Forest Wildfire Monitoring and Communication UAV System Based on Particle Swarm Optimization

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Abstract. Forest fire is one of the major disasters faced by the society at present. During the drought every year, devastating wildfires often occur all over the world, causing serious economic losses and life injuries. The effective layout of unmanned aerial vehicles in the monitoring system is the key to effectively prevent forest wildfires. Wildfires occur suddenly and rapidly, and most of them occur in dense forest areas which are difficult for firefighters to reach. Considering the factors of economy, security and capability, an efficient and accurate integrated optimization layout model of UAV is proposed. The UAV monitoring system based on this model can make the emergency operation centre best guide the active crew through two-way radio communication, so as to achieve the best effect and maximum safety. We optimized the number and combination of drones by using optimization algorithm, and got the highest scoring drone procurement plan in different types of areas. For example, when meeting low terrain without obstacles, the optimal number of drones for SSA is 20 and for Radio Repeater is 1 in high risk. Finally, we analysed the influence of global climate change, fire scale, UAV density and terrain on the optimal location of UAV.

Keywords: GASE model, ARIMA, Multi-objective optimization model, Particle swarm optimization, Environmental engineering, Unmanned Aerial Vehicle.

1. Introduction

Forest fires are one of the main disasters facing society at present. Every year during the drought, devastating wildfires often occur all over the world. Data show that from 1951 to 2013, forest fires in Australia killed 677 people and burned 22.8 billion hectares of land, causing an average annual economic loss of 1.58 billion US dollars [1]. Therefore, forest fire is highly destructive, which will cause huge loss of life and property to human society [2]. If it is not found and controlled in time, it will cause great disaster. So, it is very essential to find an effective and timely monitoring of forest fire, which can control the fire in time and avoid serious fire flooding.
UAV can monitor the fire location and coverage area, and provide convenience for firefighting through real-time data transmission [3]. A study shows that the fire detection rate using UAV technology is 87.7% [4], which shows that UAV has high value for fire detection.

UAV systems include the SSA drones’ system and the hovering drones carrying repeaters system. Because the investment for firefighting is limited, in order to make the architecture have the best performance, SSA drones and hovering drones carrying repeaters should have the best number and combination.

**Figure 1. The structure of our paper**

In this paper, according to the needs of fire tasks, combined with SSA and relay system coverage, monitoring and communication ability, safety, cost and other indicators, we propose a comprehensive evaluation model of Grade-Ability-Safety-Economy (GASE) to determine the number and mix of drones for SSA and Radio Repeater based on the frequency and scale of fire in Victoria.

The previous research is to calculate the monitoring range of UAV telemetry and the monitoring ability of complex terrain. On this basis, the model proposed by us, combined with the fire frequency, economy, safety and other factors, optimizes the number and layout of unmanned aerial vehicles by using particle swarm optimization, and the optimal scheme under different conditions. At the same time, in order to make our model adapt to the changes of future fire events, we forecast the future fire risk through the seasonal series of ARIMA model, and input the forecast data into the optimization model, and get the optimal UAV procurement scheme to adapt to the future fire risk.

2. **Architecture**

The architecture considers that firefighters communicate with Emergency Operations Center (EOC) through hovering drones carrying repeaters. And is monitored by the surveillance and situational awareness (SSA) drone. The number and combination of drones determine the performance of the architecture.

A. **Ground Station and Emergency Operations Center (EOC) [8]**

Firefighters use handheld two-way radios as their ground stations to maintain direct or indirect data communication with the emergency operations center through relay drones. EOC is the frontline fire information collection and processing center, responsible for the dispatch and distribution of firefighters and drones.

B. **Relay system [8]**.

The relay system refers to a system composed of radio transceivers carried by the UAV group.

C. **The mix of UAV systems and their number [8]**

UAV systems include the SSA drones’ system and the hovering drones carrying repeaters system. The former carries high-definition and thermal imaging cameras and telemetry sensors to monitor data from wearable devices for frontline personnel.

