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

Fighting Wildfire with Unmanned Aerial Vehicles

Summary

In this research, we developed three models to simulate the use of Unmanned Aerial Vehicle in fighting fires. We use a hexagon coordinate system to modelize the region, and apply multi-factor evaluation to represent the landscape condition of the region. We also visualize the result to have a straight forward understanding to the situation.

We use a Nervous System Model to describe the drones monitoring system. We use dynamic planning to sort out the solution: the least amount of SSA drones and repeater drones needed is 36 and 96.

We use Drone-Terrian model to design the optimal hovering positions for drones in different terrains,we also visualize the result to give out the best hovering strategy.

key words : Dynamic planning; Hexagonal coordinate system; Bushfire; Drones

Contents

1 Introduction

Australia is one of the countries around the world with the perennial problem of wildfire. Devastating fire can destroy forests, burn down houses and even causes life loss. Even though fighting fires is a dangerous task some times cause death, there are brave and selfless "Boots-on-the-ground" forward teams striving to protect civilians.

Fortunately, the advances of technology brings us Unmanned Aerial Vehicle (UAV), which provides a possible solution. WileE-15.2X Hybrid Drone is one kind of UAV. It weights 1.3 kg when equipped with certain devices. The WileE drone can keep flying for 2.5 hours or keep hovering for 2 hours if was fully charged. The drones equipped with thermal imaging cameras and telemetry sensors are called surveillance and situational awareness(SSA) drones. SSA drones can collect data from front-line personnel and detect the local temperature. Other drones equipped with radio repeater can receive signals and extend radio range.

With these two kinds of drones, we can build a monitoring and quick-reacting system to detect fire out breaks and connect the front teams to EOC.

2 Assumptions and Notations

2.1 Assumptions

Due to the lack of necessary data, we make the following assumptions:

1. Considering the flight altitude and cruise path of the drone, the possibility of the drone encountering any accident could be ignored.
2. Accroding to Bureau of Meteorology of Australian Government, lightning is the leading cause of bushfires in southeastern Australia. [1]. Since Victoria is right in the area, we would like to consider lightning as a factor that would have impact on the possibility for a certain place to catch wildfires.
3. Equal Possibility Hypothesis is adopted when modeling.
4. All UAVs are equipped with a timer.

5. All UAVs are directed by a preprogrammed system, i.e. they decide the routes for themselves.
8. The UAVs could always be charged as soon as they land at charging stations, as staffs are always available there.
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.

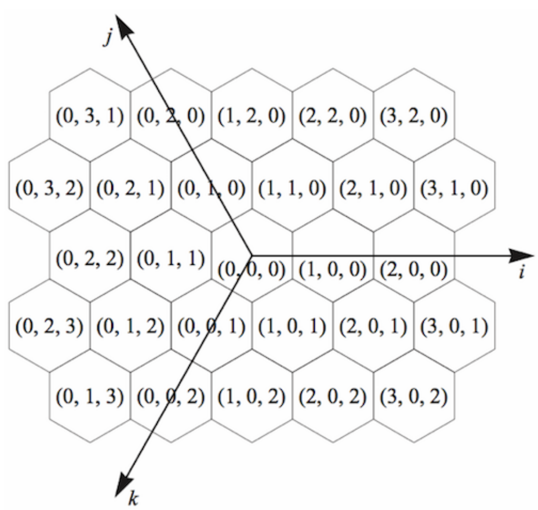

Figure 1: Map Sample with One Possible *ijk* Coordinate System

2.2.2 Notations Based on the *ijk* coordinate system

The notations used in this paper are listed as follows:

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 Risk Assessment: Bushfire Risk Model

Bushfire risk model measures the probability of catching bushfire for locations in Victoria.

3.1.1 Applying *ijk* Coordinate System

To simplify the problem, we do hexagonal paving on the map. Each of the hexagon is 22.6 km in length. In addition, We consider the effective area of radio wave signals sent by UAVs to be a spherical area of 20 km radius. Each segment is evaluated from 4 perspectives:

- Density of forest coverage,
- Elevation,
- Slope,
- Fire history,

The listed items above have impacts on two things:

- The possibility of catching fire;
- The propagation of radio wave signal.

