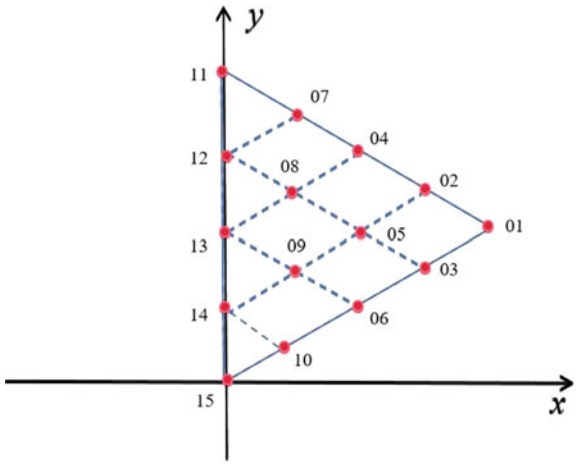


Fig. 1.7 Distribution of tapered formation UAVs at the same height

The UAVs Reach the Same Height

The distribution of tapered formation UAVs at the same height is shown in Fig. 1.7.

The coordinates of UAV can be calculated combining (7)

$$P_{\mathrm{FY0p}}\left(\frac{x_a+x_b+x_c}{3},\frac{y_a+y_b+y_c}{3},\frac{z_a+z_b+z_c}{3}\right)$$

where

$$\begin{aligned}
x_{\mathrm{FY0p}} &= \frac{x_b\sin\beta_a\cos\beta_b - x_a\cos\beta_a\sin\beta_b + (y_a-y_b)\sin\beta_a\cos\beta_b}{3\sin(\beta_a-\beta_b)} \\
&\quad + \frac{x_c\sin\beta_a\cos\beta_c - x_a\cos\beta_a\sin\beta_c + (y_a-y_c)\sin\beta_a\cos\beta_c}{3\sin(\beta_a-\beta_b)} \\
&\quad + \frac{x_b\sin\beta_b\cos\beta_c - x_c\cos\beta_b\sin\beta_c + (y_b-y_c)\sin\beta_b\cos\beta_c}{3\sin(\beta_a-\beta_b)} \\
y_{\mathrm{FY0p}} &= \frac{y_a\sin\beta_a\cos\beta_b - y_b\cos\beta_a\sin\beta_b + (x_b-x_a)\sin\beta_a\cos\beta_b}{3\sin(\beta_a-\beta_b)} \\
&\quad + \frac{y_a\sin\beta_a\cos\beta_c - y_c\cos\beta_a\sin\beta_a + (x_c-x_a)\sin\beta_a\cos\beta_c}{3\sin(\beta_a-\beta_c)} \\
&\quad + \frac{y_c\sin\beta_b\cos\beta_c - y_b\cos\beta_b\sin\beta_c + (x_c-x_b)\sin\beta_b\cos\beta_c}{3\sin(\beta_b-\beta_c)} \\
\mathrm{z}_{\mathrm{FY0p}} &= H
\end{aligned} \tag{1.29}$$

$P_{\mathrm{FY0k_1}}$ is close to P_{FY0p}, and the coordinates of $P_{\mathrm{FY0k_1}}$,$P_{\mathrm{FY0k_2}}$, $P_{\mathrm{FY0k_3}}$ are (x_1, y_1, z_1),(x_2, y_2, z_2), (x_3, y_3, z_3), in which $Z_1 = Z_2 = Z_3 = H$. If

$P_{\mathrm{FY0k_1}}$,$P_{\mathrm{FY0k_2}}$,$P_{\mathrm{FY0k_3}}$ are non-collinear, we can determine the position of plane, otherwise we search the UAV position coordinates, and find the non-collinear points.

UAVs Are Flying at Different Height

When the formation UAVs are flying at different altitudes, we adopt the multi-target dynamic scheduling model, and calculate the stochastic reconfiguration optimization combining the simulated annealing algorithm [9]. According to the simulated annealing algorithm, when the annealing temperature is high and the annealing temperature drop is slow sufficiently, the solution of system converges to the global optimal solution. The steps of simulated annealing algorithm are as follows.

Step 1. Initial Solution

We choose random initial solution x_0 to generate the iterative algorithm at the initial simulated annealing temperature T_k $(k = 0)$.

