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A new optimization model based on minimum risk and cost - UAV monitoring and early warning system

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Abstract: *The forest fire in 2019-2020 has brought devastating damage to every state in Australia, causing many casualties and huge property losses, among which the impact on New South Wales and eastern Victoria is the largest. We design a monitoring and early warning system from the perspective of emergency capacity, safety and economy, combined with the use of the model and terrain restrictions, in order to deal with the possible future forest fires. A "hierarchical structure model" is established to study the optimal combination scheme. Based on it, the penalty function is used to construct the auxiliary function, and the original constrained problem is transformed into the minimum auxiliary unconstrained problem. According to the topographic map and fire distribution map of Victoria, how to optimize the monitoring and early warning system is calculated under the condition that full coverage error can not be achieved.*

Keywords: *Analytic hierarchy process; Forest fire fighting model; Poisson distribution; Linear optimization*

1. Introduction

Due to the influence of high temperature, drought and gale climate, forest fires will occur in Australia from 2019 to 2020, which will aggravate the flammability of Eucalyptus and other high load vegetation widely distributed in hilly areas. The forest fire lasted for several months, causing serious damage to every continent. The burned area reached 18.6 million hectares, causing many casualties and property losses. At the same time, it released more than 300 million tons of carbon dioxide, which exacerbated global warming and aroused widespread concern of the international community [1].

With the development of science and technology, drone has long been used to monitor the fire in the disaster area, but due to the influence of distance and physical terrain, the signal range is limited. Recently, researchers have greatly expanded the range of front-line low-power radios by installing repeaters on hovering drones.

SSA drones can be used for monitoring and situation awareness, and Radio Repeater drones can be used to expand the radio range, but not for monitoring disaster.

SSA drones have a small range of receiving radio, if they all use SSA drones, they will use a large number of them with high cost; Radio Repeater drones have a large range of receiving radio, if they all use radio repeater drones, they will use a small number of them, which can reduce the cost but can not play a monitoring effect.

Through analysis, there must be an optimal combination of SSA drones and Radio Repeater drones to balance capability, safety and economy. The model can be realized: when the fire occurs, it can be found and perceived in time, and the work cost can be reduced to the lowest.

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2. Assumptions and notations

2.1. Assumptions

We use the following assumptions [2].

(1) SSA drones, Radio Repeater drones and Emergency Operation Center (EOC) can send and receive radio and transmit information to each other.

(2) The charging time of SSA drones is less than that of Radio Repeater drones (> 1.75h);

The flight time of SSA drones is longer than that of Radio Repeater drones (> 2.5h).

(3) The flight speed of SSA drones is the same as that of Radio Repeater drones (20m / S = 72km / h).

(4) During the charging period of the Radio Repeater drones, SSA drones also completes the charging work, while SSA drones and Radio Repeater drones do not monitor during the charging period.

(5) The cost of the Radio Repeater drones is $10000. After consulting the data, it is assumed that the cost of SSA drones is $10000.

(6) SSA drones flies in a straight line in a short distance for monitoring operation, and the flight speed remains unchanged.

(7) The areas monitored by SSA drones during flight are all effective areas, and the blind areas between detection areas are very small and can be ignored.

(8) The monitoring area of drones is circular, and the detection range is shifted in a circular area.

(9) The model should balance ability, security and economy, security and economy are equally important, and weighted average share is equal.

(10) As SSA drones, Radio Repeater drones is affected by terrain. According to the same proportion, it is assumed that the monitoring area is 20km in flat rural areas and 8km in rugged urban areas.

2.2. Notations

The primary notations used in this paper are listed as Table 1.

Table 1: Notations

Notations	Description
V	Flight speed of SSA UAV and radio repeater UAV.
S1	total flat rural area of Victoria.
S2	total area of rugged urban areas in Victoria.
S11 (S21)	monitoring area of single SSA UAV in rural flat area (urban rough area).
S12 (S22)	monitoring area of single radio repeater UAV in rural flat area (urban rough area).
T1 (T2)	time required for SSA UAV to monitor all the flat areas in rural areas (rough areas in urban areas).
m1	the number of SSA UAV monitoring in rural flat areas.
n1	the number of radio repeater UAV monitoring in urban rugged areas.
m2	the number of SSA UAV monitoring in urban rugged areas.
n2	the number of radio repeater UAV monitoring in urban rugged areas.
Q1 (Q2)	Rural flat area risk value (Urban rough area risk value).
W1 (W2)	risk cost degree of flat rural areas (rough urban areas).