The latter carries a high-power repeater to ensure communication. However, the investment for firefighting is limited. In order to make the architecture have the best performance, SSA drones and hovering drones carrying repeaters should have the best number and combination.

D. **Firefighters [8]**
Nowadays, firefighters are equipped with hand-held two-way radios and wearable devices for life monitoring in order to ensure the personal safety of firefighters and carry out real-time monitoring and disaster relief for hard-to-reach locations.

E. Particle swarm optimization algorithm

We just need to know the frequency and scale of fire, and according to the needs of fire tasks, combined with SSA and relay system coverage, monitoring and communication ability, safety, cost and other indicators, then we can use particle swarm optimization algorithm to determine the optimal solution of UAV system in this area.

3. Firefighting system of drones for SSA and Radio Repeater

In order to determine the number and mix of drones for SSA and Radio Repeater, we established a GASE model considering the size and frequency of fire, combined with capability, safety and economy. To ensure the economy is the premise to improve the working ability and safety of drone system. The economic factor depends on the cost of UAV. When the number of UAVs is more, the cost is higher. The safety depends on the density of UAV. The higher the density is, the higher the safety is. Working capacity depends on the coverage rate of UAV communication and the number of received signals. The specific analysis process is shown in the following analysis process.

3.1. The collection and feedback process of radio signal

3.1.1. Electrical signal generation process and receiving progress. We will discretize the area where the fire may occur, that is, divide the area into small squares. Then we go on with the discussion.

Due to the range of the handheld two-way radio easily affected by the terrain, Suppose the nominal range of a radio on flat and barrier free ground is $R_{\text{max}}$ km, while in the urban area, due to the influence of buildings, its nominal range is reduced to $R_{\text{min}}$ km.

As shown in Figure 2, when Signal 2 is sent out, Signal 1 can receive the signal because it is located in a flat and barrier free area, and its Boolean value is 1; when Signal 2 is sent out, because it is located in a high altitude and multi barrier area, its effective acceptance range is $R_{\text{min}}$ km, so Signal 1 and Signal 3 cannot receive the signal sent out by Signal 2 and its Boolean value is 0. When the signal cannot be received, the range of receiving signal can be expanded by the droned with Radio Repeater. The generation process of electrical signal is opposite to the receiving process of electrical signal, but the principle is the same. Therefore, we can use Boolean quantity to indicate whether the radio signal in this area is within the acceptable range.

When the radio signal in an area can be successfully received, the drones in the area can smoothly upload the monitoring data in time, which indicates that the safety factor in the area is high, even if there is a fire, it can control the fire in time. Therefore, the cumulative sum of the signals received in the partition unit can reflect the capability and safety factor of the system.

$$\text{Info}_{\text{all}} = \sum_{i=1}^{n} \text{Info}_i = \sum_{i=1}^{n} \int_{0}^{T_{\text{max}}} \sum_{j} (\text{Bool}_j) F_j \cdot f dt$$

(1.)

Where: $T_{\text{max}}$ refers to the maximum cruise time of drones,$F_j$ refers to the severity of the fire in the area.

For the Emergency Operations Center (EOC), we can divide $F_j$ into the following categories.

| Disaster risk | Low risk | Medium risk | High risk |
|---------------|----------|-------------|-----------|
| $F_j$         | 0.3      | 0.6         | 0.1       |

**Table 1.** The value of $F_j$ (the severity of the fire in the area)
We assume that the maximum flight time of Drone is $T_{\text{max}}$ hour and the recharge time for the built-in battery is $T_c$ hour. $f$ refers to the frequency which a drone completes a cruise.

$$f = \frac{T_{\text{max}} + T_c}{T_{\text{max}}} \cdot \frac{K}{T_{\text{max}}} \quad (2.)$$

### 3.2. Drones for Radio Repeater

Because we divide the disaster area into equal area squares, taking a single drone as an example, its monitoring range is a circle with its own position as the origin and a radius of $D_{\text{max}}$ km. Since we divide the disaster area into equal area squares, taking a single drone as an example, its monitoring range is a circle with its own position as the origin and a radius of $D_{\text{max}}$ km. If the vertical distance between the upper and lower adjacent drone cruising areas is $D_x$, $D_y$, and the horizontal distance between the left and right adjacent drone cruising areas is $D_x$, the area obtained by multiplying $D_x$ and $D_y$ is $S_i$. When the $S_i$ value is larger, the density of drone is smaller; when the $S_i$ value is smaller, the density of drone is larger.