3.1.2 Vegetation and Other Ground Facilities

According to Dissing and Verbyla (2003) [3], thermal circulations triggered by the heating difference among distinct types of vegetation results in a higher probability for a lightning strike to occur. However, a later research based in the State of Victoria (Kilinc and Beringer 2006) claims, that the type and the density of vegetation in Southern Australia have little impact on the occurrence rate of lightning [4]. The major cause of lightning there is the homogeneity of forests.

Besides, the leafage has a significant impact on the reflection property of radio wave, which plays an important part in the propagation process. Several different researches have estimated the decreasing rate of radio wave in various situations. Basing on these results, we consider the state have three types of region: forests, plain, cities. Then we estimated the decreasing factor and valid zone for the radio signal distinctively.

Since the given signals' frequencies are considerably high, it is difficult for the signal to bypass the high-rise barriers like skyscrapers and mountains. When the drones are passing through the plain, energy loss is little, as the signal only passes through the atmosphere. Under this condition, the radius of the signal's valid zone reaches it's maximum of 20 km. However, high obstacles diminished the zone and the radius reaches it's minimum of 5 km when passing the urban areas. When flying or hovering in the forest regions, the ground signal from front-line personnel's devices and the aerial signal from other drones act differently. According to the experiments of 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]).

In the model of Meng's team, the foliage loss in forest region is defined by the equation below:

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

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 the signal is considered to be undetectable if its strength is lower than -70 dBm. It indicates that when the strength loss is over 18 dB, the point would be regarded as an inaccessible point. Applying Equation (1) to the data we have, it could be verified that the decreasing coefficient for different area are as the equations below:

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

3.1.3 Elevation and Slope

As mentioned above, the Mountains often cause radio signal loss. Hence, it is natural to introduce an elevation factor α that can be used to evaluate the impact of elevation on causing bushfires.

Lightning strikes were so related to local elevation and slope that many scholars have been using topographic methods to predict bushfires in mountainous areas [7]. Previous researches show that strike density has a great leap when the elevation reaches 800 meters, and then it increases linearly with elevation [4]. Besides, lightning strikes is more likely to formed in the mountainous areas, comparing to the areas with only one high-rise peak [7].

3.1.4 Fire History

The burned areas tend to catch fires 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.

3.1.5 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:

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

3.1.6 Future situation in a decade

To predict the changing situation in the next decade, we reevaluate the area in the future with the 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 UAV Arrangement: Nervous System Model

Widespread bushfires in Southeastern Australia are usually preceded by strong winds, a small-scale burning forests can evolve into destructive fires. To minimize such damage, we feel obliged to set a bushfire monitoring and alarming system. In this section, we would introduce a model imitating the nervous system. This model is aiming to figure out the best arrangement of UAVs.

In our model, drones with thermal imaging cameras and telemetry sensors (denoted as drone I) are send out to petrol around the state, detecting fire outbreaks and sending back images. they are working as sensors of the nervous system. Correspondingly, the drones with radio repeaters (denoted as drone II) act as the ganglion, they receive signals and send them out immediately, the command center is the brain in this system.

Our goal is reached by two steps. The first is to find the best routes for dronesI. The following two items can help the monitoring and alarming system react to fire outbreaks in time:

- The whole state is within the monitoring system's valid zone;
- The places that are more probable to catch fire should be paid more attention to.

To further the discussion, two new functions was introduced: first for signal strength, denoted as $Str(i, x, y, z, t)$, and second for average signal density of one point, denoted as $E(x, y, z, t)$:

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

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

In the former discussion, we construct the function to evaluate how high the possibility is for a point to catch fire. Here, similarly, 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: for any drone I, the possibility to discover a bushfire outbreak immediately is high. Here we set the threshold to be 80%, i.e. $\lambda_{\text{safe}} = 0.8$.