Step 2. The Objective Function

When the temperature fluctuates around T_k, we continue the following operation until T_k reaches a stable equilibrium state. The difference of the solution $\left|f(x) - f(x')\right| = \Delta f$ is solved. If $\triangle < 0$, x' is feasible, otherwise, x' is accepted according to $\min(1, \exp(-\Delta f / T_k)) > \mathrm{rand}[0, 1]$.

Step 3. Annealing Cooling

We select the annealing coefficient C to annealing cooling. Among them $T_{k+1} = C_{T_k}$,$k = k + 1$,$C \in (0, 1)$, it should be noted that the initial annealing temperature should be high, and annealing temperature drops slow sufficiently.

Step 4. The End of Annealing

We judge that the simulated annealing is finished according to the termination annealing temperature. If the annealing temperature satisfies the convergence condition, the simulated annealing process ends, otherwise, returns to step 2.

The annealing temperature determines the optimal the solution of function, and the system accepts the non-optimal solution through the spatial probability. The simulated annealing algorithm can jump out of the local extremum and converge continuously, then get the global optimal solution. The multi-objective dynamic scheduling model is

$$\begin{cases} f_i^{(k+1)} = f_i^{(k)} + x_i^{(k)}(1 - f_i^{(k)}) \\ \sum_{k=1}^{k} \sum_{i=1}^{15} x_i^{(k)}(s_i^{(k)} + s_i^{(k)} \times f_i^{(k)}) \leq 15S \\ q^{(k)} = p^{(k+1)} \end{cases} \tag{1.30}$$

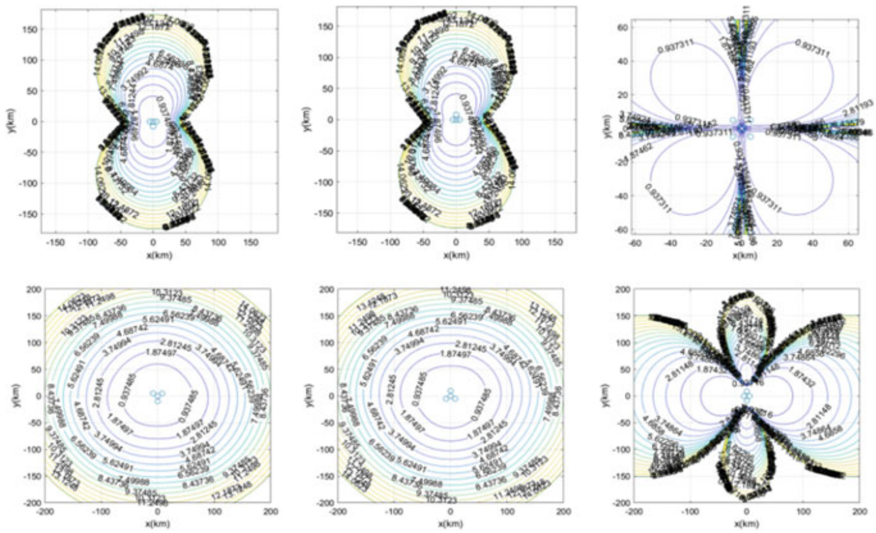


Fig. 1.8 Positioning accuracy under different formation shapes of UVAs

Scheduling Scheme of UAV Formation in Different Shapes

In actual, there are many UAV formations, such as t-type, y-type, diamond-type, and so on. Therefore, many simulation stations are used to simulate, and the positioning accuracy of various stations is compared according to the GDOP. According to the GDOP, the positioning accuracy of *Y* and inverted *Y* formations is higher than other formations. The GDOP of two UAV formations is more uniform than other UAV formations, so it is suitable for large-scale formation of UAVs. At the same time, the formation of the UAV can maintain strong positioning accuracy when it is disturbed by electromagnetic interference.

In Fig. 1.8, we present the comparison of positioning accuracy of bearings-only UAVs with different formation shapes, and give the specific adjustment scheme according to the dynamic scheduling model.

1.4 Conclusions

In this paper, the formation of a cluster of UAVs during formation flying is discussed, and a suitable positioning model is constructed by using multi-objective dynamic programming. Taking the regular and simple circular formation scenario as the starting point, a multi-objective dynamic optimization model based on bearings-only is established on the premise of knowing part of the UAV's position information and number, and the adaptive adjustment scheme in the real scene is discussed.

Acknowledgements This work was supported by the National Natural Science Foundation of China under Grants No. 12105365.

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