The horizontal distance between the left and right adjacent drone cruising areas is equal to the product of maximum cruise speed and cruise time. We assume that the cruise speed of Drone is $v$. The maximum cruise time is $T$. By dividing the average area of the total disaster area by $S_i$, we can get the number of drones for Radio Repeater in the area.

When the drone's cruise trajectory is shown in Figure 2, there will be a certain dead angle, which makes the drones unable to monitor the disaster situation in the dead angle area. Therefore, in order to improve the drone's working ability and safety factor, we set the drone's cruise area to be repeatable.

![3D plane picture](image)

**Figure 2.** Changed overlapping cruise zone

Through the figure, we can get the overlapping cruise area of the left and right adjacent drones (as is shown in the orange area in the figure) through geometric calculation. Also, we can get the overlapping cruise area of the front and rear adjacent drones (as is shown in the dark blue area in the figure).

$$S_{\text{orange}} = 2R^2 \arcsin\left(1 - \left(\frac{D_x}{2R}\right)^2\right) - D_x \sqrt{R^2 - \left(\frac{D_x}{2}\right)^2} \quad (3.)$$

$$S_{\text{dark}} = 2R^2 \arcsin\left(1 - \left(\frac{D_y}{2R}\right)^2\right) - D_y \sqrt{R^2 - \left(\frac{D_y}{2}\right)^2} \quad (4.)$$

Where: $R$ refers to the radius of the cruise area. Specially, if $D_x \geq 2R$, $S_{\text{orange}} = 0$; if $D_x \geq 2\sqrt{2}R$, $S_{\text{orange}} = 0$.

By combining formula (2) and (3), we can get the coverage rate in the rectangle.
Specially, if \( D_x \leq 2\sqrt{2} R \) and \( D_y \leq 2\sqrt{2} R \), \( K_{\text{cover}} = 1 \), that is full coverage.

The working ability of drones with radio repeater is also related to the coverage rate. When the coverage rate is higher, the communication range is larger, which indicates that the working ability of UAV is stronger.

### 3.3. Drones for surveillance and situational awareness (SSA)

The simplified diagram of observation area of single drone for SSA is the same to the simplified diagram of observation area of single drone for Radio Repeater. According to the requirements of "security video surveillance infrared thermal imaging equipment", we can set the monitoring radius of SSA as 2.05km.

For the drones for SSA, they monitor all kinds of information in the disaster area in real time and feedback the actual situation in time. For each drone for SSA, the cumulative sum of the signals received in the partition unit can reflect the capability and safety factor of the system.

\[
SU_R_{\text{all}} = \sum_{i=1}^{n} SU_R_i = \sum_{i=1}^{n} \int_0^{T_{\text{max}}} F_j f(d) dt
\]

For the SSA, we can divide \( F_j \) into the following categories.

**Table 2. The value of \( F_j \)**

| Disaster risk         | Low risk | Medium risk | High risk |
|-----------------------|----------|-------------|-----------|
| \( F_j \)             | 0.1      | 0.4         | 0.5       |

### 3.4. The number and the mix of drones for SSA and Radio Repeater

In order to remove the dimension of different objectives, we multiply each objective by a coefficient \( \lambda \). In this way, the multi-objective programming model is transformed into a single objective programming model, and then the particle swarm optimization algorithm is used to solve the optimal solution. The comprehensive evaluation model of GASE can be summarized as follows:

\[
\text{max } GASE = K_{\text{cover}} \text{ Info}_{\text{all}} + \lambda_0 \frac{R}{D_x D_y F_j} + \lambda_1 K_{\text{cover}} \text{ SU}_R_{\text{all}} + \lambda_2 \frac{1}{D_x D_y F_j} - \lambda_3 n
\]

Where: \( K_{\text{cover}} \) is the coverage rate.