3. Model construction and solving

Full coverage monitoring and early warning capability of the combined system of SSA drones and Radio Repeater drones is necessary. According to the physical topographic map and fire hot spot distribution map of Australia, combined with the functional parameters of repeater, hybrid drone and other equipment, the combination mode of SSA drones and Radio Repeater drones is determined. Our main goal is to make it meet the requirements of all kinds of complex terrain conditions, at the same time, reduce the investment cost and improve the safety performance [3].

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3.1. Establish Combinatorial Optimization Model (Refer to the Forest Fire Fighting Model)

In rural flat areas:

According to the hypothesis, the area detected by an SSA drones per unit time is (S11 + 10V). As shown in Figure 1.

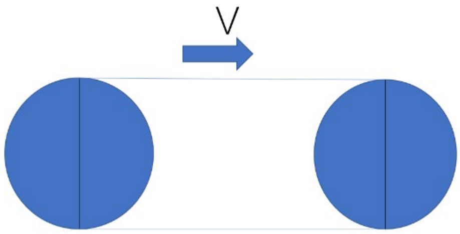

Figure 1: Detection area of SSA UAV in unit time

The time required for all SSA drone monitoring to monitor all rural flat areas.

$$T_1 = \frac{S_1}{m_1(S_{11} + 10V)} \tag{1}$$

The area not to be monitored during the work is

$$(S_1 - m_1 S_{11}) \tag{2}$$

The risk value of areas not monitored in the process of work is

$$T_1(S_1 - m_1 S_{11}) \tag{3}$$

The risk value generated during charging is

$$\frac{T_1 * 1.75 * S_1}{2.5} \tag{4}$$

The equipment cost incurred is

$$10000m_1 + 10000n_1 \tag{5}$$

The degree of risk cost in flat rural areas

$$W_1 = T_1(S_1 - m_1 S_{11}) + \frac{T_1 * 1.75 * S_1}{2.5} + 10000m_1 + 10000n_1 \tag{6}$$

Restrictions:

At all times, the monitoring range of all SSA drones and Radio Repeater drones is larger than the total area of rural flat areas.

$$m_1 S_{11} + n_1 S_{12} \geq S_1 \tag{7}$$

And m_1， n_1 are integers， $m_1, n_1 > 0$ (8)

In rugged urban areas:

In the same way, Time required for all SSA drones to monitor all rugged urban areas

$$T_2 = \frac{S_2}{m_2(S_{21} + 4v)} \tag{9}$$

The area not to be monitored during the work is

$$(S_2 - m_2 S_{21}) \tag{10}$$

The risk value of areas not monitored in the process of work is

$$T_2(S_2 - m_2 S_{21}) \tag{11}$$

The risk value generated during charging is

$$\frac{T_2 * 1.75 * S_2}{2.5} \tag{12}$$

The equipment cost incurred is

$$10000 m_2 + 10000 n_2 \tag{13}$$

The degree of risk cost in urban rugged areas

$$W_2 = T_2(S_2 - m_2 S_{21}) + \frac{T_2 * 1.75 * S_2}{2.5} + 10000 m_2 + 10000 n_2 \tag{14}$$

Restrictions:

At all times, the monitoring range of all SSA drones and Radio Repeater drones is larger than the total area of rugged urban areas.

$$m_2 S_{21} + n_2 S_{22} \geq S_2 \tag{15}$$

$$\text{And } m_2,\ n_2 \text{ are integers, } m_2, n_2 > 0 \tag{16}$$

Carry in the data and use Lingo to solve the problem

When the number of SSA drones and Radio Repeater drones is 92 and 154 respectively, the risk cost is the lowest, and the lowest value is 3369140.

When the number of SSA drones and Radio Repeater drones is 20 and 134 respectively, the risk cost is the lowest, and the lowest value is 1746038.

3.2. Optimize the Position of the Hovering VHF/UHF Radio Repeater Drone

3.2.1. Model Establishment-Penalty Function

In order to optimize the problem, the repeater and SSA drones positions are used to optimize the model according to different terrain and fire size. The basic idea of penalty function is to construct an auxiliary function, which transforms the original constrained problem into a minimum auxiliary unconstrained problem[4]. Under the condition of different complexity of terrain and different fire size, the purpose of repeater optimization is to keep the highest amount of information transmission and the lowest cost.

According to NASA and acrgis images, the terrain of Victoria is as Figure 2.

