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Multi-UAV Cooperative Coverage Path Planning in Plateau and Mountain Environment

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Abstract—**In the environment where the topography of the plateau and mountainous terrain fluctuates, it is necessary to develop an optimal inspection plan when using a group drone to carry out detection and reconnaissance missions in this area. The overall inspection program is divided into two phases: the global optimal route planning, which is based on the parallel search strategy, establishes a nonlinear programming model with the minimum and maximum detection width as the objective function. Then it finds the track and duration of the entire area with a single drone in the least number of turns;In the local planning stage, the search area is divided according to the initial position and endurance of the group drone. An integer programming model is established and the minimum number of drones required is obtained by using a genetic algorithm. A patrol scheme is formulated to complete the continuous inspection task. The final simulation results show that this method of trajectory planning is effective and efficient.**

Keywords—multi-UAV; cooperative coverage path planning; parallel search strategy; nonlinear programming; area segmentation;

I. INTRODUCTION

UAV photogrammetry is more flexible, efficient, and more maneuverable than traditional aerial surveying. In areas where high-resolution remote sensing image data such as high mountains are lacking, it has great application prospect. In particular, the complexity of future battlefields and the multiplicity of operational missions make UAVs increasingly invaluable. Compared with single drone, when faced with a large area search task, multiple UAVs can effectively cover the entire detection area and shorten the time to complete the task. Multiple UAVs has better detection efficiency and greater task fault tolerance than single drone.

Multiple drone collaborative coverage path planning (CPP) can be defined as: Multiple UAVs coordinate each other and treat coverage areas together to traverse, making the overall performance index optimal. This article focuses on the unknown large-area reconnaissance area, and how to effectively allocate and control multiple UAVs to achieve the largest continuous reconnaissance coverage in the region at the lowest cost.

At this stage, extensive research has been carried out on two-dimensional multi-UAV flight path planning both at home and abroad, especially the convex polygon area has achieved fruitful results. Literature [1] proposed a multi-UAV cooperative CPP algorithm based on UAV mission performance evaluation and task area division. Literature [2] uses the wolf population algorithm to plan the unmanned aerial tracks known to the starting point and the end point. The planned track safely avoids the threat. Literature [3] established the mission cost model of UAV mission, and used layered fuzzy reasoning to solve the performance evaluation index of UAV. Based on the performance evaluation index, an area-based region segmentation method was used to achieve the distribution of multi-UAV search mission region. Literature [4] gives an efficient “ point-edge ” width algorithm that can effectively solve the problem of UAV coverage path planning in convex polygonal regions. However, there are relatively few studies on multi-UAV coverage trajectory planning for 3D terrain. Even if the complex region is decomposed into simple basic regions, there is no optimal coverage trajectory in the basic region.

Usually, the solution to multi-UAV cooperative area coverage search problem is divided into two steps: search area segmentation and single-machine coverage path planning. In this paper, we think in reverse. Taking the plateau mountain environment as the background, we first establish a nonlinear programming model based on the parallel search strategy to solve the shortest time and flight path for a single UAV to detect the entire area. Then, the search area is divided according to the initial position and life time of the drone, and a multi-objective integer programming model is established. Finally, the number of drones required for continuous detection and the corresponding inspection plan are solved..

II. THE MAIN RESTRICTIONS

For drones that perform reconnaissance and reconnaissance missions, the main constraints to be considered include terrain restrictions, drone angle restrictions, flight altitude restrictions, maximum viewing angles, effective detection distance limits, and battery life limits.

A. Terrain Restrictions

Since the commonly used digital elevation model DEM is stored in the form of a grid, the actual task space has continuously changing geographical position and height values. In order to simulate the real natural terrain better, when it comes to the height of non-grid points, it needs to be solved by using terrain interpolation. Terrain interpolation needs to take into account both the interpolation accuracy and the interpolation speed. Bilinear interpolation [3] has the advantages of simple structure, small amount of calculation and good interpolation precision, which can meet the requirements of track planning. Bilinear interpolation is a two-dimensional linear interpolation based on the elevation of the four grid points nearest to the given point (x, y). As shown in the figure, assuming that the grid spacing is *d*, and the relative coordinate distance between the node to be solved and the node (x_i, y_j) is $(\Delta x, \Delta y)$. Defining $\tilde{\Delta x} = \Delta x / d$, $\tilde{\Delta y} = \Delta y / d$. Bilinear interpolation equation can be expressed as:

$$g\left(\Delta\tilde{x}, \Delta\tilde{y}\right) = h_{i,j}(\Delta\tilde{x}\Delta\tilde{y} - \Delta\tilde{x} - \Delta\tilde{y} + 1) + h_{i+1,j}(-\Delta\tilde{x}\Delta\tilde{y} + \Delta\tilde{x}) \quad (1)$$
$$+h_{i,j+1}(-\Delta\tilde{x}\Delta\tilde{y} + \Delta\tilde{y}) + h_{i+1,j+1}(\Delta\tilde{x}\Delta\tilde{y})$$

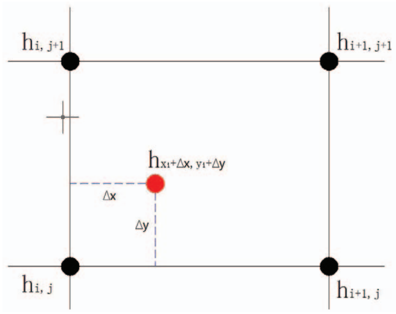

Fig.1. Bilinear interpolation

B. Turning Angle Restriction

Due to the limitations of aircraft maneuverability, especially flying in the plateau and mountainous environment, the UAV's tilt angle needs to be strictly controlled during turning. The maximum climb / fall angle and maximum turning angle need to be considered. The maximum turning angle here can be calculated using the minimum turn Radius equivalent replacement. Drone flight turn radius is not less than r. In the parallel search, the angle of each turn is 180°, so the distance between the two detection routes must be greater than or equal to 2*r*:

$$D_{L_i - L_{i-k}} = kd \geq 2r \quad (2)$$

In the formula, L_i represents each straight-line track and *k* represents the number of grids between two adjacent straight-line routes.

The maximum dive angle of UAV is $\theta_{\max}$:

$$\arctan\left(\frac{|z(i, j+1) - z(i, j)|}{d}\right) \leq \theta_{\max} \quad (3)$$

In the formula, $z(i, j)$ represents the UAV's elevation.

C. Flight Height Limit

UAV must maintain a sufficient safe distance with the ground, in order to effectively reduce the probability of touchdown. At the same time, the detection devices carried by the unmanned aerial vehicles have limited the maximum flight altitude. Once the altitude is exceeded, the accuracy of the detection device can not meet the requirements.

D. Maximum Viewing Angle and Effective Detection of Distance Limitations

Detection range of the detection device is affected by its own performance. The factors that need to be considered are the maximum viewing angle and the effective detection distance.

E. Life Time Limit

Due to the limited load of fuel, drone life is often one of the most important factors to measure its performance. At the same time, due to the impact of maneuverability, a certain amount of time must be allowed between maintenance and maintenance of the UAV performing two tasks. It can prevent malfunctions and accidents. Maximum life time is $t_{\max}$. For each UAV, the flight path should meet:

$$\sum l_i \leq v t_{\max} \quad (4)$$

$$l_i = \sum_{j=0}^{n-1} \sqrt{d^2 + [z(i,j) - z(i,j+1)]^2} \quad (5)$$

In the formula, *v* represents the average speed of the UAV and l_i indicates the distance corresponding to a straight-line course L_i.

III. Search Strategy to Determine

The detection area of the detection device carried by the UAV is shown in the figure. It can assume that the drone always flies parallel to the ground, regardless of changes in attitude angle. The detection range at the detector height *h* from the ground is a circle with radius $R = h \cdot \tan\theta$.

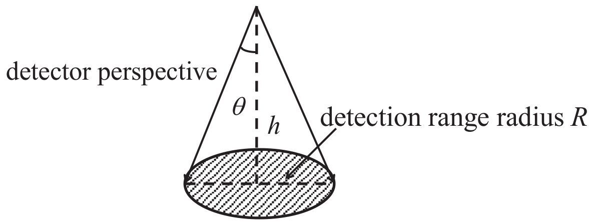

Fig.2. Detection area

It can be seen from the literature that in order to improve the efficiency of reconnaissance and search of a UAV, the reconnaissance and search route of a UAV should be as straight as possible. The cost of its straight-line flight is the minimum, and its fuel consumption is also the lowest. Therefore, the optimized search path should be as few as possible. Based on the above analysis, for the plateau mountainous mission area, the most effective search coverage method is to use the scanning line search method, that is, parallel search.