Then, we normalize the objective function and use the ergodic algorithm of Matlab to calculate the optimal solution which minimize the cost, maximize the capacity and safety.

When purchasing drones, we should coordinate the fire risk degree and topography of different areas. Therefore, we will measure the geographical environment of the fire place through two indicators.

Firstly, it is divided into flat area (less obstacles) and rugged area (more obstacles) according to landform. Meanwhile, the terrain is divided into flat and barrier free suburbs, urban areas with dense buildings and high and barrier areas. As the impact of high terrain and barrier areas on disaster is similar to that of urban areas with dense buildings, we integrate the latter two into one case for analysis.

Secondly, according to the fire grade, it can be divided into low-risk area, medium risk area and high-risk area. By pairing up, we divide the fire areas into six categories. Therefore, we can get the probability of fire in six areas as follows.

**Table 3. Fire probability in six types of areas**

| Cases                        | Low risk  | Medium risk | High risk  | The sum |
|------------------------------|-----------|-------------|------------|---------|
| Low terrain without obstacles| 3.952%    | 2.632%      | 1.416%     | 8%      |
| High terrain with obstacles  | 45.448%   | 30.268%     | 16.284%    | 92%     |
| The sum                      | 49.4%     | 32.9%       | 17.7%      | 100%    |
Meanwhile, we use particle swarm optimization algorithm to calculate $D_x, D_y, D_x', D_y'$. Thus, the number and the mix of drones for SSA and Radio Repeater can be obtained. The algorithm steps and program block diagram for the number and the mix of drones for SSA and Radio Repeater are shown below.

**Figure 3. Flow chart of particle swarm optimization algorithm**

**Algorithm 1: Particle Swarm Optimization**

| Algorithm 1: Particle Swarm Optimization |
|------------------------------------------|
| **Input:** size: The number of population |
| dim: The maximum dimension                |
| ger: Iterations                          |
| $D_{max}$: The maximum value of $D_x$ and $D_y$ |
| $D_{min}$: The minimum value of $D_x$ and $D_y$ |
| $V_{max}$: The maximum value of $V$     |
| $V_{min}$: The minimum value of $V$     |
| **Output:** $D_x, D_y, D'_x, D'_y$       |
| 1 Initialize $c_1 = 0.135$: Inertia weight |
| 2 $c_2 = 0.135$: Self-learning factor    |
| 3 $c_3 = 0.135$: Group learning factor; |
| 4 best $\leftarrow$ Calculate the optimal solution of the initial population |
| for $i \in [1, dim]$ do                  |
| for $j \in [1, size]$ do                |
| 5 Update the learning factors of each parameter and the corresponding parameter |
| 6 $cur \leftarrow$ Calculate the optimal solution of the current population |
| 7 best $\leftarrow$ max(best, cur)       |
| 8 endfor                                   |
| 9 endfor                                   |

**Figure 4. The steps of particle swarm optimization**

### 3.5. Location of drones with Radio Repeater in complex terrains

When the drones for radio repeater are in complex terrain, that is, in the environment of high mountains and buildings and so on, its optimal position of drones and the performance of intermediate signal transmission and reception will be greatly affected. The survey shows that the optimal position of drones for radio repeater and the performance of intermediate signal transmission and reception are closely related to the propagation and coverage of relay signal [5].
The geometric relationship is shown in the figure above, where \( h \) refers to the height of drones for Radio Repeater; \( L_n \) refers to the maximum receiving radius of repeater signal; \( L_n' \) refers to the actual receiving radius of repeater signal in different terrain; \( L_d \) refers to the maximum transmission radius of repeater signal; \( L_d' \) refers to the actual transmitting radius of repeater signal in different terrain.