Figure 2: Topographic map of Victoria

Victoria is located in the southeast coast of the Australian mainland, and the northwest part is adjacent to South Australia and New South Wales, which is the smallest continental state in Australia. The northeast is a mountainous area with towering peaks, mostly between 1000 and 2000 meters above sea level. In the southeast, there are vast forests, numerous caves and lakes. In the west, there are vast hills and grasslands.

Fire distribution diagram taking the fire data of December 2019 of NASA as an example. NASA shows fire distribution map in December 2019 is shown in Figure 3.

Figure 3: NASA shows fire distribution map in December 2019

3.2.2. Model Hypothesis and Verification

The fire area is $D=(d_{ij})_{mxn}$, the area is S.

The terrain complexity of each position corresponding to D can be calculated by matrix $A=(a_{ij})_{mxn}$

When the number of survival points corresponding to D is n, the location of fire-fighting point is (P_1,P_2,K,P_n)

∴the distance from the fire fighting point to EOC is d=(d_1,k,d_n)

The number of hovering repeater drones is recorded as μ

The objective function and constraint conditions based on the problem of the maximum amount of transmitted information can be expressed as

$$\begin{aligned} &Maxsum(News) \\ &\min|n_j-n_i|\le\min\{H_i,H_j\} \\ &S.t.\min|n_i-Q|\le H_i \end{aligned} \tag{17}$$

Flying speed $v_i\in[0,20]$

∴The optimal value iteration equation is expressed as

$$Q(s,a)=u+r\sum p(s'/s,a)_{\min}Q(s',a') \tag{18}$$

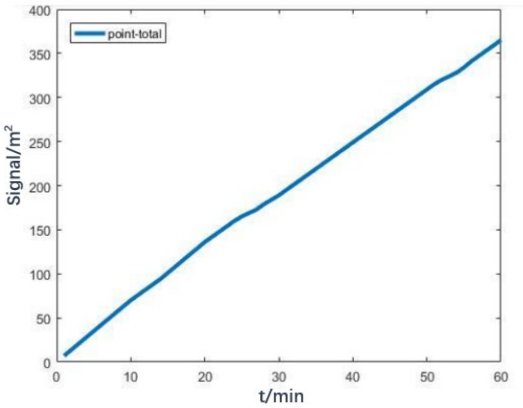

Figure 4: Trend of EOC signal reception and repeater UAV signal transmission

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The EOC received the repeater drones signal (information amount) in unit time basically presents a positive proportion trend with the increase of time, and the optimization direction is to seek the optimal solution under the error that the repeater of drones cannot fully cover[5]. Trend of EOC signal reception and repeater UAV signal transmission is shown in Figure 4.

4. Sensitivity Analysis

4.1. Sensitivity Analysis of AHP Model

The analytic hierarchy process (AHP) regards the research object as a system and makes decisions according to the thinking mode of decomposition, comparative judgment and synthesis. It has become an important tool for system analysis after mechanism analysis and statistical analysis. The idea of the system is not to cut off the influence of various factors on the results, and the weight setting of each layer in the analytic hierarchy process will directly or indirectly affect the results, and the influence degree of each factor in each layer on the results is quantitative, very clear. This method can be applied to the systematic evaluation of unstructured characteristics and multi-objective, multi criteria, multi period, etc. However, for the scheme layer of the model, only the scheme considered by the modeler can be selected, which can not provide a new scheme for decision-making. Secondly, the accurate calculation of eigenvalues and eigenvectors is more complex. When we collect the data of judgment matrix, the interaction between various elements can only be represented by the data of strong or weak correlation, without accurate value. The method used in finding the eigenvalues and eigenvectors of the judgment matrix is the same as that used in multivariate statistics.

4.2. Sensitivity Analysis of Forest Fire Model

Forest fire-fighting model was originally used to model the relationship between the number of firefighters and the degree of fire, fire-fighting efficiency and fire-fighting cost. In this problem, the number of UAV is directly proportional to the cost and the fire fighting efficiency. Referring to the forest fire model, this paper makes a risk assessment on the range difference caused by the difference between urban and rural terrain. The disadvantage of this model is that the risk evaluation value is not accurate enough, and the energy consumption of UAV itself has not been considered effectively.

5. Conclusion

This model is suitable for different terrain and different size of fire monitoring. Through the analysis and solution of the model, we can determine the optimal number and combination of SSA UAV and radio repeater UAV, and achieve the balance of capability, safety and economy.

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