Problem Chosen	2022	Team Control Number
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Summary

Australia is undergoing huge wildfires in every state. To protect people and safety and property, we establish a model to use two types of drones to help Country Fire Authority (CFA) conduct "Rapid Bushfire Response", and front-line personnel communicate with Emergency Operations Center (EOC).

We use Victoria Fire Report Data[2], using fire report places in certain time period to represent locations where fires happened on average. This allows us to take into account of factors such as fire size and frequency, economic cost and safety, weighted region area covered by drones.

We set Fast Response Model for deployment of drones for fast response, we quantify the coverage with a weighted quantity. We build a model to investigate its' relationship with the economic cost. For a certain coverage by drone, we devise a strategy to distribute SSAs by using k-means with special distance function and we use minimum spanning tree to distribute repeaters to connect them. We show the mathematical properties to such distance to ensure the correctness of our algorithm.

We set Fire Prediction Model for second part of problem. we divide Victoria into several zones, and use statistics of zones in different time to form a time series. We predict the time series using convolutional Long Short-Term Memory (convLSTM).

We set Pearl Model and Spur Model for Deployment of drones for front-line personnel in different circumstances, we use separate deployment strategies for small and big sized fire considering the effect of terrain.

The sensitivity analysis shows robustness in our model. Meanwhile, we combine all the models to finish the annotated Budget Request to help CFA with acceptable cost.

Keywords: Clustering, Minimum Spanning Tree, ConvLSTM, Terrian;

Contents

1 Introduction

1.1 Background

Wildfire spreads rapidly in Australia. In fire season, it's devastating for people's safety and properties. Victoria's Country Fire Authority (CFA) uses different means to protect its people. Drones carrying high definition & thermal imaging cameras and telemetry sensors were sent for surveillance and situational awareness (SSA). Drone repeaters, transceivers that automatically rebroadcast signals at higher powers can help connect Emergency Operations Center (EOC) with SSA and front-line employees with VHF/UHF bands.

1.2 Problem Restatement

1.2.1 Limits

- Drone-related
  - Cost $1000 per drone
  - Flight Range 30 km
  - Transmission Range 20 km
  - Flight Speed 20 m/s
- Fire-related
  - Size
  - Frequency

1.2.2 Targets

- Deployment of drones for fast response
  - Reduce cost
  - Increase weighted coverage

- Fire Prediction
- Deployment of drones for front-line personnel in different circumstances
  - Build models for different fire size
  - Build models considering different terrians