From the figure, when the drones are on the plane of the maximum chord length of the sector, the range of the received signal is the largest. Therefore, in order to improve the efficiency of the system, we assume that the drones with radio repeater are all on the plane of the maximum chord length. From this we can get the geometric relation in this case.

\[
h_0 = L_n \sin \theta, \quad 0^\circ < \theta < 50^\circ
\]

The signal receiving area of radio repeater is as follows.

\[
 RA = \pi L_n'^2
\]

The signal transmission area of radio repeater is as follows.

\[
 SA = \pi L_d'^2
\]

If \( h \geq h_0 \), \( L_n' = L_d \cos \alpha, \quad \theta \leq \alpha \leq 90^\circ \); \( h < h_0 \), \( L_n' = \frac{h}{\tan \theta} \), \( L_d' = \sqrt{L_d^2 - h^2} \).

We can set the position model of drones with radio repeater in complex terrain as a single objective optimization model.

\[
\begin{align*}
\text{max} & \quad \frac{RA}{RA_{\text{max}}} + \frac{SA}{SA_{\text{max}}} \\
\text{s.t.} & \quad h_0 = L_n \sin \theta, \quad 0^\circ < \theta < 50^\circ \\
& \quad \begin{cases} 
L_n' = L_d \cos \alpha, \quad h \geq h_0 \\
L_n' = \frac{h}{\tan \theta}, \quad h < h_0 
\end{cases} \\
& \quad \begin{cases} 
L_d' = \sqrt{L_d^2 - h^2}, \quad h < h_0 \\
\theta \leq \alpha \leq 90^\circ 
\end{cases}
\end{align*}
\]

4. Simulation and evaluation

Based on the factors of economy, safety and performance, the comprehensive optimization layout model of UAV in monitoring system is evaluated. The combination and quantity of unmanned aerial vehicles (UAVs) required by UAV deployment schemes under different geographical environments and fire scales are given. The influence of increasing fire risks on UAV demand and the influence of geographical environment on the optimal space position of UAVs are discussed.
A. Parameter design
In this section, based on the forest fires in Victoria, Australia, and combined with the data of related equipment, the parameters of simulation experiments are given, as shown in the following table.

| Simulation parameters                                      | Numerical value |
|------------------------------------------------------------|-----------------|
| The maximum range of the handheld radio                    | 5km             |
| The range of the handheld radio in complex areas           | 2km             |
| The relay radius of the drone                              | 20km            |
| The sensing radius of the SSA drone                         | 2.05km          |
| The endurance time of the drone                            | 2.5h            |
| The cruise speed of the drone                              | 12m/ s          |
| Drone charging time                                         | 1.75h           |

B. The influence of scheme score and drone density

From the figure above, we can know that before reaching the optimal solution, with the increase of $D_x$, the density of UAVs decreases, which leads to the decrease of the total number of UAVs and the cost. Since the decrease of capability and security is less than the decrease of cost, the total score increases. After reaching the optimal solution, since the decrease of capability and security is greater than the decrease of cost, the total score decreases.

Moreover, before reaching the highest score, with the increase of the number of drones, the cost increases, and the work ability and safety also increase. But since the increase of the work ability and safety is greater than the increase of the cost, the total score increases with the increase of the number of drones. After reaching the highest score, because the increase of work ability and safety is less than the increase of cost, the total score decreases with the increase of quantity.

C. Impact of global climate change and fire risk
We take Victoria in Australia, where mountain fires occur frequently, as an example. From Kaggle [6], we can find the frequency of fires occurred in a day and the average area of a fire in Victoria. We can search the fire frequency data of Victoria in recent ten years through the website (Global Forest Watch) [7], and then draw the relationship between the fire frequency and the year and month through MATLAB.
From the picture, we can see that the frequency of fire has a certain growth trend and periodicity, so we use the seasonal series of ARIMA model, according to the historical data of Victoria, to predict the development trend of fire in Victoria in the next 10 years (See in Figure 5.2).

