Application of Minimum Spanning Tree in the Solution of Forest Fire Intelligent Drone Deployment

Dongxiao Liu*, Tianyi Zhao
Beijing University of Posts and Telecommunications, Beijing, 100876

*Corresponding author: dongxiaoliu@bupt.edu.cn

Abstract. In recent years, devastating wildfires have occurred in all states of Australia, and the wildfires in eastern Victoria have been extremely affected. In order to prevent the disaster from happening again, we built a model to warn the wildfires in Victoria. First, we extracted the Victorian fire data from NASA's official website. After sorting by credibility and flame temperature, we performed grid division and labeling based on latitude and longitude and the number of fires per unit time. Then, we used the k-means method to cluster the locations of wildfires, and obtained three clusters. Second, we divide wildfires into two categories, wildfires near the cluster center and others not. Among them, 3 regions are near the cluster center, and 4 region is away from the cluster center. For wildfires near the cluster center, remote sensing detection drones are used to fully cover the fire, and use the minimum spanning tree algorithm to solve the position of the repeater drone. For other wildfires, we establish a nonlinear programming equation to find the combination of drones with the lowest rate for the alarm missed by the fire, and get the number of telemetering drones is 65, the number of repeater drones is 49. Third, we map the data of different distances in the three-dimensional topographic map to the two-dimensional plane according to the geographic data of Victoria, and use the Dijkstra algorithm to obtain the approximate distance between the two points in the given point set. Then use the minimum spanning tree to solve, get the number of telemetering drones is 65, the number of repeater drones is 52, it is still close to the solution of model 1 after adding the terrain, indicating that the optimization result is successful.

1. Inference
In recent years, devastating wildfires have occurred in all states of Australia, and the wildfires in eastern Victoria have been extremely affected. In some places, the flame height can reach 70 meters and the temperature can reach 1000 degrees Celsius. Under the strong winds in the northwest, the fire has been burning, damaging the land of Australia.

According to forecasts, the dryness of the weather may continue to intensify, and the temperature will rise again to fuel the fire. The Emergency Operations Center (EOC) urgently needs an effective plan to warn of fires.

Considering the background information, we need to solve the following problems:
1. Consider the needs and terrain of observation and communication tasks, consider the size and frequency of fire incidents, and design an optimal combination of telemetering drones and relay drones to quickly respond to fires in the jungle.

2. Consider the impact of actual terrain conditions on the signal transmission of DRONEs equipped with repeaters, and optimize the deployment positions of DRONEs in different terrains with different firepower.

3. Calculate the cost according to the model and annotate Budget Request for CFA to submit to the Victoria State government.

2. Fire Determination and Drone Deployment Model

2.1. Wildfire Size Statistical Model

Based on NASA satellite fire data statistics, we believe that its brightness can represent its flame size. First, the data is sorted by confidence and brightness. In the confidence interval [0,100], data with confidence greater than 50 is selected as the sampling point. Extract its latitude, longitude, and flame information. The data sample is shown in Table 1, Shown on the map as Figure 1:

| latitude     | longitude | brightness | confidence |
|--------------|-----------|------------|------------|
| -37.3387     | 141.4589  | 417.1      | 100        |
| -37.2865     | 143.1513  | 100        | 100        |
| -36.8122     | 143.8633  | 365.5      | 100        |
| -37.3301     | 148.5312  | 326.4      | 81         |
| -37.307      | 147.916   | 313.5      | 71         |

| Figure 1. Wildfire distribution before clustering |

Some rules can be obtained from the fire distribution map. Most of the fires are always concentrated in one part, and a few are scattered in other places. In order to better find the law of fire occurrence, we use the K-means clustering method to find the fire. Incident center.

The K-Means algorithm uses distance as the evaluation index of similarity, and uses the sum of squared errors from the sample point to the category center as the evaluation index for the quality of clustering. Through an iterative method, the overall classification error sum of squares function is minimized method.