Then we are going to link the two types of drones, as in the nervous system the sensors should be linked to the brain. Follow what we mentioned in previous sections, we omit the signal loss caused by forests. However, we would take the influence of high buildings into consideration. And here we define two kinds of vectors $D_i(t) = [d_{ij}(t)]$ and $Q_j(t) = [b_{jk}(t)]$ to represent the signal paths 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 ensure that the command center can react to any outbreaks in time, the signal paths should keep unimpeded at all time. Therefore, the variables are limited by the following inequality constraints:

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

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

The last factor considered in this section is the charging strategy 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. These ideas triggered the constraints below:

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

$$\text{Denotion: } k(n, t_{\text{fly}}, t_{\text{hov}}) = n \cdot Br - PF \cdot t_{\text{fly}} - PH \cdot t_{\text{hov}},$$

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

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 Generalization: Drone-Terrain Model

In the first model, we evaluated the hexagonal segments of region from 4 aspects; In the second model we considered the decreasing rate in different terrains. Now, in this model, it was high time to combine the former two models. In this section, our goal is to figure out the best hovering positions for monitoring fires of different sizes on different terrains.

It is reasonable to assume that the front-line staff teams would never enter a burning forest, thus, the valid zone of radio signal need to cover only the frontier of any fires. A tricky way to maintain the signal path is to keep the drones static. Meanwhile, the drones need to come back when nearly running out of battery. Therefore, in this model, arranging the drones as below might work well:

- Drone IIs are supposed too keep in touch with the front-line teams;
- Drone Is are supposed to monitor and report data from front-line personnel's wearable devices;
- All the drones will return to the charging stations as long as any fire spotted, except the ones that are components of the communication network.

To satisfy these requirements, we re-calculate the signal strength average signal density as below:

$$Str_\chi(i,x,y,z) = u \cdot \left[\overline{\omega} \cdot 8 - \|(x,y,z) - M(i)\|\right], \chi = \text{I,II}, \tag{13}$$

$$E_\chi(x,y,z) = \sum_{i=1}^{N} Str_\chi(i,x,y,z)\chi = \text{I,II}, \chi = \text{I,II}, \tag{14}$$

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

We also require that the front-line drones be connected to the command center. This is described by the constraints below:

$$d_{ij}(t) = \begin{cases} 1, & \text{if } 0 < \|M(i,t) - R(j,t)\| < 8, \\ 0, & \text{otherwise}, \end{cases} \tag{15a}$$

$$b_{jk}(t) = \begin{cases} 1, & \text{if } 0 < \|R(k,t) - R(j,t)\| < 8, \\ 0, & \text{otherwise}, \end{cases} \tag{15b}$$

$$\sum_{j=1}^{N_{\text{rep}}} d_{ij} \geq 1, \quad i = 1, 2, \cdots, N_{\text{SSA}} \tag{15c}$$

$$\sum_{k=1}^{N_{\text{rep}}} b_{jk} \begin{cases} \geq 1, & \text{if } \sum_{i=1}^{N_{\text{SSA}}} d_{ij} \geq 1, \\ \geq 2, & \text{otherwise,} \end{cases} \tag{15d}$$

4 Sensitive Analysis

4.1 Sensitivity of parameters

To construct the above models, several constant parameters were used. Their values are given by us and now listed in the table below.

Table 2: Parameters and Their Values

Parameter	Value
$\overline{\omega}$	$0.25/0.5/1$
γ	0.58
ϵ	0.5
α	8.68×10^{-6}
η	2.35
PF	1.2
PH	1.5

While other parameters are set based on formal experiments and researches, the index ϵ is artificially given. So here we want to analyze the reliance of our model on the value of ϵ, we use the amount of drones needed to represent the behaviour of models, the results are listed below.

Table 3: The Model's Reliance to the Parameter

Parameter	ValueAfter rounding
$\epsilon = 0.3$	$N = 36 + 96$
$\epsilon = 0.5$	$N = 36 + 96$
$\epsilon = 0.7$	$N = 37 + 100$

From the table above, we can see that the simulation results of the model have little reliance on the value of ϵ, which means that our model is valid and our conclusion is reasonable.

5 Conclusion

The Bushfire Risk Model was first introduced to quantitize and label the terrain of Victoria with the special *ijk* coordinate system. Then the possibility for any place to catch fire was evaluated, and the future situation was predicted.

Based on the Nervous System Model and safety evaluation principles in Section 3.1.2, the optimal arrangement was attained. According to the program simulation, the best choice is to use **36 SSAs and 96 Repeaters**.