Using different scanning directions, the number of turns of UAVs in the search area is different. For the polygonal area, when the direction of the scan line is parallel to one side of the polygon, the number of turns in the path covered by the area is the smallest. It has been documented in the literature [4]. As shown in FIG. 3, The number of search turns on the left is obviously less than on the right. So for a rectangle search area, turn is less along the long side.

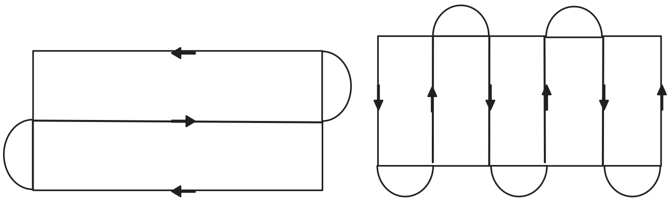

Fig.3. Effect of search direction on search distance

IV. Total Flight Path Analysis

A. Flight Path Rrepresentation

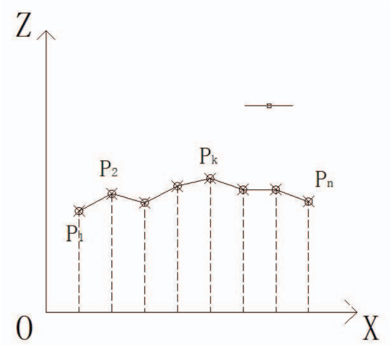

Fig.4. Track cross section

In order to improve the accuracy of the result and to facilitate the solution, it is required that the track point of the UAV is just above the known elevation coordinate point. Because UAVs fly fast, the flight path of each UAV can be regarded as a straight line in every short period of time. Therefore, the trajectory of all UAVs can be considered as the trajectory of the UAV. As shown in FIG. 4. UAV's flight path can be expressed as the time series of track points $\{P_1, P_2, \cdots, P_n; l_i\}$.

B. Detection Range

If you can find each track point perpendicular to the track width of the probe line, then the entire track line detection range is also obtained. Coverage is calculated by projecting the area on the plane. With a vertical plane over a track point to intercept a section, you can get a visual representation of the detection width:

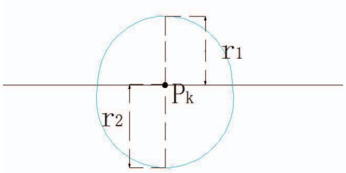

Fig.5. Probe width plan

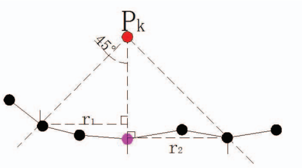

Fig.6. Detection width section

Where, r_1 and r_2 respectively represent, when the UAV at the point p_k, maximum detection width on both sides of the route. The maximum effective detection distance of the detection device is 500m, and the maximum viewing angle is 45 degrees. It can be calculated based on the geometric relationship between the value of r_1 and r_2:

$$r_1 = \frac{d(z(i,j) - \mathrm{h}(i - q_1 - 1, j)) - d(1+q_1)(\mathrm{h}(i-q_1, j) - h(i - q_1 - 1, j))}{d + h(i - q_1 - 1, j) - \mathrm{h}(i - q_1, j)} \tag{6}$$

$$r_2 = \frac{d(z(i,j) - \mathrm{h}(i + q_2 + 1, j)) - d(1+q_2)(\mathrm{h}(i+q_2, j) - h(i + q_2 + 1, j))}{d + h(i + q_2 + 1, j) - \mathrm{h}(i + q_2, j)} \tag{7}$$

In the formula, $q_1 = [r_1 / d]$, $q_2 = [r_2 / d]$, [] indicates rounding to 0.

C. Track Planning

Under constraint conditions, we can find the value of r_1 and r_2 of each straight-line track. We plan for each straight path to make it as large as possible. The mathematical expression is:

$$\begin{cases} \max\{\min(r_1), \min(r_2)\} \\ s.t. g(z) \geq 0 \end{cases} \tag{8}$$

In the formula, $g(z)$ is constraint.

