Problem Chosen	2021	Team Control Number
B	MCM/ICM Summary Sheet	2103901

Fighting Forest Fires: A Better Rescue Plan

Summary

From the past 2019 to 2020, a forest fire of unprecedented scale and duration has attracted great attention worldwide in Australia. Globally, the frequency of fires has been on the rise in recent years. In order to improve efficiency, drones are more and more widely used in fire-fighting. We are required to establish a model to plan the optimal path and quantity of two drones, and also need to submit a budget request.

First we divide problem 1 into two parts (Radio Repeater & SSA drones) for optimization, while problem 3 is mainly optimized for Radio Repeater drones. And we creatively propose a sector planning area working strategy. For the first half of problem 1 and problem 3, we first obtain the number of repeater drones required for different posts at different distances from the EOC by planning the time flow of drones' shift. Next we use PSO to simulate the optimal drones deployment under uniform terrain differences. Based on the actual terrain data of Victoria, we improve the algorithm for non-uniform terrain differences to obtain the optimal results. Finally, using this algorithm, we simulate the fire-fighting equipment requirements in Victoria and concluded that 6.75 Radio Repeater drones are expected for each EOC system in general.

For the second half of Problem 1, we first explore the effect of different refresh periods on the number of SSAs required for each route, then trying to design 3 plans based on the imaging principles and given parameters. We explore an idea and find that only 3 routes are needed to traverse the entire plan area. Then we use a refresh period of 44 min to estimate the budget and consider that each EOC system is expected to have 9 SSAs. In addition, although all 3 plans satisfy the inverse correlation property, the 3 plans have different mutation point locations.

For the budget part of question 1, we think that CFA should equip each fire point with one EOC. We investigate and calculate a 90% percentile sequence of fires per day for the past 17 years to obtain an estimate of 69 EOCs to be deployed. For question 2, we use an ARIMA time series model to predict the trend in the number of 90% percentile fires per year over the next decade. The results indicate that there is an 85% confidence that the fires in the next decade won't exceed the severe years of 2006, 2009, and 2019. And having 69 EOCs can still handle more than 90% of the fires.

Finally, we perform a sensitivity analysis on the percentile specified, and the results indicated that 90% is not sensitive and suitable to be chosen as an indicator to give our final budget.

Keywords: keyword1; keyword2

Contents

1 Introduction

1.1 Problem Background

Over the past years, due to the climate change and other contributing factors, forest fires are be coming increasingly frequent and menacing. Forest fires will cause damage to the ecosystem and even threaten the global ecological security. In particular, if using improper distinguishing measures at the initial outbreak, under the influence of severe weather such as high temperature, drought, and gale, the fires could spread more erratically, which seriously threatens the safety of the city and is not conducive to the harmony and stability of the society[1]. Among them, the large-scale wildfires in Australia in 2020 are the most catastrophic. In this large-scale wildfire, the burning of forests released about 400 million tons of carbon dioxide, causing severe haze weather, affecting global air quality and further exacerbating global warming[2].

Therefore, facing the trend of more frequent forest fires, in order to improve the preparedness and reduce casualties, it is of great practical significance to use the combination of drones and sensing technology to plan an optimal rescue plan. We regard ourselves as a working group for CFA, hoping to find a high-quality rescue plan through thinking and testing.

1.2 Restatement of the Problem

To complete this plan, we need to focus on the following 3 objectives.

- Establishing a planning model to determine the number of SSA and Radio Repeater drones. The model should be the most economical while ensuring the completion of observation and communication tasks.
- Forecasting changes in the possibility of extreme fire events in the next ten years and adjusting the model to adapt to the changes, then simulating the increase in equipment cost.
- Considering the actual terrain of Victoria and the sizes and locations of fires , then establishing a model to optimize the locations of hovering radio-repeater drones.

1.3 Our Work

This is an optimization problem that is closely related to practical applications and needs to be fully considered. Due to the different nature of the tasks performed by the two types of drones that need to be planned, the optimization goals and impact factors are also different, so we start simulation from a simple planning area.

In problem 1, we first select a fan-shaped planning area that is not too large for the drones to operate. For firefighting deployment in large areas, we propose a fire-fighting strategy of gradually surrounding the fire from outside to inside every day.

2 Assumptions

In order to better design algorithms and models to solve the problem, we make the following ***basic assumptions***. There can be other assumptions in each question.

