Unmanned Aerial Vehicle system layout based on two-layer interconnection model

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Abstract. Based on the Australian wildfire in 2019, this paper obtains the grid risk coefficient through the cellular automata model, and linear model and uses the cluster gravity method to select the location of EOC. Finally it gives the two-layer interconnection model constructed by SSA UAV and radio repeater UAV and the UAV system model of UAV two-layer interconnection coverage planning. It aims to create a safe and economic disaster monitoring system. The security, that is, the connectivity coverage rate of UAV system and the economy, that is, the total number of UAVs, are taken as the objective functions. The constraints are the minimum standard limit of coverage rate and connectivity rate, the limit of divided area, the limit of divided area inspection cycle, and the limit of the relationship between the built-in battery consumption and the number of on-the-job UAVs. According to the PSO-ACO fusion algorithm, the optimal number and combination of the two types of UAVs are obtained. The adaptability of the model to extreme fire events in the next ten years is verified by grey weight Markov prediction.

1. Introduction
Since Australia entered the fire season in July 2019, fires have swept across the country, among which the most serious fires happened in the economically developed and densely populated eastern Victoria. Houses burned down, thousands of residents were forced to flee their homes, causing huge property losses and casualties. Today, the Australian people's struggle against wildfires continues.

The UAV system mainly includes the following two types of drones. The SSA UAVs carry a thermal imager and a remote sensing transmitter to detect and perceive the peripheral fire situation. Radio Repeater UAVs carry Repeaters that extend the range of radio signals for transmission from the front lines and command centers. UAV technology has the advantages of fast flight speed and strong real-time performance. Therefore, it plays an important role in the detection of fire detection and rescue detection. But how to deploy drones to adapt to different terrains and different fire conditions to achieve both safety and economy? Answering this question well can contribute more to the protection of human property safety and the sustainable development of the ecological environment.
2. Materials and Methods

2.1 Cluster-center of gravity method

In order to achieve the least cost and fastest command, this paper decides to use the cluster-center of gravity method to select the location of the EOC, the emergency rescue command center [1].

First, perform cluster analysis on the fire size and geographic coordinates of the fire area, and after the intersection of the two clustering results, determine the second-level emergency rescue command center based on the priority of the degree of disaster.

Secondly, based on the second-level emergency rescue center, the center of gravity method is used to obtain the Q coordinate of the first-level command center.

2.2 Double-layer interconnection model

Due to the different tasks and performance of SSA drone and radio repeater drone in the monitoring process, their distribution requirements and deployment methods are also diverse. SSA drones have smaller communication radius and better mobility. It is necessary for them to monitor comprehensively of the area within a certain period. Situations that there is no surveillance in non-key areas for a certain period of time is permitted; while the radio repeater drones have larger communication radius. In the realization of signal multi-level transmission, the impact of chain breakage is considerable, thus rearrange and replace in time is quite important to ensure data transmission. The deployment methods for SSA drones and radio repeater drones are as follows:

2.2.1 Dynamic division of regional convex polygons

In this article, we adopt the method of divide and conquer strategy, that is, first perform regional segmentation and deploy drones, and then use scan lines, spiral lines, etc. to patrol and monitor. To solve the problem well, we divide the mission area dynamically according to the possibility of fire, and assign an SSA drone to patrol each divided area.

1) The Graham algorithm is used to expand the total area of UAV monitoring into a convex polygon area, and then perform the area of convex polygon.

2) Disperse \(Q_{SSA,0}\) nodes in the convex polygon area to construct triangles, and insert these triangles into the triangle linked list.

3) Calculate the task degree \(M_{i}(t)\) of each triangle area, insert more nodes in the area with higher task degree, find the triangle whose circumscribed circle in the triangle list contains this node, and record it as the influence triangle of the insertion point. If these triangles have common edges, deletes the edges of the triangle, and then connect the newly added node with affected vertices of the triangle to form a new triangle.

4) Disperse the point sets of neighboring regions in areas with low triangle task degree, reduce the number of nodes and regenerate triangles.