For the grid of $m \times n$, we will find m groups' $L_i = \{P_1, P_2, \cdots, P_n; l_i\}$. On this basis, detection routes are selected. Assuming that the straight line k has been identified, the basic criteria for the selection of the next straight line is:

$$P\left\{\frac{n(r_2^k + r_1^{k+\lambda} \geq \lambda d)}{N}\right\} \geq \xi \tag{9}$$

P is the frequency value in the formula. ξ is the corresponding threshold value. For each straight-line route, the number of the track points is N, which equals to n. $n(r_2^k + r_1^{k+\lambda} \geq \lambda d)$ denotes the number of track points whose sum of detection distances of two track points on the same column is greater than the distance between the routes in the selectable routes L_k and $L_{k+\lambda}$. That is the number of red track points shown in Figure 7:

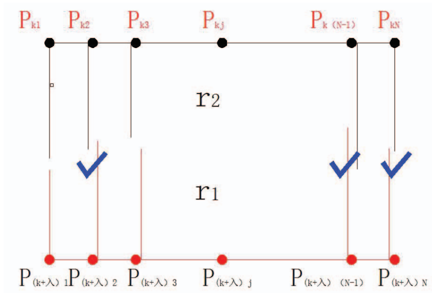

Fig.7. Probe width matching diagram

According to the guidelines, all the straight-line routes are selected. The UAV passes through all the selected routes to complete the entire area exploration. The total area usage time T and the flight path will be find.

V. Determination of Inspection Program

Requiring exploration coverage as much as possible, the development of drone exploration requires continuous 24h. The number of UAV is undetermined. The interval between two inspections is not more than t hours. Based on the parallel search strategy, every t hours, the base needs to provide a certain number of UAVs to the outside world. A certain number of UAVs will return within a certain period of time. Considering that the life of the drone is $t_{\max}$, the entire area is divided into 2h, 3h, 4h, 5h, 6h, 7h,...hrs to consider. In the case of a well-defined area, there will be a fixed number of drones per hour. When the area is divided arbitrarily, the maximum number of unmanned aerial vehicles in the 24-hour period is the minimum number of required drones.

A. Integer Programming

From the foregoing we can see that the time of the total area is T h. According to the initial position of the UAV, the whole area is divided into $t_{\max}-1$ classes. The number of 2h area (referring to the area between 1h and 2h for completing a probe) is x_2 , and the number of 3h area is x_3 ... the number of $t_{\max}$ area is $x_{t_{\max}}$ .For all regions, the following conditions should be fulfilled:

$$\sum_{i=2}^{t_{\max}} i x_i = T \tag{10}$$

In the formula, x_i is integer.

When 24h is divided into 24 segments, UAVs are dispatched from 0h and the same number of UAVs are dispatched every th. So when $t = jh$, the total number of aircraft dispatched is $j\sum_{i=2}^{t_{\max}} x_i$. When the detection is completed, there will be continuously unmanned aircraft to return. When $j \le 8$, there will be some unmanned aerial vehicles need to be trained $g(j)$ h. So when $t = jh$, the number of aircraft out::

$$n_j = \begin{cases} j\sum_{i=2}^{t_{\max}} x_i - \sum_{i=2}^{t_{\max}} (\frac{2j-i}{2}+1)x_i \to j \le t_{\max} \\ (j+g(j))\sum_{i=2}^{t_{\max}} x_i - \sum_{i=2}^{t_{\max}} (\frac{2j-i}{2}+1)x_i \to j > t_{\max} \end{cases} \tag{11}$$

In the formula, $g(j)$ is custom function:

$$g(j) = \begin{cases} 0 & \text{When j is a even number} \\ 1 & \text{When j is an odd number} \end{cases} \tag{12}$$

For each division of the region, there will be a maximum value of n_j . The minimum and maximum values of n_j under any division are obtained. The corresponding regional division is the inspection program that meets the requirements.

$$\begin{cases} \min\{\max(n_j)\} \\ s.t.\sum_{i=2}^{t_{\max}} x_i = T \end{cases} \tag{13}$$

VI. Simulation Analysis

A range of 43.7km × 58.2km mountain elevation data is generated randomly, including a total of 874 × 1165 grid points. The grid spacing is 50m. Drone base coordinate is A (30,0) km. UAV parameters setting are as follows:

TABLE I. Parameter Settings

Average speed	*Maximum battery life*	*Minimum turning radius*	*Climbing angle*	*safe distance*
100km/h	8h	100m	-15°~+15°	50m
Maintenance time during two operations		*Maximum detection distance*	*Maximum perspective*	*Maximum flight altitude*
1h		500m	45°	2000m

A. Flight Altitude Selection and Terrain Interpolation

The maximum effective detection height of the drone relative to the ground is $500/\sqrt{2}$ m. Taking into account the flight altitude limit, fly height correction is performed for data greater than 1950m and greater than $2000-500/\sqrt{2}$ m in 874*1165 data. For the rest of the data, the height of flight adds $500/\sqrt{2}$ m to the original data.