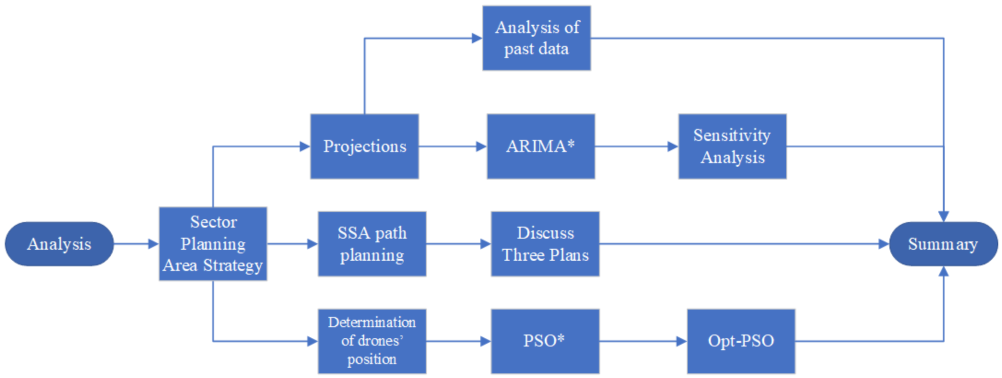


Figure 1

- We assume that the drones are flying at a constant speed, ignoring the effects of take-off and landing and air wind speed. Therefore, given the same distance, whatever speed the drone flies at, the energy consumed are the same.
- We assume that maximum hovering time (maximum flight time2.5h) and the maximum flight distance(30km) consume the same energy and have a linear relationship. So every 5 minutes of hovering is equivalent to flying one kilometer at any speed.
- Affected by the actual terrain, we assume that the minimum signal radius from the handheld device is 2km and the maximum is 5km.

3 Notations

Some valid signs and definitions are as follow.

The primary notations in our paper are listed in Table1 .And there can be some other notations to be illustrate later.

4 Radio Repeater Drones Planning Model

4.1 Model Preparation

4.1.1 Problem analysis

In task 1, we are required to establish a model to determine the optimal numbers and mix of SSA drones and Radio Repeater drones for CFA. The SSA drones perform observation tasks, and the Radio Repeater drones perform communication tasks.

- Considering that the latter involves the distribution of people and has many impact factors (such as terrain), we first establish a model to discuss the optimal number of Radio Repeater drones.
- As we are known that the maximum range of the drones is 30km, the area of the surrounding fire that an EOC could handle is limited. Therefore, we decided to delimit a planning area as a daily fire treatment area with a perimeter of less than 30 km.

Notations	Description
D_1	Maximum range of the drones
T_2	Maximum hover time of the drones
T_3	Charging time of the drones
V_1	Power consumption speed at full speed
V_2	Power consumption speed at hovering power consumption speed
V_3	Power consumption speed at charging speed
R	Radius of sector fire area
R_0	Radio Repeater signal radius
R_1	Handheld device signal radius
V_{max}	Maximum travel speed of the drones
θ	Topography factor of sector area

Table 1: Notations A

- To maximize the use of drones, we set the EOC on the outer circumference of the fire area.

Therefore, The following is the overall strategy of the rescue.

Combining the supply and rest requirements of firefighters and drones, we take daily planned actions. We relocate the EOC to the vicinity of the fire scene every day, and then dispatch firefighters, Radio Repeater drones and SSA drones into the planning area for a day of rescue operation. After the work of the day is over, the EOC will be moved to another location the next day according to the situation.

4.2 The Foundation of Model

4.2.1 Area design

First of all, we need to determine the shape of the planning area. The planning area is limited by the circumference, and we know that the ratio of the area of the circle to the circumference is the largest. Considering that the work area may need to be combined and extended, equilateral triangles are better in this regard. At this moment, we suddenly call to mind the field of view of animals. It's fan shape, and the information from the fan shape is received and processed at the center of the circle just like EOC. Using the principle of bionics, we designed the planning area as a fan shape with an apex angle of 60 degrees, while combining the advantages of a circle and an equilateral triangle. EOC coincides with the sector center point O.