When fires are spotted by the monitoring system, UAVs will be directed as follow:

- Drones with SSA that are close to the fire will be sent immediately to keep the area on fire covered by signal.
- Drones with repeaters will form the communication web.
- Except the necessary drones, other drones will be send back to charge and stand by.

Besides, The optimal positions of hover drones are depending on different regions. In our research, three locations are taken into consideration, which is Harieteville (forests of high elevation), Melbourne (urban area), and a place between Omeo and Orbost (plain). The hovering positions are shown in the graphs below.

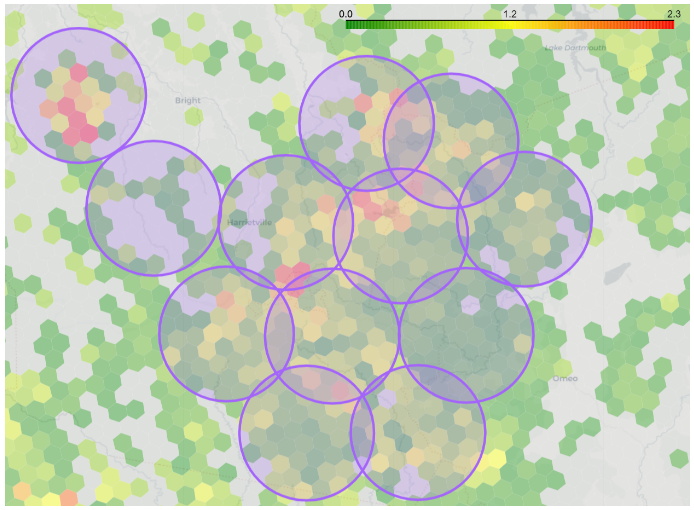

Figure 2: Forests of Elevation > 800 meters

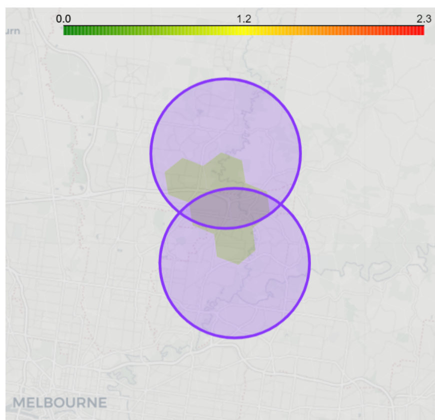

Figure 3: Urban Area

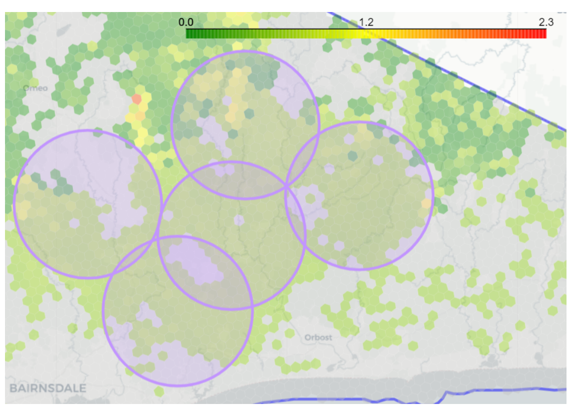

Figure 4: Plain Area

The changing likelihood of fire events over the next decade in our model was partly illustrated below:

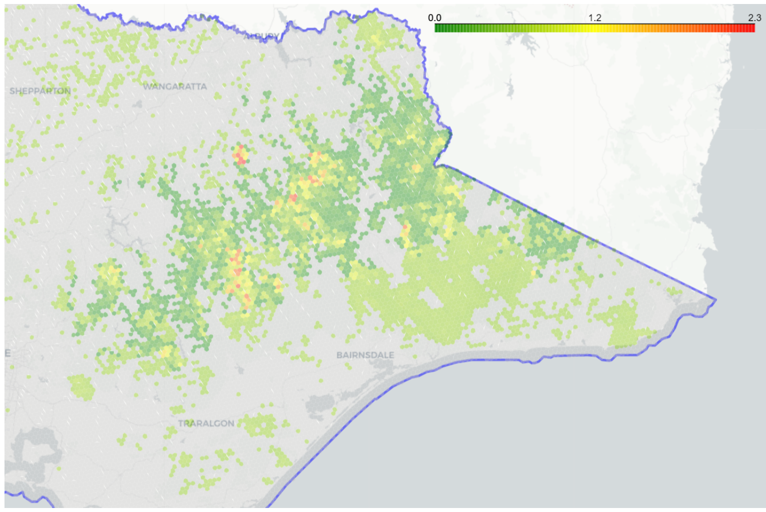

Figure 5: Condition at 2020

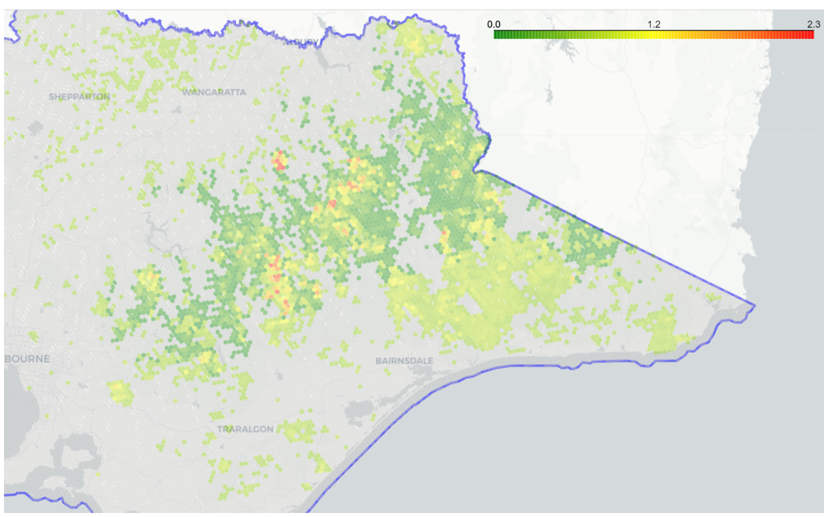

Figure 6: Condition at 2030

We predict that if the likelihood for huge fires rise the cost on radio repeaters and thermal cameras will rise since they will be put into a hot environment constantly, which rise their risk of breaking. Electricity bills and labour cost will rise, because more people is needed to direct the drones system and drones should charge more frequently.

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 ELEMENT AND SUMMARY

The following are necessary cost elements of the Project:

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

ITEM NAME	QUANTITY	UNIT PRICE	EXTENDED PRICE
UVA(s)	40	$1,000	$40,000
Repeater(s)	100	$1,000	$100,000

Table 4: The Model's Reliance to the Parameter

Item Name	Total Estimated Cost
Drones (including 2 types)	140, 000

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]

References

[1] "When bushfires make their own weather - social media blog - bureau of meteorology," http://media.bom.gov.au/social/blog/1618/when-bushfires-make-their-own-weather.

[2] "The h3 core library documentation: Coordinate systems," https://h3geo.org/docs/core-library/coordsystems.

[3] D. Dissing and D. L. Verbyla, "Spatial patterns of lightning strikes in interior alaska and their relations to elevation and vegetation," *Canadian Journal of Forest Research*, vol. 33, no. 5, pp. 770–782, 2003.

[4] M. Kilinc and J. Beringer, "The spatial and temporal distribution of lightning strikes and their relationship with vegetation type, elevation, and fire scars in the northern territory," *Journal of Climate*, vol. 20, no. 7, pp. 1161 – 1173, 01 Apr. 2007.

[5] Y. S. Meng, Y. H. Lee, and B. Ng, "Path loss modeling for near-ground vhf radio-wave propagation through forests with tree-canopy reflection effect," *Progress in Electromagnetics Research M*, vol. 12, pp. 131–141, 01 2010.

[6] ——, "Empirical near ground path loss modeling in a forest at vhf and uhf bands," *Antennas and Propagation, IEEE Transactions on*, vol. 57, pp. 1461 – 1468, 06 2009.

[7] L.-I. Jiao, Y. Chang, D. Shen, Y.-M. Hu, C. Li, and J. Ma, "Using boosted regression trees to analyze the factors affecting the spatial distribution pattern of wildfire in china," *Chinese Journal of Ecology*, vol. 34, pp. 2288–2296, 08 2015.