D. Optimal UAV scheme
By traversing, we can get the number of drones for SSA and Radio Repeater with the highest GASE.

| Cases                             | Drones     | Number of drones |
|-----------------------------------|------------|------------------|
|                                   |            | Low risk | Medium risk | High risk |
| Low terrain without obstacles     | SSA        | 1        | 3           | 20        |
|                                   | Radio Repeater | 1       | 1           | 1         |
| High terrain with obstacles       | SSA        | 27       | 34          | 81        |
|                                   | Radio Repeater | 12      | 7           | 4         |
| Low terrain without obstacles     | SSA        | 4        | 7           | 32        |
| (After adjustment)                | Radio Repeater | 2       | 2           | 2         |
| High terrain with obstacles       | SSA        | 4        | 7           | 132       |
| (After adjustment)                | Radio Repeater | 2       | 2           | 2         |

E. Influence of environment on space position of UAV
Similar to the solution of problem one, through particle swarm optimization, we get the optimal position of UAV in different landforms, different fires and small scale.

From the pictures, we can know that before reaching the peak, the higher the height of UAV, the higher its working ability and safety, so the total score increases with the increase of height. After
reaching the peak, with the increase of UAV height, its working ability and safety decrease, so the comprehensive score decreases with the increase of UAV height.

Through the particle swarm optimization algorithm, we can get the optimal solution when the minimum elevation of signal transmission is 30 ° in the case of complex landform.

\[ h = 2.5 \text{ km} \]

A. Influence of environment on UAV comprehensive optimization layout model

When the fire area is large, the more drones for SSA and Radio Repeater will be sent to monitor the situation. Therefore, in general, the fire area that "rapid bushfire response" needs to deal with is one of the factors that affect the comprehensive score of the system. Therefore, we draw the comprehensive score curve of the system under different areas through MATLAB

![Comprehensive score curve under different areas](image)

Figure 11. Comprehensive score curve under different \( \bar{S} \)

From the figure above, it can be seen that the model is rather sensitive to higher the fire area that "rapid bushfire response" needs to deal with. Furthermore, each curve has an optimal correspondence, which is at the peak of the curve. Meanwhile, it can calculate the number of drones for Radio Repeater.

B. Sensitivity Analysis with respect to pitch angle of drones

When the position of drone is different, the pitch angle between drones and electrical signal is different. If the pitch angle increases, the actual range of receiving and transmitting signals of drones decreases. Moreover, because the working ability and safety factor of drones are related to its actual receiving and transmitting signal area, the pitch angle is a major factor affecting the system. So, we draw the corresponding curves at different pitch angles to observe their influence on the system.

![Corresponding height change curves under different pitching angles](image)

Figure 12. Corresponding height change curves under different pitching angles

As is shown in the figure above, we can draw a conclusion that the system is rather sensitive to lower the pitch angle of drones for radio repeater. Before reaching the peak, with the increase of UAV height,
the total evaluation score shows exponential growth in different degree. Furthermore, the smaller the pitch angle, the greater the optimal comprehensive score.

5. Conclusions and Future Work
In this paper, we comprehensively consider the frequency and scale of fires, according to the needs of firefighting tasks, combined with SSA and relay system coverage, monitoring and communication capabilities, safety, cost and other indicators, establish an evaluation model to measure different procurement plans to improve the efficiency of forest wildfire monitoring and prevention.

In fact, the occurrence of fire is also affected by human activities and some other factors, which needs careful consideration. But this is not the focus of this paper, so we simplify it.

In the optimization process of UAV procurement scheme, we have balanced performance and cost, but this does not mean that it is 100% safe. Greater than the budget and procurement volume of our scheme may lead to a substantial increase in the cost-effectiveness ratio of the procurement scheme, but it will also bring better security. We believe that life is the most precious.

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