Using the following formula, we can calculate the radius of the sector:

$$R + R + \frac{\pi}{3}R = D_1 \Rightarrow R = \frac{D_1}{2 + \frac{\pi}{3}} = 9.845 \text{ km} \tag{1}$$

4.2.2 Analysis of the Given parameters

According to the aforementioned basic assumptions, we have the given parameters and the following derivation process.

Given the same distance, the drones consume the same amount of power for the same distance. So after determining the target location, the drone should always go at full speed to save time while consuming a certain amount of power.

1) If traveling, the drones can range D1=30km, so the traveling power consumption speed at full speed is calculated by the formula:

$$V_1 = \frac{1200}{30 \times 1000} \times 100\% = 4\%/\min \tag{2}$$

2) If hovering, the drones can support T2=2.5h, so the hovering power consumption speed is calculated by the following formula:

$$V_2 = \frac{1}{2.5 \times 60} \times 100\% = 0.67\%/\min \tag{3}$$

3) T3=1.75h for full charge, so charging speed is calculated by the following formula:

$$V_3 = \frac{1}{1.75 \times 60} \times 100\% = 0.95\%/\min \tag{4}$$

4.2.3 Characterization of successful communication

It is known that the condition for the two-way communication between the Radio Repeater drones and the handheld device is: the distance between the two is smaller than the smaller signal propagation radius among them, that is, the handheld device signal radius R1. Since R<R0, any Radio Repeater drone within the sector must be able to communicate with the EOC headquarters in both directions. Furthermore, a necessary and sufficient condition for the handheld device to be able to communicate with the EOC is: the distance between the handheld device and any Radio Repeater done or the EOC is less than R1.

To represent the problem more clearly, we draw a radius of R1 at each Radio Repeater drone post and at the EOC, as well as a point at each firefighter's location. So all points need to be covered by at least one circle to ensure that each firefighter can have a two-way communication with the EOC at any time. A diagram of the coverage conditions is shown in Figure 2-(a).

4.2.4 Classification discussion of shift

The total power consumption consists of that of traveling and hovering. Limited by the given total power, we have to reduce the sum of the travel distance to increase the hovering time. Obviously, since the power consumption of the drones runs out quickly and so every drone needs to return to the EOC periodically to recharge, then another drone will be needed to continue to hover at the post when the previous one leave. From the assumption above, we begin to think about how many drones are needed to complete the shift for a post at a distance d (km) from point O?

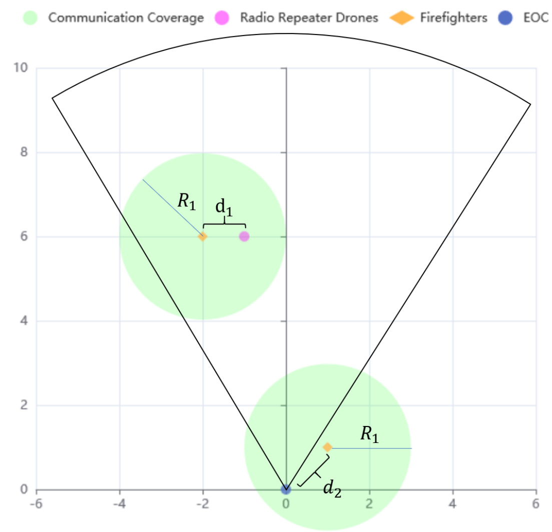


Figure 2 Diagram of the coverage conditions

We propose the following shift strategy to maximize the use of drones.

Each aircraft takes off from point O, flies straight at maximum speed to its post and starts hovering on duty, and returns to point O to recharge and rest when there is just enough power left for the return trip.

And the traveling and hovering time can be calculated as follows.

1) Maximum flight speed $v_{\max} = 20\ \mathrm{m/s} = 1.2\ \mathrm{km/min}$
2) Time to post one way $t_1 = \frac{d}{v_{\max}}$
3) Round trip flight power consumption $e_1 = 2 \times t_1 \times V_1$
4) Hovering duty power consumption $e_2 = 1 - e_1$
5) Hovering duty hours $t_2 = \frac{e_2}{V_2}$

According to the assumption, every post is required to have a drone on duty at all time, so the moment the number k drone leaves the post is exactly the moment the number k+1 drone arrives. Thus we have the following situations.