Considering that the maximum angle of climb (subduction) is $\pm 15°$, the vertical turning angle between two adjacent points is calculated by Eq. (3). If the condition is not satisfied, the correction is made by increasing or decreasing the height $z(i, j+1)$ to meet the requirement.

Bilinear interpolation of terrain results is shown as below:

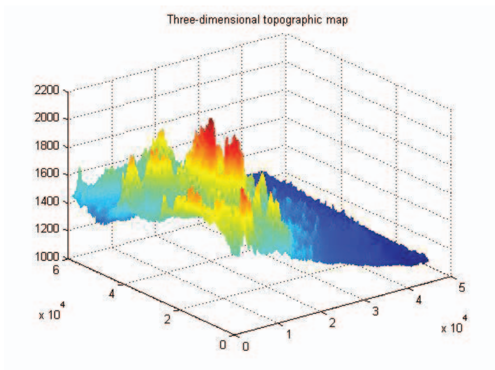

Fig.8. Three-dimensional topographic map

B. Track planning

For the grid, from formula (6) (7), we can get 874 groups of $L_i = \{P_1, P_2, \cdots, P_n ; l_i\}$. Each group contains 1165 track points on both sides of the maximum detection width r_1 and r_2 . On this basis, we can select the exploration routes. The first route is calculated as the third straight line. The next straight line is selected by the formula (9) in the model. After many attempts, the final selection threshold ξ

is 0.8. The number of routes obtained is 71. The total detection time is 43h, and the coverage of the entire area reaches 97.79% (projected to the horizontal plane). The total flight path is shown as below.

C. Integer planning

For the integer programming model (13), the genetic algorithm[7] is used to find the global optimal solution. The population of the genetic algorithm is set to 30. The replication probability is 0.8, and the crossover probability is 0.2. The number of required minimum drones is 21, and the results for the scoring area are as follows:

TABLE II. RESULTS FOR THE SCORING AREA

x_2	x_3	x_4	x_5	x_6	x_7	x_8
1	2	1	2	1	1	1

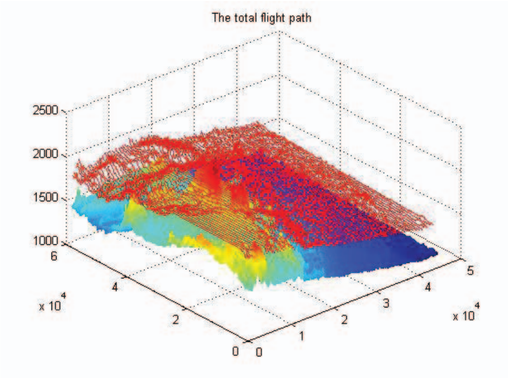

Fig.9. The total flight path

Based on the zoning results, the previously obtained trajectory is divided in time according to the distance from the base. A specified number of UAVs are dispatched from the base every two hours. Therefore, the deployment of UAV programs is:

Assuming that the inspection is started from 0 o'clock, a drone is transferred to each zone every 2 hours.

VII. CONCLUSION

In this paper, the issue of multi-UAV co-coverage in the path planning of plateau mountain environment is studied. It is decomposed into two sub-problems: total flight path analysis and search area allocation. According to the principle of the least number of turns, if the drone covers the area along the long side of the rectangular area by means of a scanning line, the shortest flight distance can be obtained. On this basis, the continuous detection problem is converted into a planning problem. The minimum number of drones is required and the inspection plan is obtained when the area is arbitrarily divided.

Using parallel search strategies to detect areas can largely avoid duplicate detection while maintaining a high coverage. In the future, different search strategies can be used to optimize the routes and discuss and compare with parallel search strategies. In addition, due to the limitation of the minimum turning radius, the path from the initial position to the search starting point will be different, which is also the direction of future research.

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