5) Perform local optimization on the newly generated triangles. If there are common edges between the two newly generated triangles, combine the two triangles into a quadrilateral. Check this quadrilateral with the maximum empty circle criterion. If the fourth vertex is in the circumscribed circle formed by the other three vertices, the diagonals of this quadrilateral are interchanged to ensure that each newly generated triangle meets the Delaunay regulations[2]. Insert the newly generated triangle into the Delaunay triangle list.

6) Continue to add and delete nodes to the large triangle according to the steps 3, 4, and 5, until the concentration of each triangle tends to balance. Complete the construction of the Delaunay triangle grid. Finally, the initial value of the number of replacement SSA drones is obtained.

7) Search all triangles in the triangle list in turn, and find the triangles adjacent to the current triangle. Shape and store the connection between the outer center of the current triangle and the outer center of the adjacent triangle in the Voronoi edge list; if there is no adjacent triangle, use the vertical line of the side instead of the outer center connection and save it in the edge list.
(8) The traversal of the triangle linked list comes to an end and the Voronoi diagram is obtained. It can be clearly found that the area demarcated near the high frequency point of the fire is smaller, and further patrols are more vigorous. In the same way, calculate the area $s_i(t)$ of each divided area, the area risk factor $\mu_i(t)$ and the total area $TN$.

2.2.2 The influence of terrain on range

In each patrol area generated by the Voronoi diagram, a drone is assigned to search. Apply scan line and spiral line to deploy drones in order to achieve full coverage.

In flat and barrier-free areas, the standard range of SSA drones $R_{s,\text{max}}$ is higher, while in urban areas, its standard range is greatly reduced by obstacles to $R_{s,\text{min}}$, if the flatness of the defined area is $\Theta$, we get the formula of $R_s$.

When the patrol radius $R_s$ decreases due to the influence of physical terrain, the period $\tau$ becomes longer, and the maximum patrol area decreases.

2.2.3 Relative distance

In the initial stage of deployment, assume that $Q_{rp, o}$ radio repeater drone is randomly deployed in the air of the mission area. The coverage radius of each radio repeater drone is $R_{rp}$, at that time, there are a lot of overlapping coverage phenomena and blind areas in the drone network. Thereafter, according to the relative distance algorithm, radio repeater drone position scrolls with iteration to reduce the coverage redundancy and blind areas of the mission area as much as possible. Finally, after a limited number of movements, the flight of the radio repeater drone reaches a stable state; when there is a radio repeater drone interrupted, adopt the same method to rearrange thus achieve effective full coverage of the task area.

a. The relative distance between the uncovered area grid and the drone

The main factor affecting the radio repeater drone is the relative distance between the uncovered area grid and the drone in the sensing range. First, rasterize the task area to get the total number of the grids and the coordinates of the grid center point $(x_g, y_g)$. When the distance between the uncovered grid and the drone is less than the maximum movement step $SL_{\text{grid}}$ affected by the relative distance, the drone moves toward the uncovered grid. The relative distance is represented by $d_{ig}$, and the distance vectors in the x-axis direction and the y-axis direction are $d_{igx}$ and $d_{igy}$.

When the uncovered grid is sensed, the drone's position is updated to:

$$
\begin{align*}
    x_i(t+1) &= x_i(t) + d_{igx} e^{\frac{1}{d_{ig}}} \\
    y_i(t+1) &= y_i(t) + d_{igy} e^{\frac{1}{d_{ig}}}
\end{align*}
$$

b. The relative distance between drones

There is also a relative distance between each drone and its neighbors. If the relative distance between the neighbor drone is less than the preset threshold, in order to ensure the drones will not overcrowd in an area. The drone will move away from its neighbor drone with its maximum movement step $SL_{UAV}$ affected by the relative distance of the direction movement. If the distance between two adjacent drones
is greater than the threshold and less than the communication radius, the UAV will move towards the neighbor drone to minimize the coverage blind area. Else, there is no effect.