1.3 Our Work

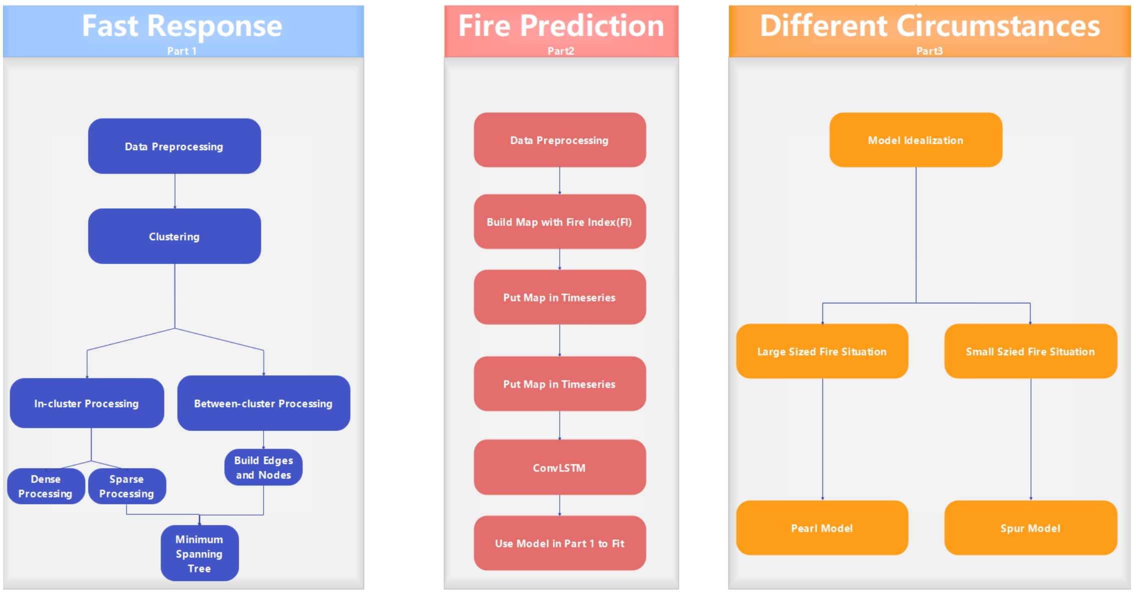

Figure 1: Our Work

2 List Of Symbols

Definition	Description
$dist$	Distance between two points in Euclidean coordinate system
R_e	Radius of earth
$\Delta\varphi_{lat}$	Thange of latitude
$\Delta\lambda_{lon}$	Thange of longitude
eps	Tf the distance between two points is lower or equal to (eps), these points are consi
$minPoints$	The minimum number of points to form a dense region.
x_0	Distance to drone when the fire is recorded in our data

Definition	Description
x_1	Distance to drone when drone detect fire
$dis_{j,t}$	The shortest distance of fire location indexed j to the nearest drone at distance x fro
r_c	The radius of drone in idealized condition.
$vs_{j,x}$	The spread rate of fire at the rim of fire area indexed j at distance x from the drone
$p_{j,x}$	The probability for drones to detect rim of fire location j at distance x from the dron
v	Stable spread rate which is assumed to simply the model
WCL	Weighted coverage loss : describing the loss the weighted area for a deployment str
r_o	Outer-radius of drone, meaning the furthest distance the drone can detect, that is, 5(
$tWCL$	Threshold for WCL to determine how much SSA should be deployed.

3 General Assumptions

- We use one year data in Victoria with data provided by Earth Data to represent the general cases in Australia. However, our model to this case adapt to arbitrary cases, so it's without losing generality.
- We assume once the fire is within the detective range of drones, it will be found out without delay.
- We assume the spread rate of fire is stable and at a certain value, which is not the case in real world, but one can use the original formulae given in the model to simply modify the model.
- Only 20 years of data is used for machine learning, the error produced is within the acceptable range.
- The terrain situation can be more complicated in real world, we idealize mountain and other barriers as parabolic-like object.

4 The Models

4.1 Fast Response Model

To discuss the possible deployment of drones in order to detect fire and transmit the signal to EOC, we design Fast Response Model to maximize coverage and minimize the cost. To represent the fire distribution, fire frequency and fire size, we come up with several well-designed indices and use fire location in certain period to represent those factors with minimum lost of information. Since it's not economically efficient to cover all the land of Victoria because the drones are able to move and the fact that fire can spread and then be detected, we use weighted covering lost(WCL) to represent the cost for not covering all the possible locations of fire. We use the data in 2020 for case study, but the strategy we adapt and the data we compute is generic and can be used in various situation.

After sensitivity test, we proved the robustness of the model. It can be showed that the Fast Response Model can be used in different size of fire, different frequency of fire, and different distribution of fire in state of Victoria and other places in the world.

4.1.1 Data Pre-processing

For the sake of CFA, our model should only be considering the fire situation within the range of state of Victoria. The data we obtained from NASA database is contains noise and locations out of border. The first step of data pre-processing is meant to sift out all the illegal point with criteria mentioned above. Considering the spatial location of noise point, we use DBSCAN clustering with ball tree [5] algorithm, and is implemented by sci-learn project[4]. Since the data contains latitude and longitude, to define the distance function for clustering one need to use the haversine formula[1] to calculate the great-circle distance between two points.

$$dist_{i,j} = 2 \cdot R_e \cdot \arctan\left(\sqrt{\frac{\sin^2(\frac{\Delta\varphi_{lat}}{2}) + \cos\varphi_i \cdot \cos\varphi_j \cdot \sin^2(\frac{\Delta\lambda_{lon}}{2})}{1 - (\sin^2(\frac{\Delta\varphi_{lat}}{2}) + \cos\varphi_i \cdot \cos\varphi_j \cdot \sin^2(\frac{\Delta\lambda_{lon}}{2}))}}\right) \tag{1}$$

This ensures the correctness of clustering.