- The first drone departure time

$$t_{\text{leave}}^{(1)} = t_1 + t_2 \tag{5}$$

- The moment of departure of the number k drone

$$t_{\text{leave}}^{(k)} = t_{\text{leave}}^{(k-1)} + t_2 = t_1 + k \times t_2 \tag{6}$$

- And if the first UAV goes back to the headquarters to fully charge the battery and then immediately departs again to the post, its earliest arrival time is as follows.

$$t_{\text{again}} = t_{\text{leave}}^{(1)} + t_1 + T_3 + t_1 = 3t_1 + t_2 + T_3 \tag{7}$$

- If the post has k drones on handover shifts, then the first drone must be available when the number k aircraft leaves the post, the time meets the following conditions.

$$t_{\text{again}} < t_{\text{leave}}^{(k)} \tag{8}$$

And shift status diagram of 2/3/4 drones can be seen in Figure 2 & Figure 3 . Through these three pictures, we can know the status of each drone in a certain shift at any time.

$$k = \begin{cases} 2 & ,0 < d < \frac{27}{7} \\ 3 & ,\frac{27}{7} \leq d < 9 \\ 4 & ,9 \leq d < R \end{cases} \tag{9}$$

And shift status diagram of 2/3/4 drones can be seen in figures below. Through these three pictures, we can know the status of each drone in a certain shift at any time.

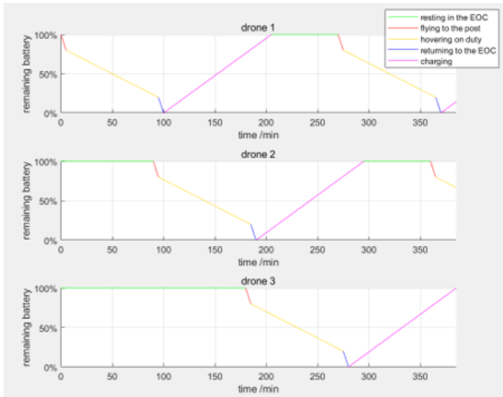
4.3 Particle Swarm Optimization Algorithm

According to the analysis of the actual configuration of firefighters, we realize that we need about 200 firefighters to work in the fan-shaped area we set. So we wrote a program "maker" to simulate the different distribution of people in the area, such as random or cluster distribution, and get 200 points each time.

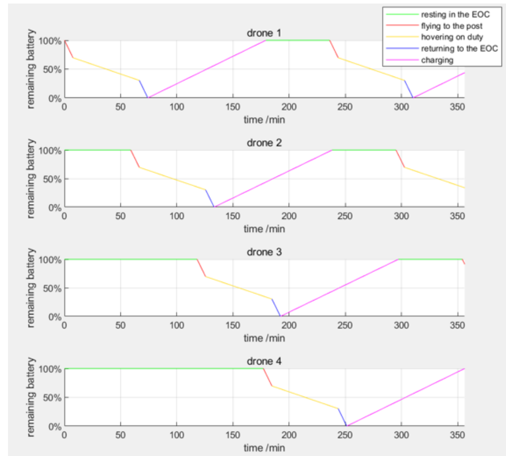
After the simplification and calculation of the above steps, the optimal planning of Radio Repeater drones can be realized based on genetic or particle swarm algorithm. PSO simulates the motion behavior of organisms in a group of birds or fish. It is an excellent meta-heuristic algorithm and population intelligence algorithm. The algorithm has fewer parameters, which means it is easy to implement, and has strong global convergence capabilities[3].

Since PSO is simpler in steps than GA, and the results can be more accurate and converge faster, we choose PSO for planning. There are the following instructions for using PSO to plan the optimal number of Radio Repeater drones.

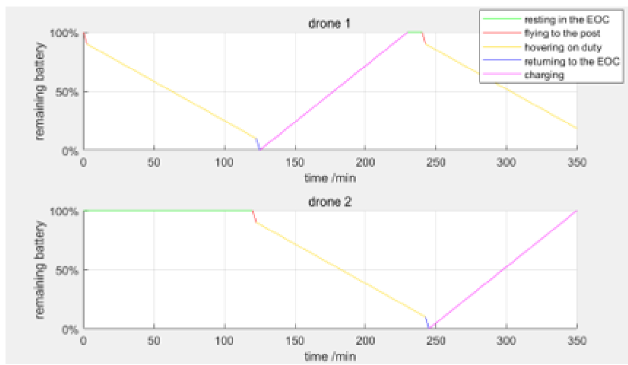
- Input parameters Considering the influence of the topography of the fire area on the signal range of the handheld device, our program take the signal radius R1 of the handheld radio and the firefighter distribution location as input parameters. Meanwhile, using the forward normalization method, the terrain factor of the whole sector plan area is defined as $\theta = \frac{R_1 - 2}{5-2}$.
- Optimization objectives To guarantee the safety of all firefighters, the current number of firefighters who can communicate in both directions is the first objective; on the basis of ensuring 100% of firefighters can communicate with the headquarters EOC in both directions, the cost required to perform the mission is further optimized, so the number of repeater drones is the second objective.



