Problem Chosen	2021 MCM/ICM Summary Sheet	Team Control Number
B		2120710

Fighting Wildfire with Unmanned Aerial Vehicles

Summary

在这里写 summary

key words : 关键词 1; 关键词 2; 关键词 3

Budget Request

Project name: Equipment Procurement for Rapid Bushfire Response
Date submitted: February 8th, 2021

This Budget Proposal provides necessary costs associated with the above named project (the "Equipment Procurement for Rapid") which we would like to pursue . Costs for the Project have been itemized in this Budget Proposal below and justification has been provided for each cost element. Should you have any questions related to this Budget Proposal, please do not hesitate to contact the undersigned.

PROJECT DESCRIPTION

The state of Victoria has a long history of bushfires, which causing life loss and property damage of varying sizes every year. In the recent years, with advances in technology, we have the opportunity to further reduce the impact of bushfires in Victoria. To better protect lives, interests, and the ecosystem of the state, a new division of **CFA**, named as Rapid Bushfire Response, would be intended to found, which would aiming at responding quickly to bushfires.

PROJECT PURPOSE

In order to equip the proposed new division, it was necessary to build a effective and sensitive monitoring system for bushfires, which could strongly assist the front-line personnel in the daily work of bushfires management. Thus, **CFA** need the budget to purchase SSA drones and Radio Repeater drones for the monitoring.

COST ELEMENTS

The following are necessary cost elements of the Project:

COST SUMMARY

This budget was developed by **CFA** of Victoria with adequate modeling that supported this estimate. By the signature below, we hereby certify that this

Budget Proposal reflects the best estimate of the true and necessary costs for the Project, and the information provided herein is accurate, complete and current as of the date of the signature below.

Country Fire Authority, VIC Australia
[First Name][Last Name]
[Titile]

Contents

1 Introduction

1.1 Restatement of the Problem

Many people...Therefore we are facing the following problems:

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1.2 Our Works

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2 Assumptions and Notations

2.1 Assumptions

Due to the lack of necessary data, we make the following assumptions to help us perform modeling:

1. The circumstance remain unchanged in the time interval we investigated.
2. We omit the possibility of any other kinds of aerial vehcle or flying creature hitting our UAV.
3. Accroding to Bureau of Meteorology of Australian Government, litghting is the major causation of bushfire in some area, Victoria included [1]. Based on this fact, we evaluat the possibility for a certain place to catch fire with the possibility of a lightning to occour there.
4. We adopt the Equal Possibility Hypothesis when our UAVs are patrolling for the purpose of monitoring any outbreak of fire.Under this hypothesis, an area of high possibility to catch fire indicates the frequency of fire outbreak here is high, thus the command center should pay closer attention to this area to alarm fire outbreaks timely.
5. All UAVs are equipped with a timer.

6. All UAVs are directed by a preprogrammed system given by us, which means they are all automatic.
7. Staffes are always available in any charging stations, which guarantees the UAVs will always work in the stanterd situation.
8. A drone can carry either a set of thermal imaging cameras and telemetry sensors or a radio repeater. The former combination can and can only detect any fire outbreak while the later combination can and can only extend the valid zone of radio wave signals.
9. Since recovering the lost drones is difficult and sometimes even physically impossible, and the cost of buying new ones are very high, we would not allow any drone to land outside the charging stations.

2.2 Notations

2.2.1 *ijk*-coordinate system

Before illustrating the notations for model construction, we would like to introduce a special coordinate system called ***ijk*-coordinate system** [2], which was first proposed by Uber Technologies Inc.

Discrete hexagon planar grid systems naturally have 3 coordinate axes spaced $120°$ apart. We refer to such a system as an *ijk* coordinate system, for the three coordinate axes i, j, and k.

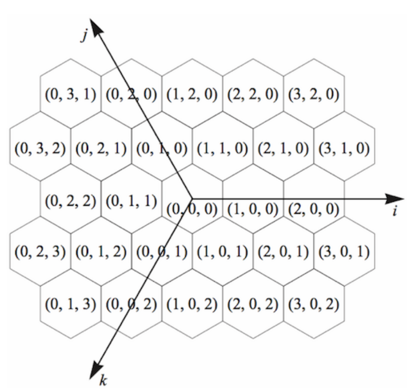

Figure 1: One possible map example that using the *ijk* coordinate system

2.2.2 Notations

Here are all the notations and their meanings in this paper.