To define a noise point which is inefficient to cover it, we define two variables eps and $minPoints$ according to DBSCAN conventions.

To more easily obtain the optimized value, we first normalize data with standard normalization, then we set

$$\begin{cases} eps = 0.15 \\ minPoints = 8 \end{cases} \tag{2}$$

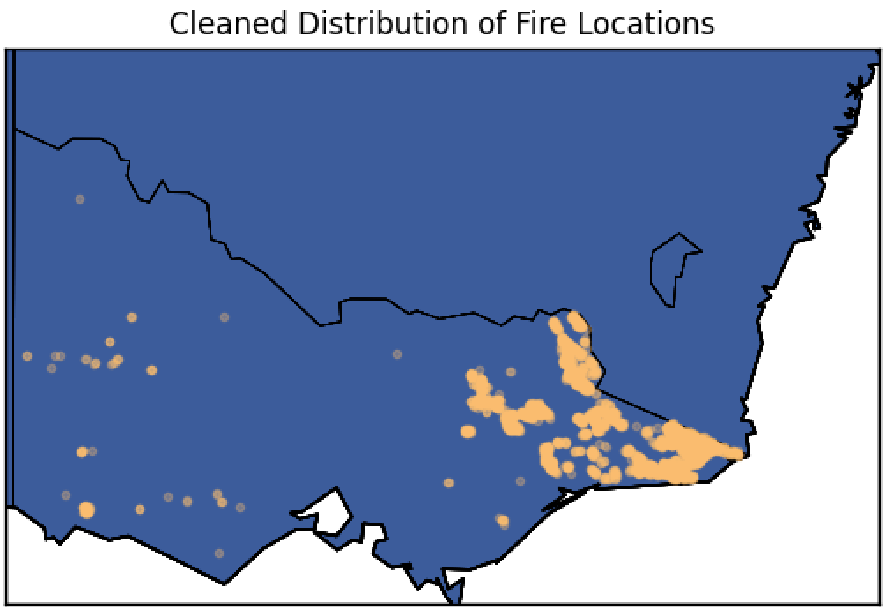

Figure 2: Cleaned Fired Distribution

4.1.2 Deploying SSA

To deploy drones in a way that reaches the target of fast response, we first need to quantify the target using one index, which we define it as weighted covering lost(WCL).

$$WCL = \sum_j \left(\int_{x0}^{x1} (x - r_c) \cdot (1 - p_{j,x}) \cdot vs_{j,x} \right) dx \tag{3}$$

To simplify our model, we assume $vs_{j,x} = v$, which is a stable value, then we have.

$$WCL = \sum_j \left(\int_{x0}^{x1} (x - r_c) \cdot p_{j,x} \cdot v \, dx \right)^2 \tag{4}$$

In order to simply the model as well as simulate the distribution of p_j, we use Ridge Distribution to set $p_{j,x}$, which is the probability of rim of fire at the position which is x km from the nearest SSA, as following

$$p_{j,x} = \begin{cases} \frac{1}{2} - \frac{1}{2}\sin\frac{\pi}{r_o}(x - \frac{r_o}{2}), & 0 \leqslant x \leqslant r_0 \\ 0, & x > r_0 \end{cases} \tag{5}$$

This gives us

$$WCL = \sum_j \left(\int_{x0}^{x1} (x - r_c) \cdot (\frac{1}{2} + \frac{1}{2}\sin\frac{\pi}{r_o}(x - \frac{r_o}{2})) \cdot v \, dx \right)^2 \tag{6}$$

We use the concept of substitution distance($sdist$) to investigate the deployment strategy.

$$sdist = \left\| \int_{x0}^{x1} (x - r_c) \cdot (\frac{1}{2} + \frac{1}{2}\sin\frac{\pi}{r_o}(x - \frac{r_o}{2})) \cdot v \, dx \right\| \tag{7}$$

We define $sdist$ in a way that guarantees $sdist$ is positively correlated to x which is the distance to the center, that is, the place where the nearest drone is deployed.