(a) Shift status diagram of 3 drones



(b) Shift status diagram of 4 drones



(c) Shift status diagram of 2 drones

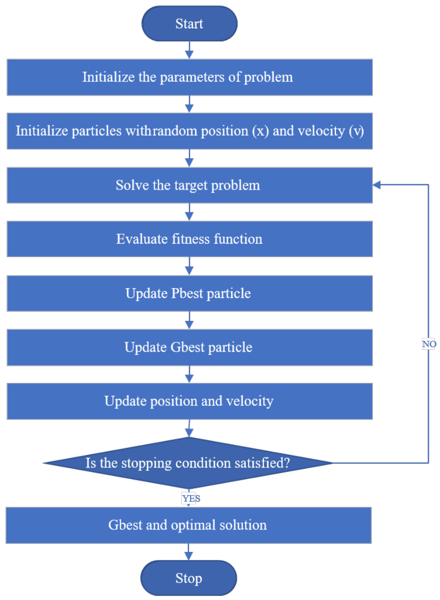
Figure 3

- Algorithm output UUnder each value of R1 changing from 2km to 5km, the final result is the coverage solution with the highest value of optimization objective function. The Figure 4-(a) below is the flow chart of the PSO.

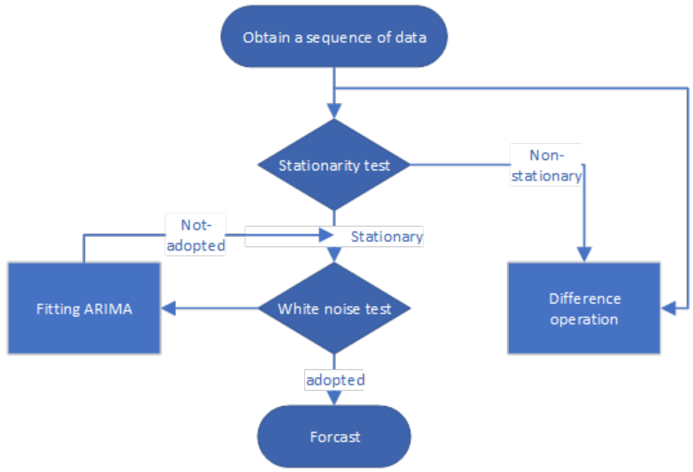
4.4 Optimize the PSO

Different terrain will affect the signal range of firefighters' handheld devices, reducing it to 2 km. And in fact, the terrain in an area is often uneven. The aforementioned model we developed is only applicable to uniform terrain in a single simulation. So to cope with the complex terrain, we optimize the PSO and solve the problem in two steps.

- Determination of drones' position We determine the location information and height data where the personnel are located based on the scanning results of SSA. Then the 3D coordinates are input into the particle swarm algorithm and the results are re-calculated. We take the terrain data obtained from Google Maps and combine it with the randomly generated personnel location to perform the simulation calculation again. Finally Figure 5-(a) is generated.