Table 1: Notations used in model construction

Notation	Meaning
$M(i,t)$	Location of the i-th drone I at time t
$R(j,t)$	Location of the j-th drone II at time t
$h(x,y,z)$	Elevation of the point (x,y,z)
$S(x,y,z)$	Fire history of the point (x,y,z) in the passed 5 years
$a_i(x,y,z)$	Fire history of the point (x,y,z) in the $2020-i$-th year, $i \in [1,5] \cap \mathbb{N}$
$F(x,y,z)$	Vegetation and urbanizing condition of the point(x,y,z)
$Str(i,x,y,z,t)$	Signal strength of the i-th drone at point (x,y,z) at time t
$E(x,y,z,N)$	Supervisory density of the point (x,y,z) when there are N drones in the field
$Slope(x,y,z)$	Maximum slope of the point (x,y,z)
γ	Factor related to the weight of slope in causing bushfire
$\beta(x,y,z)$	Weight of slope in causing bushfire
$\omega(x,y,z)$	Decreasing rate of signal at point (x,y,z)
α	Factor related to the weight of elevation in causing bushfire
$Chg(q,x,y,z)$	Location of the q-th charging station
$V_{\max}$	Maximum flying velocity of a drone
N_{SSA}	Amount of drone I
N_{rep}	Amount of drones II
PF	Power consumption for a flying drone
PH	Power consumption for a hovering drone
$t_{\text{fl}}(t,l)$	Flight time of the l-th drone until time t
$t_{\text{hov}}(t,l)$	Hovering time of the l-th drone until time t
T	Duration of a day (i.e. $T = 1440\,\text{min}$)
t	Current time
Br	Total battery power of a drone
Ini	Location of the EOC

3 Model Construction

3.1 Multi-factor Evaluating Model

In this section, we introduce a H3 and multi-factor evaluating model to data-orienting the topographic conditions of the state Victoria in Australia.

First, in order to simplify the question, we cover the state with hexagons in dense tiled layout. We consider that the valid zone of radio wave signal radiated by a UAV is a spherical area of radius 20 km, and the length of each side of hexagon is 1.22 km.

Next, we evaluated each segment from 4 dimensions, which are: density of forest coverage, elevation, slope and fire history. We consider the influence of the listed dimensions from two aspects: how dose it influence the possibility to catch fire for the area and how does it influence the propagation of radio wave signal. The mechanism and significance of these factors are discussed below.

3.1.1 The Influence of Vegetation and Other Ground Facilities

According to Dissing and Verbyla (2003) [3], thermal circulations triggered by differential heating among distinct types of vegetation results in a higher probability for a lighting strike to occur. But according to a later research based in the State of Victoria (Kilinc and Beringer 2006 [4]), vegetation type and density in Southern region of Australia have little impact on the occurrence rate of lightning. Mainly because of the homogeneity of forests.

On the other hand, the leafage has a significant impact on the reflection behavior of radio wave, which plays an important part in the propagation process. Different researches have been done to estimate the decreasing rate of radio wave in varies situations, the shared mechanism underneath is Fresnel's Law. We divided the surroundings into three categories: forests, plain, cities, then we estimated the decrease factor and valid zone for the radio signal distinctively.

Since the given signal's frequency ranges from 300 megahertz to 3,000 megahertz and from 30 megahertz to 300 megahertz, which are considerably high, so it is difficult for the signal to steer by high-rise structures, including tall buildings and mountains. When our drones are passing through the plain area, the the energy lose for the signal strengths is in the air, so the radius of the valid zone for the signal reaches it's maximum of 20km. When the drone is passing a urban area, high obstacles diminished the zone and the radius reaches it's minimum of 5km. When the drones are flying or hovering in forest region, two situations should be discussed separately, the ground signal from wearable devices on front-line personnel and the aerial signal from another drone. According to the data of the experiments done by Y.S. Meng.et.al (2010) [5], when the signal is launched in woods, the signal strength decreases linearly with the frequency of radio wave, and distance (Y. S. Meng.et.al 2009 [6]).