When the distance between drones is less than the threshold, the drone's position is updated to:

\[
\begin{align*}
x(t+1) &= x(t) + SL_{UAV} \frac{d_{ij}}{d_{ij}^U} e^{-\frac{1}{d_{ij}^U}} \\
y(t+1) &= y(t) + SL_{UAV} \frac{d_{ij}}{d_{ij}^U} e^{-\frac{1}{d_{ij}^U}}
\end{align*}
\] (2)

c. The relative distance between the boundary and the drone base station

In order to prevent the drone from exceeding the boundary and invalid coverage, the drone needs to move according to the boundary position. The location update formula is similar to the above.

2.3 SSA drone and radio repeater drone double-layer interconnection criteria

2.3.1 The purchase and priority replacement rule

When the coverage rate of SSA drones or the coverage rate of radio repeater drones after mobile rearrangement does not meet the minimum requirements, replacement drones must be deployed to ensure safety. When there are no idle drones, extra drones must be purchased and added to the system.

For SSA drones that are far away from EOC, multi-level radio repeater drones are required to send back information, and each repeater needs to take care of multiple SSA drones, which also means radio repeater drones are vital. When the coverage rate of the inner radio repeater drone is low, it will cause all peripheral information to be unable to track in time, causing disastrous consequences. So when there is a substitute, priority is given to substitute radio repeater drones. In addition, priority should be given to substitutes for high-risk areas to prevent untimely monitoring caused by unreasonable allocation. And the priority level between the above two depends on the following formula:

\[
\begin{align*}
\text{When } & Q_s(t) \neq 0 \text{ and } \alpha(t) > \alpha_{lim} \text{ and } C_{ov}(t) > C_{ov,lim} \\
\text{if } & (\alpha(t+1) - \alpha(t))TN \leq \mathcal{S}_i(t) \mu_i(t) \\
Q_{SSA,s}(t+1) &= Q_{SSA,s}(t) + 1 \\
\text{else } & Q_{p,s}(t+1) = Q_{p,s}(t) + 1
\end{align*}
\] (3)

2.3.2 Connectivity state variables

SSA drones that cannot directly transmit signals to send data back to EOC must transmit information via one or more radio repeater drones. If the chain break, the information perceived by SSA drones fail to return to EOC, thus introduce connected state variables.

2.4 UAV double-layer interconnection coverage planning model

The deployment method or coverage plan of the drone largely determines the coverage of the drone network, network connectivity status, and patrol monitoring cycle. Only when the coverage rate is high enough and the connectivity rate is guaranteed, can safety be guaranteed, which requires as many drones as possible. But at the same time, we must also consider economy by giving up 100% coverage, focusing on key areas, and buying as few drones as possible.
2.4.1 Objective function
The objective function of the optimization model is the optimal safety and economy: the safety index is the UAV system connectivity coverage rate, and the coverage is successful only if both SSA drone monitoring and transmission through radio repeater drone are successful; the economic index is the total UAV number, including the original deployed UAV and the purchased replacement UAV, \( Q_{SSA} \) and \( Q_{rp} \), uses the last moment value of the dynamic model.

\[
\max G_{ov}(t) = \frac{\sum_{i=1}^{\infty} S_i(t) \mu_i(t) \lambda_i(t)}{TN}
\]

\[
\min Q_{SSA} + Q_{rp} = Q_{SSA,0} + Q_{SSA,s} + Q_{rp,0} + Q_{rp,s}
\]  

(4)

2.4.2 Constraints
(1) Minimum standard limit on coverage rate and connection rate
For safety, we set a minimum security guarantee. The coverage of SSA drones and radio repeater drones must meet the standards, and the final signal connectivity rate of the entire system must also be greater than the minimum.

(2) Restricted area
The total area traveled by each drone cannot exceed the maximum of travel distance \( L \) and the distance traveled in one period \( \tau \) at the maximum speed \( v \). \( \alpha \) is the number of turns

\[
S_i(t) \leq \min(2v\tau R_x + \alpha \pi R_s^2, L)
\]  

(5)

(3) Limits on the inspection period
For the divided area with high fire risk, the area of its own area is small, and the patrol cycle should be shorter in order to detect the fire in time. The area influence time coefficient is \( \rho \) and \( \tau_0 \) is the longest flight time, so the period \( \tau \) is limited to

\[
\tau \leq \rho \tau_0 \frac{\mu_{max} - \mu}{\mu_{max} - \mu_{min}}
\]  