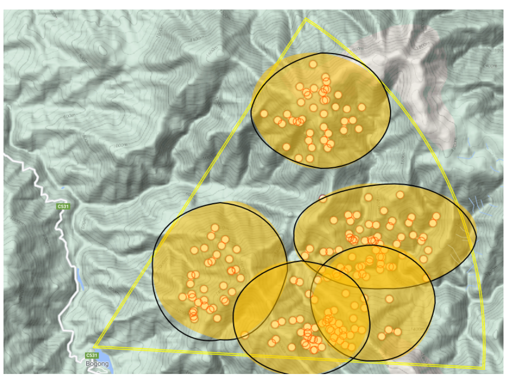


(a) Flow chart of the PSO

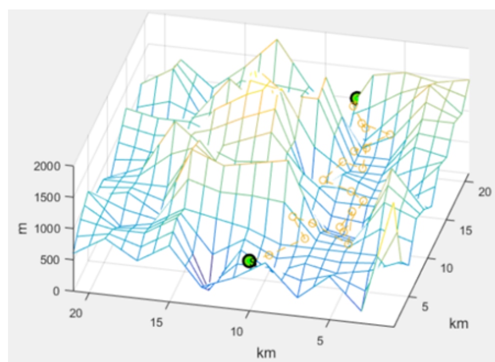


(b) ARIMA

Figure 4



(a) Actual communication state diagram



(b)

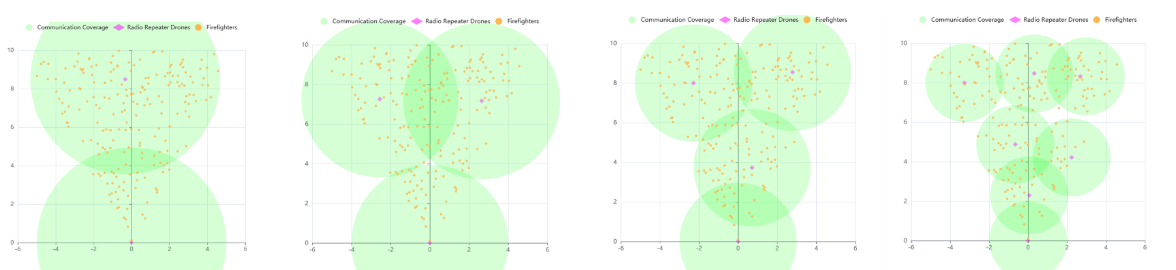
Figure 5

- Drones' flight path optimization Due to the interference of terrain factors, the flight height of the drones will be limited to a certain extent. In order to prevent the drones from colliding with the hillside, we obtain the cross section of the drones' height and set the interface area of the mountain part as the forbidden area. The shortest path planning is carried out according to the determined location, and finally the path planning is carried out using ant colony algorithm to obtain the shortest path for the drones to fly from the EOC to the hovering points. The path planning result in 3D space is shown in Figure 5-(b).

4.5 Analysis of the result

First, through planning the process of repeater drones shifting status, we obtain the minimum number of drones required for different sentinel distances from EOC, which is used as the weight of a position in the following algorithm

- Then we generate n=200 firefighters(Represented as orange dots in the figures below), randomly distributed them in the sector and simultaneously changed the radius of the handheld device R1 and observed the output of the algorithm separately. As a result, when we take the values of R1 as 2, 3, 4 and 5, respectively we obtain the following drones' planning strategy in Figure 9.
- Considering the size and frequency of fire events, the distribution of firefighters will not actually be a random distribution as shown above, but form an aggregated distribution around some points where the fire situation is more severe. Therefore, we re-generated the point map of firefighters with some aggregation randomly and re-performed the above process to obtain the following results in Figure 10.



(a) $R = 5$ (b) $R = 4$ (c) $R = 3$ (d) $R = 2$

Figure 6 Group 1 of the four post distribution maps

- Finally, we apply the algorithm to the actual terrain. The original particle swarm optimization algorithm is optimized and an improved algorithm is designed to adapt to the complex terrain changes. The optimization path effect diagram is shown in Figure 10.

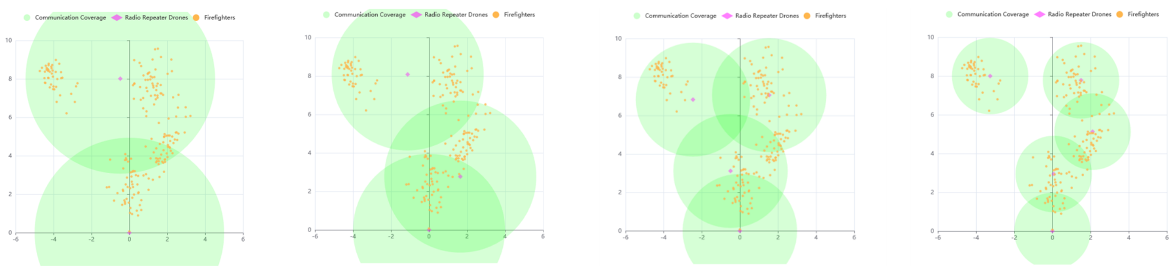
In Figure 6, we can clearly see that as the communication radius (radius of the green circle) is shortened from 5km to 2km, the number of Radio Repeaters drones increases from 2 to 7. In Figure 9 of the non-uniform distribution of firefighters, compared with the uniform distribution, we find that not only the distribution of Radio Repeater drones have changed a lot, but the corresponding number is also different.