According to their model, the foliage loss in forest region is defined by the equation below:

$$L(\text{dB}) \cong 0.48 f^{0.43} d^{0.13} \tag{1}$$

Considering the drone-to-drone signal propagation, we simply omit the influence of trees, for it is reasonable for flying vehicles to stay above the forests. According to Meng, the background noise is around -75 dBm, so we consider the signal to be undetectable if its strength is lower than -70 dBm. Which means that when the strength loss is over 18 dB, we consider this point to be inaccessible. Using Equation (1) and the data we have, we can verify the decreasing coefficient for different area as follow:

$$\overline{\omega}(x, y, z) = \begin{cases} \overline{\omega}_{\text{city}} = 0.25, \\ \overline{\omega}_{\text{forest}} = 0.5, \\ \overline{\omega}_{\text{plain}} = 1 \end{cases} \tag{2}$$

3.1.2 The Influence of Elevation and Slope

As we mentioned above, the Mountains would worsen the signal, thus, it is natural to introduce an elevation factor A here to evaluate the impact of elevation on causing bushfires.

Annual lightning strikes were so connected to local elevation and slope that many scholars have been using topographic methods to predict bush-fire in mountainous regions [7]. Previous research has shown that strike density has a great leap while the local elevation reaches 800 meters and increases linearly with elevation [4], and it is more likely for a mountainous area to form strikes comparing to an area with only one high-rise peak [7].

3.1.3 The Influence of Fire History

Burned area is more likely to be caught on fire in the future, according to Musa Kilinc and Jason Beringer [4]. Because ecological environment has been destroyed in the fire, which results in a low capability of local temperature and low capacity of water. None the less, the coked ground with dark shade will absorb more heat than green forests. All these traits formed a hot dry area which can be easily lighted by strikes.

3.1.4 Functionizing the state of certain location

To describe a certain location (x, y, z) in the *ijk* coordinate system, we adopted a series of functions...

The elevation of the location is denoted by $h(x, y, z)$, while its slope is denoted by $Slope(x, y, z)$, which means the maximum slope around one point:

$$Slope(x,y,z) = \max\left\{\frac{\|h(x,y,z) - h(x+m,y+n,z+k)\|}{|m|+|n|+|k|}\right\}, \quad m,n,k \in \{-1,0,1\}, \tag{3}$$

Besides, The unit of $h(x, y, z)$ and $Slope(x, y, z)$ are both meters. The weight of $Slope(x, y, z)$ in causing bushfires is

$$\beta(x,y,z) = \gamma \cdot \max\left\{\frac{Slope(x,y,z) - Slope(x+m,y+n,z+k)}{|m|+|n|+|k|}\right\}, \quad \gamma \text{ is a constant, and } m,n,k \in \{-1,0,1\}, \tag{4}$$

The vegetational and urbanizing condition $F(x, y, z)$ is defined as the following equation:

$$F(x,y,z) = \begin{cases} 1, & (x,y,z) \text{ locates in forests,} \\ 0, & \text{otherwise.} \end{cases} \tag{5}$$

The influence of fire history is quantified by bushfire frequency in the passed 5 years (i.e. 2016-2020) :

$$S(x,y,z) = \sum_{i=1}^{5} (1+\epsilon)^{\frac{1}{i}} \cdot a_i, \quad a_i = \frac{f_i}{23}, \tag{6}$$

Here f_i is the amount of fire cases in the $n-i$-th year.

Then we define a function $V(x,y,z)$ to represent how possible a point will catch fire. It is defined below :

$$\begin{aligned} V(x,y,z) = & V_1(x,y,z)\cdot V_2(x,y,z), \\ \text{Note:} \qquad V_1(x,y,z) = & \,[0.58F(x,y,z) \\ & + \alpha\,(h(x,y,z)-800)\cdot\beta\cdot u(h(x,y,z)-800)], \\ V_2(x,y,z) = & \left[1+\frac{\ln\left(1+S\left(x,y,z\right)\right)}{3}\right], \end{aligned} \tag{7}$$

here $u(\delta)$ is the stair function:

$$u(\delta)=\begin{cases}1, & \delta>0,\\ 0, & \delta\le 0.\end{cases} \tag{8}$$

3.1.5 Future situation in a decade

To predict the changing situation in the next decades, we reevaluate the area in the future with the multi-factor model above. Since we do not take extreme events into consideration (severe war, earthquake, tsunami, meteorolite, EI Nino etc.), the landscape and urban constructions will not change much in the next decade.