To balance economical costs and safety, we set a threshold for WCL, $tWCL$ which is currently set to a certain value in our later investigation, but it can be adjusted according to real situation. It will be illustrated more thoroughly in the following section about sensitivity and robustness. We use modified $k - means$ cluster to determine the positions of SSAs, which is described as follows

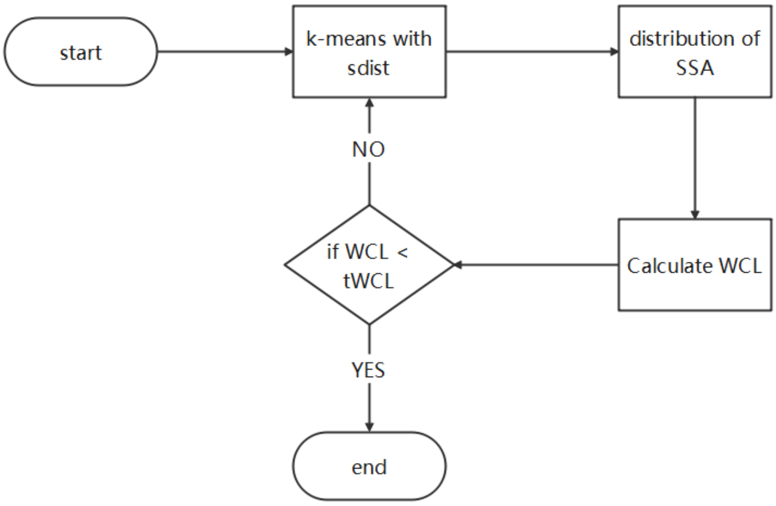

Figure 3: deploy SSA flowchart

This allows us to cluster the locations to their respective drones. k-means algorithm is used here since the $sdist$ is positively correlates to distance. So the correctness of the algorithm can be ensured.

(a) clustering of fire location (b) SSA distribution

Figure 4: SSA and fire locations

Given the fire location distribution, we plot the SSA's location as above. The range is marked as well. It can be observed that the fire is frequent and in large scale at the east of state of Victoria. Our distribution perfectly fit the situation can reduce WCL to acceptable level.

4.1.3 Deploy Repeaters

The second part of Fast Response Model is connecting all the SSAs using the least repeaters. We solve this problem by divide and conquer and with the help of minimum spanning tree.

For Dense Cluster, we choose to shrink several SSAs into one, since when it's dense, one repeater can cover multiple SSAs. Then we build minimum spanning tree on the repeaters.

For Sparse Cluster, we choose to build minimum spanning tree directly.

Combined both situation, we succeed in connecting all SSAs in a way that guarantees both the stability of connection and minimum economic cost.

Dense Cluster For dense cluster, we choose shrink point strategy. For every dense cluster which is formed by a set of SSAs, we use an algorithm to settle the distribution of core repeater.

A core repeater is defined as, the repeater that can receive signal from SSAs.

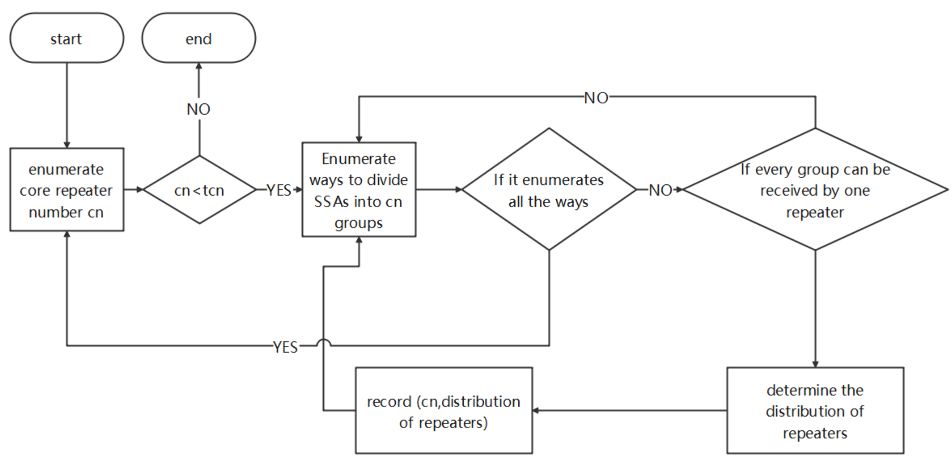

Figure 5: Strategy for Dense Clutser

We want the combination of core repeaters to be in a way that allows the minimum number of repeaters to be distributed and all the SSAs' signal can be received. There seems to be no elegant solution to this problem because it is NP

problem. However, the small number of SSAs allows us to use brute force to compute such distribution.