For the data set \((x_1, x_2, \ldots, x_n)\), and each \(x_i\) is a \(d - \text{dimensional}\) feature vector. We divide this data set into \(k\) different categories of \(S = \{s_1, s_2, \ldots, s_n\}\) Among them, the sum of squared distances from all elements in the category \(S_i\) to the category center \(U_i\) is \(\sum_{x_j \in S_i} ||x_j - u_i||^2\). The purpose of classification is to minimize the sum of the sum of squared distances of the \(k\) categories. Expressed as:
The images before and after clustering are shown in Figures 4 and clustering process is as follows Figure 2:

![Diagram of K-means clustering process](image)

**Figure 2.** K-means clustering process

### 2.2. The Working Mode of the Drone

In the fire detection task, the drone carrying the repeater works mainly by hovering. It is responsible for communicating with the personnel controlling the remote sensing telemetering drone on the ground through VHF/UHF radio to ensure the smooth line between EOC and front-line personnel.

To calculate the distance, we need to convert longitude and latitude into kilometers. Suppose the earth is a smooth sphere of radius R:

1. The distance between the two points which differ by 1° on the surface of the coil is:
   \[ 2\pi R/360 = 108\text{KM} \]  
   \[ (2) \]

2. The distance between two points with a difference of 1° on the same latitude is:
   \[ 2\pi R \times \frac{\cos(\text{latitude})}{360} = 88\text{KM} \]  
   \[ (3) \]

We grid the map of Victoria based on the maximum range of the drone, which is 30KM. The area of the unit square is 30KM*30KM. For a remote sensing unmanned aerial vehicle, the area covered by a spiral is the largest. We believe that a remote sensing drone carries a wide-angle camera with a shooting range of \( \theta \) degrees and a flying altitude of \( h \) meters. The calculation formula of shooting radius is:

\[ h \times \tan \theta \]  
\[ (4) \]

Let \( h = 400\text{m} \) and \( \theta = 85^\circ \). Get the shooting radius is 4KM. The length of the outer ring of the drone detection area is \( 4 \times (30\text{KM} - 2 \times 4\text{KM}) = 96\text{KM} \), The length of the inner ring is \( 4 \times (30\text{KM} - 2 \times 8\text{KM} - 2 \times 4\text{KM}) = 24\text{KM} \). Therefore, the length of the basic path covering the whole region is 110KM. Relative to the ultimate flight length of the drone \( 2.5h \times 20\text{m/s} = \)

\[ arg\text{min} \sum_{i=1}^{k} \sum_{x_j \in S_i} ||x_j - u_i||^2 \]

\[ (1) \]
There is still a lot of redundancy. Therefore, the drone can be competent for the task of single area detection.

In the real forest fire rescue dispatching, since the most important data signal is to be transmitted to the EOC, the communication link must be kept unblocked. Therefore, it is necessary to ensure the uninterrupted operation of the relay unmanned remote sensing machine. Considering the limited battery of the drone and the actual communication cannot be interrupted.

According to the problem setting: the longest working time of the drone is 2.5h, and the charging time is usually 1.75h. We might as well set the number of drones in operation as $x$ and the number of drones in charging as $y$ to make it full load operation establishment equation.

$$\frac{x}{2.5} = \frac{y}{1.75}, \frac{x}{y} = 1.43$$

In other words, when there are 3 drones at work, 2 spares need to be prepared.