The only changing factor is the fire history, which was evaluated by Equation 6. When assessing the situation in the future, $V(x,y,z)$ should be the possibility of catching bushfires on that year instead. For instance, if $V(x,y,z)>867.35$ holds for sometime in the next decades, it means the possibility of catching bushfires is 95% .

3.2 Use Nervous System Model to find the best arrangement of UAVs

Widespread bushfires in Australia are usually preceded by strong winds, a small-scale burning forests can evolve into destructive fires. So in other to minimize the damage caused by bushfires, it is reasonable to build up a monitoring and alarming system to supervise the region before any outbreaks. In this section, our group build up a model imitating the nervous system to sort out the best arrangement of UAVs.

In our model, drones with thermal imaging cameras and telemetry sensors (drone I) are send out to petrol around the state, detecting fire outbreaks and sending back images, they are working as sensors of a nervous system. While drones with radio repeaters (drone II) act like ganglion, they receive signals and send them out immediately, the command center is the brain in this system. Our goal is achieved by two steps. First, find the best routes for dronesI. In order to react to fire out breaks timely, the monitoring system should

- Cover the state with its valid zone,
- Pay closer attention to the points who have higher probability of catching fire.

To further the discussion, we have two new functions: first for signal strength, and second for average signal density of one point:

$$Str(i,x,y,z,t) = u\left(8 - \|(x,y,z) - M(i,t)\|\right), \tag{9a}$$

$$E(x,y,z,N) = \sum_{i=1}^{N_{\text{SSA}}} \frac{1}{T}\int_0^T S(i,x,y,z,t)dt, \tag{9b}$$

From the discussion in section 1, we construct the function to evaluate how high the possibility is for a point to catch fire, and here we introduce a function $Judge(x,y,z)$ defined as $Judge(x,y,z) = \frac{\eta \cdot E}{V} - 1$ to judge whether a point is safe enough, by safe enough we mean the possibility for any drone I to discover a outbreak immediately is high. Here we set the threshold to be 80 percent, thus $\lambda_{\text{safe}} = 0.8$.

Second, we should link the sensors to the brain. As discussed in the section 1, we omit the signal loss caused by forests, but we take the influence of high buildings into consideration. So here we define two kinds of vectors $D_i(t) = [d_{ij}(t)]$ and $Q_j(t) = [b_{jk}(t)]$ to represent the signal path from sensors to the center. The vectors are defined as below:

$$d_{ij}(t) = \begin{cases} 1, & \text{if } 0 < \|M(i,t) - R(j,t)\| < 8, \\ 0, & \text{otherwise}, \end{cases} \tag{10a}$$

$$b_{jk}(t) = \begin{cases} 1, & \text{if } 0 < \|R(k,t) - R(j,t)\| < 8, \\ 0, & \text{otherwise}, \end{cases} \tag{10b}$$

Here i denotes the number of drone Is, while j and k denote the number of drone IIs.

To guarantee that the command center can react to any out break in time, the signal paths should keep unimpeded at all time, then the variables are limited by the following inequality constraints under this requirement.

$$\sum_{j=1}^{N_{\text{rep}}} d_{ij} \geq 1, \quad i = 1, 2, \cdots, N_{\text{SSA}} \tag{11a}$$

$$\sum_{k=1}^{N_{\text{rep}}} b_{jk} \begin{cases} \geq 1, & \text{if } \sum_{i=1}^{N_{\text{SSA}}} d_{ij} \geq 1, \\ \geq 2, & \text{otherwise,} \end{cases} \tag{11b}$$

One last thing should be considered in this section, which is the recycle of drones. Under assumption 9 (see section 2.1), none of our drones would be allowed to go further than the distance they can get back to charging stations before they run out of buttery. This give the constraints below.

$$t_{\text{hov}} + t_{\text{fly}} = t - 105n, \tag{12a}$$

$$\begin{aligned} \text{Denotion: } & k(n, t_{\text{fly}}, t_{\text{hov}}) = n \cdot Br - PF \cdot t_{\text{fly}} - PH \cdot t_{\text{hov}}, \\ & k(n, t_{\text{fly}}, t_{\text{hov}}) \geq \frac{\min\{\|M(i,t) - Chg(q)\|, q\}}{0.417 \cdot V_{\max}}, \ \forall t \forall i, \\ & k(n, t_{\text{fly}}, t_{\text{hov}}) \geq \frac{\min\{\|R(j,t) - Chg(q)\|, q\}}{0.417 \cdot V_{\max}}, \ \forall t \forall j, \end{aligned} \tag{12b}$$

Here 0.417 is the transformation coefficient between real velocity and grid velocity, and n shows how many times that i-th drone went back to any charging station.