We define cn to be the number of core repeaters needed, $nSSA$ to be the SSA that are distributed, we define tcn to be the maximum number of core repeaters that are allowed, it's obvious that $tcn \leqslant nSSA$. For simplicity of implementation, we set $tcn = nSSA$

Sparse Cluster and Final Linking Now there are only sparse SSAs and sparse repeaters, it's natural to link them by Kruskal algorithm to make a minimum spanning tree.

The first step is to build the graph with nodes and edges.

- Nodes are SSAs and repeaters, which is reasonable since they are sparse and can be discretized.
- Edges have weight defined below. Considering if the range of drones are tangent to each other, the transmission stability will be lowered, we introduce transmission random factor trf

$$Ew_e = \max\left(\left\lceil \frac{dis_{i,j} - 2r_c - trf_e}{2r_c} \right\rceil, 0\right) \tag{8}$$

Transmission factor is defined below to reduce the situation where ranges of drones are tangent, where $randi(x)$ function is to randomly produce a real number within interval $[0, x]$

$$trf_e = randi\left(1 - \left(\left\lceil \frac{dis_{i,j} - 2r_c - trf_e}{2r_c} \right\rceil - \frac{dis_{i,j} - 2r_c - trf_e}{2r_c}\right)\right) \tag{9}$$

Then we use Kruskal Algorithm[3] as described below to make a spanning tree.

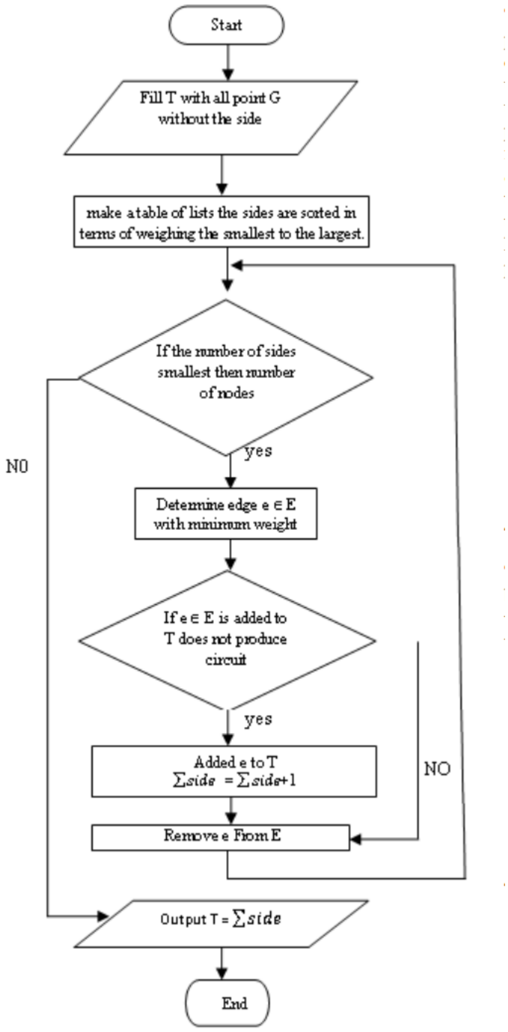

Figure 6: Strategy for Dense Clutser

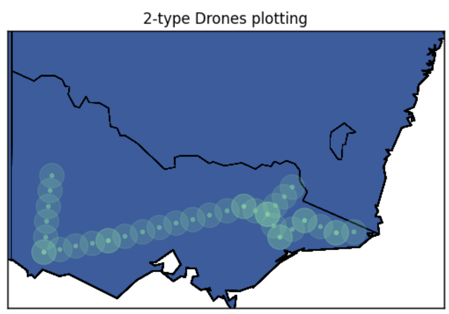

Figure 7: The general drone distribution

Because of the introduction of trf_e and the use of divide and conquer strategy, the outcome is not only stable but also efficient as shown.

5 Conclusions

Conclusions

6 Model Evaluation And Improvement

6.1 Strength

6.2 Weakness

6.3 Improvement

References

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