2.3. Stand Guard and Patrol Models

2.3.1. Near the cluster center. In the face of a fire situation that is close to the entire map, it is obviously not advisable to spread the drone network over the entire map. We divide the points on the map into two
categories. One has a high probability of fire and the other has a high probability. There is a fire. Therefore, question 1 becomes the following form:

\[
\text{Solution} = \min_{\text{damage caused by wildfires}} \left\{ \min_{\text{drones combination}} \right\} \\
\{ \text{High probability of fire location} \} \\
+ \{ \text{Extreme probability of fire location} \}
\]  

(6)

Therefore, based on the clustering results, we believe that the locations near the cluster center are very likely to have fires. To meet this requirement, we use regular polygons to circle these points, and let \( S \) be the area of the polygon and \( P \) be the sum of the points, such that:

\[
k = \frac{P}{S}
\]

(7)

The proportionality factor is the largest. For those areas, we will have surveillance teams based here to detect fires.

In this area, we use detection drones to cover the monitoring points and use the minimum spanning tree algorithm to solve

We use the Kruskal algorithm, the initial minimum spanning tree edge number is 0, and each iteration selects a minimum cost edge that satisfies the condition and adds it to the edge set of the minimum spanning tree.

2.3.2. Outside the cluster center. The points outside the circle are also very likely to have fires. We still need to deploy patrol teams to fly regularly to detect fires. It will monitor the high-frequency areas where the fire occurs in the form of squad deployment and patrol.

![Figure 5. Reconnaissance mode of telemetering drone group](image)

Assuming that the number of telemetering drone aircraft is \( x \), the number of repeaters is \( y \), in the fire warning area, the city area/fire warning area = \( p \). The communication distance of VHF/UHF in urban areas is 2km, and the communication distance in rural areas is 5km. At this time, the average communication distance is:

\[
L_{\text{avg}} = p * 2 + (1 - p) * 5 = 5 - 3p
\]

(8)

Since it is necessary to ensure that the detection drone can communicate with EOC at any position in the fire prevention area, and the communication range of each repeater drone is 40km, the maximum number of repeaters required by each drone is:
\[ y = \frac{(R-L_{\text{avg}}-15)}{40} \times x \]  \hspace{1cm} (9)

When the telemetering drone has explored all areas in the fire warning area, the second round of inspections will be started after an interval of two months. Therefore, the interval \( T \) for each area to be inspected is equal to the time to inspect all areas + 2 months of inspection interval:

\[ T = \frac{\pi R^2 t}{x^2 \pi + 15^2} + 24 \times 60 = \frac{R^2 t}{x^2 15^2} + 24 \times 60 \]  \hspace{1cm} (10)

Assuming that the interval between fire occurrence length \( X \) and the probability of fire occurrence follow an exponential distribution, which is:

\[ X \sim \exp(\lambda) \]  \hspace{1cm} (11)

Cumulative distribution function:

\[ F(x) = p(X \leq x) = 1 - e^{-\lambda x} \]  \hspace{1cm} (12)

When each area is not explored, the probability of a fire is:

\[ P = 1 - e^{-\lambda T} \]  \hspace{1cm} (13)

**Total cost:** = telemetering drone cost + repeater drone cost + fire damage cost

Objective function:

\[ \text{Cost} = (x + y) \times 10000 + P \times \pi \times R^2 \times m \]  \hspace{1cm} (14)

Restrictions

\[
\begin{cases}
L_{\text{avg}} = p \times 2 + (1 - p) \times 5 = 5 - 3p \\
Y = \frac{(R-L_{\text{avg}}-20)}{40} \\
T = \frac{R^2 t}{x^2 15^2} + 24 \times 60 \\
P = 1 - e^{-\lambda T}
\end{cases}
\]  \hspace{1cm} (15)

In Figure 6, each dot represents that a fire has occurred there. The more yellowish the color, the higher the number of fires. In 4 circular areas, patrols are used to detect fire.
3. Repeater Drone Position Optimization Model

When we want to study the influence of terrain on the layout of drones, the problem extends from a two-dimensional problem to a three-dimensional problem. The problem will become more complicated after adding terrain data. If the drone is increased infinitely from the ground, the performance of the drone will be greatly wasted. We assume that the distance from the drone to the ground is less than the height of the mountain. The distribution of drones is divided along the mountains.