3.3 Model for Rapid Bushfire Response

Once any fire is spotted, command center will respond to the situation immediately, making sure that the communication network build up by UAVs will available in as possible a short time as possible. As discussed in section 1, the signal from forward teams will be weaken by vegetation and elevation. So here we should reconsider the signal strength around the fire,

$$Str'(i,x,y,z,t) = u \cdot [\overline{\omega} \cdot 8 - \|(x,y,z) - M(i,t)\|] \tag{13}$$

then we recalculate the average signal density of one point depending on time,

$$E(x,y,z,N,t) = \sum_{i=1}^{N_{\text{SSA}}} \frac{1}{T} \int_0^T S(i,x,y,z,\tau)d\tau, \tag{14}$$

when the new signal density surpass the threshold we set, we regard this point to be accessible and hover the drones to hold the signal. The time interval between the moment fires have been spotted and the time the communication network has been build is the reacting time, and we want it to be as short as possible. Under these assumptions we can find out an efficient way to re-construct the distribution of drones.

3.4 Model for Hovering Drones for Fires of Different Sizes on Different Terrains

In the first model, we evaluated each hexagons from 4 aspects, and in the third model we considered the decreasing rate in different terrains, so in this model we combine this two models to sort out the best hovering positions for fires of different sizes on different terrains.

It is reasonable for us to assume that the forward teams will never go inside a burning forest, so the valid zone of radio signal only need to cover the premier of any fires. Since we want to keep the drones static to hold the signal path, and at the same time, we need them to come back when they are running out of buttery, so we arrange the drones as below:

- We need drone IIs to keep in touch with the front teams;
- We need drone Is to monitor and report data from wearable devices on front-line personnel;
- As long as there is a fire spotted, except the drones needed to build the communication net, other drones will go back to charge stations to stand by.

To satisfy these requirements we again recalculate the signal strength average signal density as below,

$$Str_{\chi}(i,x,y,z) = u \cdot \left[\overline{\omega} \cdot 8 - \|(x,y,z) - M(i)\|\right], \chi = \text{I,II}, \tag{15}$$

$$E_{\chi}(x,y,z) = \sum_{i=1}^{N} Str_{\chi}(i,x,y,z)\chi = \text{I,II}, \chi = \text{I,II}, \tag{16}$$

because the drones are now static, the signal now is a constant as time changes.

We also need the forward drones to be connected to the command center. This restriction is described by the formulas below.

$$d_{ij}(t) = \begin{cases} 1, & \text{if } 0 < \|M(i,t) - R(j,t)\| < 8, \\ 0, & \text{otherwise}, \end{cases} \tag{17a}$$

$$b_{jk}(t) = \begin{cases} 1, & \text{if } 0 < \|R(k,t) - R(j,t)\| < 8, \\ 0, & \text{otherwise}, \end{cases} \tag{17b}$$

$$\sum_{j=1}^{N_{\text{rep}}} d_{ij} \geq 1, \quad i = 1, 2, \cdots, N_{\text{SSA}} \tag{17c}$$

$$\sum_{k=1}^{N_{\text{rep}}} b_{jk} \begin{cases} \geq 1, & \text{if } \sum_{i=1}^{N_{\text{SSA}}} d_{ij} \geq 1, \\ \geq 2, & \text{otherwise}, \end{cases} \tag{17d}$$

4 Model Simulation

4.1 Nervous System model for UAVs Monitoring System

4.1.1 Adapting for Future

4.2 Modeling for Rapid Bushfire Response

4.3 Model for the hovering drones SSA and Radio Repeater

5 Sensitive Analysis

5.1 ensitivity of parameters

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5.2 Robusticity of the models

6 Strength and Weakness

6.1 Strength

6.2 Weakness

7 Conclusion

We build a.....interesting findings:

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Appendices

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Appendices A

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