(6)

(4) Restrictions on the relationship between built-in battery consumption and the number of drones in service
The number of in-service drones changes over time. During the dynamic optimization process, the system may add newly purchased drones at any time. At the same time, the drones return to the ground after each \( t_e \) since the power is exhausted, and re-work after each charge period \( t_e \cdot Q_{SSA,s}(\Delta t) \) And \( Q_{rp,s}(\Delta t) \) are the number of newly purchased drones in the time interval \( \Delta t \), and the formula for calculating the number of drones in service after the moment \( \Delta t \) is:

\[
Q_{SSA}(t + \Delta t) + Q_{rp}(t + \Delta t) = (Q_{SSA}(t) + Q_{rp}(t)) \left(1 + \left[ \frac{\Delta t}{t_e} \right] - \left[ \frac{\Delta t}{t_e} \right] \right) + Q_{SSA,s}(\Delta t) + Q_{rp,s}(\Delta t)
\]  

(7)

2.5 PSO-ACO fusion algorithm
For the above-mentioned nonlinear programming problem, when the system has a certain calculation scale, it is an extremely complex NP problem. Therefore, we use the particle swarm and improved ant colony fusion algorithm (PSO-ACO fusion algorithm) [5] to handle it.
2.6 Prediction
The gray Markov model solves the problem of inaccurate prediction caused by data fluctuations when there is a large random situation, and at the same time makes the entire prediction process no longer need long time series data, which is for some sudden public events seem to be particularly important.

3. Results & Discussion
According to the cluster-center of gravity method, the position of EOC is 34.1753° south latitude and 145.9558° east longitude.

Using PSO-ACO fusion algorithm to solve the planning model. The figure shows the change in results as the number of iterations increases. The numbers of SSA drones and radio repeater drones become steady in the 42nd and 55th iterations, respectively. Their optimal number ranges are (1309, 1338) and (304, 328). The optimal number range of UAV system combination is (1625-1650), with an average value of 1,630, of which 1,319 are SSA drones and 311 are radio repeater drones.

![Figure 1 Solution result iteration graph](image1)

The operation mode of the UAV system is shown in the figure below. The red dots are the deployment position of the SSA drones, the black dots are the deployment position of the radio repeater drone, the green dot presents the EOC position, and the blue line is the information transmission path (only part of the path is shown: the lower left area shows details). It can be seen from the figure that the SSA drone near the EOC position can be automatically transmitted back without any radio delay drone. The red circle in the picture is the range of the particular radio repeater drone. It can be seen that there is no SSA drone in its range, but it is still very important because all SSA drones within the range of two red lines all rely on it to transmit information back to the EOC.

![Figure 2 UAV system combination diagram](image2)
4. Conclusions
Collect Victorian data from the Australian Bureau of Statistics. The data includes vegetation coverage, wind index, rainfall, urban distribution, urban greening, historical fires, location and scope. Apply grey weight Markov prediction to predict changes of various data in the next ten years.

By importing the predicted value of the next ten years into the risk coefficient algorithm, the risk coefficients of each grid in the next ten years can be obtained, and then the clustering-center of gravity method can be used to re-select the location of the EOC, and the EOC in the next ten years. The site selection is shown in the figure below[6]:

![Figure 3: Schematic diagram of EOC site selection in the next ten years](image)

Finally, substituting the recalculated risk factor and EOC site selection in the next ten years into the dual-layer interconnection model of SSA drones and radio repeater drones, the number of SSA drones and radio repeater drones in the next ten years can be obtained as follows:

![Table 1: SSA drone and radio repeater drone number forecast](image)

The combination of SSA drones and Radio Repeater drones in the next ten years will be more complex and diverse. Due to space limitations, this article will not show the combination forecasts of the two types of UAVs in the next ten years. The prediction plans for the next ten years are consistent with common sense, and it can be verified that the model in this paper can adapt to extreme fire events in the next ten years under the condition that the vegetation, meteorological conditions, fire source, and historical fire points of the previous year can be obtained.

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