3.1. Distance Optimization Model

Then the distance problem between drones becomes a path problem in a three-dimensional plane. We try to use the Dijkstra algorithm to obtain an approximate solution of the distance between two points. We divided the map into grids. Treat each grid as a processing node, and each grid only leads to eight adjacent squares. Building a grid diagram, we select a target point that needs to be calculated, calculate the distance of surrounding points according to Dijkstra algorithm, and put the surrounding points into the queue to be processed. After processing the right and lower right nodes, the waiting queue changes are shown in Figure 8:

![Figure 6. Fire location and frequency](image)

Step by step, the calculated distance is compared with the current distance, and the distance between the target point and the whole point can be obtained.

As shown in the figure below, this graph is a distance graph generated around the coordinates [-36.7625, 145.33]. The z-axis value in the graph represents the distance from the coordinate [-36.7625, 145.33] as the starting point to each point.
When we have a point set that needs to be optimized, we can obtain the distance map of all points like this, and realize the three-dimensional distance mapping to a two-dimensional plane, as shown in Figure 1. In this way, the actual geographic distance between points in any point set can be obtained. After that, the optimal connection layout of the relay drone can be obtained through the minimum spanning tree algorithm.

4. Conclusion

Need to use 8 telemetering drones to coverage. Taking telemetering drone No. 1 and telemetering drone No. 2 as examples, the communication distance of VHF in telemetering drone No. 1 is $d_1$, the communication distance of VHF in telemetering drone No. 2 is $d_2$, and the distance between area 12 is $d_{12}$. The number of repeaters required to connect telemetering drone No. 1 and No. 2 is:

$$n = \frac{d_{12} - d_1 - d_2}{40}$$  \hspace{1cm} (16)$$

For area one: The area radius $R=100km$, through the map data, calculate the proportion of the city $p=0.412$.

In 4 months, there were 187 fires in Region 3, so the fire interval per unit area.

$$h = \frac{24+4+30}{187+152} \cdot \frac{1}{152} = 0.0014609375$$  \hspace{1cm} (17)$$

| Area       | telemetering drone | repeater drone |
|------------|---------------------|----------------|
| Yellow Area| 15                  | 8              |
| Blue Area  | 11                  | 6              |
| Red Area   | 31                  | 23             |

Figure 8. Telemetering and Repeater drones distribution
Since the detection interval is 2 months, it is possible to use only one set of telemetering drones and repeaters drones to detect four areas in sequence within two months. So, the required number of telemeters drone = max (x1, x2, x3, x4) = 10, the required number of repeaters = max (y1, y2, y3, y4) = 20.

From the results, it is still close to the solution of model 1 after adding the terrain, indicating that the optimization result is relatively successful.

References
[1] Rabta, Boualem, Christian Wankmüller, and Gerald Reiner. "A drone fleet model for last-mile distribution in disaster relief operations." International Journal of Disaster Risk Reduction 28 (2018): 107-112.
[2] Zhu, Tao, et al. "Cooperative search strategies of multiple UAVs based on clustering using minimum spanning tree." International Conference on Swarm Intelligence. Springer, Cham, 2018.
[3] Park, Wookeun, Seongmin Seo, and Joonbum Bae. "A hybrid gripper with soft material and rigid structures." IEEE Robotics and Automation Letters 4.1 (2018): 65-72.
[4] Cruz, Henry, et al. "Efficient forest fire detection index for application in unmanned aerial systems (UASs)." Sensors 16.6 (2016): 893.
[5] McKenna, Phill, et al. "Measuring fire severity using UAV imagery in semi-arid central Queensland, Australia." International Journal of Remote Sensing 38.14 (2017): 4244-4264.
[6] Salehi, Mahsa, et al. "Dynamic and robust wildfire risk prediction system: an unsupervised approach." Proceedings of the 22nd ACM SIGKDD International Conference on Knowledge Discovery and Data Mining. 2016.