In summary, by adjusting the parameters, our model is suitable for forest fires of different scales and frequencies, and can be applied to actual complex terrain.

5 SSA Drones Optimal Path Planning

5.1 Notations

Some valid symbols are shown in this part.



(a) $R = 5$ (b) $R = 4$ (c) $R = 3$ (d) $R = 2$

Figure 7 Group 2 of the four post distribution maps

Notations	Description
t_0	Scan cycle
H	The ground breadth that can be monitored by SSA drones
L_Y	Field length of captured image
β	SSA thermal imaging camera field of view
D_Y	Route interval width
q_Y	Lateral overlap rate

Table 2: Notations B

5.2 Assumptions

- We assume that the SSA drones and the Radio Repeater drones will not collide even if their trajectories intersect and overlap. This can be solved by flying at different altitudes.
- We assume that the SSA drone transmits data back to the headquarters within a certain range from the wearable device. And the fire monitoring data such as thermal imaging cameras are also transmitted instantaneously, regardless of the delay time caused by signal propagation.
- We assume that thermal imaging cameras are powerful enough to provide the data we need without being affected by heavy smoke in the air.

5.3 Optimal Path Planning

5.3.1 Brief description of arrangement ideas

Due to the different mission nature of Radio Repeater drones and SSA drones, we use different planning methods to optimize the SSA drones' path.

SSA drones periodically and dynamically traverse the entire sector plan area to monitor the fire and simultaneously collect data from wearable devices on firefighters. Similar to Radio Repeater drones, SSA drones need to be considered for charging and changing duty. However, considering that the fire situation actually does not change much in a relatively short period of time, and the monitoring data is not necessary to report for full real-time, so we think the SSA drones can be allowed to collect information from a location twice in a row at most t0 (min), which can be called “scan cycle”. To facilitate organization and arrangement, we divide the entire sector of monitoring tasks into several trajectories, and each trajectory is arranged for k SSA drones, so we can reduce the number of SSA drones required per trajectory k by increasing t_0.

Based on the aforementioned second assumption, we believe that the SSA drone has the ability to instantly transmit data signals back to the headquarters when collecting data from wearable devices and monitoring fires. For a trajectory route of lengths, one drone needs to be launched from the headquarters every t0 (min), and each drone is fully charged again (can be launched again) after the time $\frac{s}{v_{\max}} + T_3$. So that k simply satisfies the inequality below.

$$k \times t_0 > \frac{s}{v_{\max}} + T_3$$

Due to the discrete nature of k, we can obtain the value of k below.

$$k = \lceil \frac{\frac{s}{v_{\max}} + T_3}{t_0} \rceil$$

After bringing in the value of k we get the following correspondence(Table).

Table 3 The number of drones corresponding to the k value. In actual situation, we can decide

SSA drones required per trajectory k	2	3	4	5
Minimun scan cycle t_0/min	65	44	33	26

Table 3

the value of t0 specifically based on the sizes and frequencies of fires. However, in our next budget, we take the value t0=44min , k=3.

5.3.2 Route parameter design

Since the technical parameters of SSA drones are not given in the background of the problem, we follow the requirements of the "Low-altitude Digital Aviation Regulations" and operational mission requirements, using the ground monitoring station software to design the aerial photography area. Mainly include the following two parameters.

1) Set the aerial height According to the required Drawing scale, and refer to the map scale and map resolution value comparison table (Table 4), we can determine the ground resolution of aerial photography, and then use formula19 to calculate the aerial height.

$$H = \frac{f \times GSD}{a}$$

Where H is the photographic altitude; f is the focal length of the objective lens; a is the pixel size; GSD is the ground resolution of the aerial image.

Mapping scale	GSD/cm
1:500	$<= 5$
1:1000	8∼10
1:2000	15∼20

Table 4

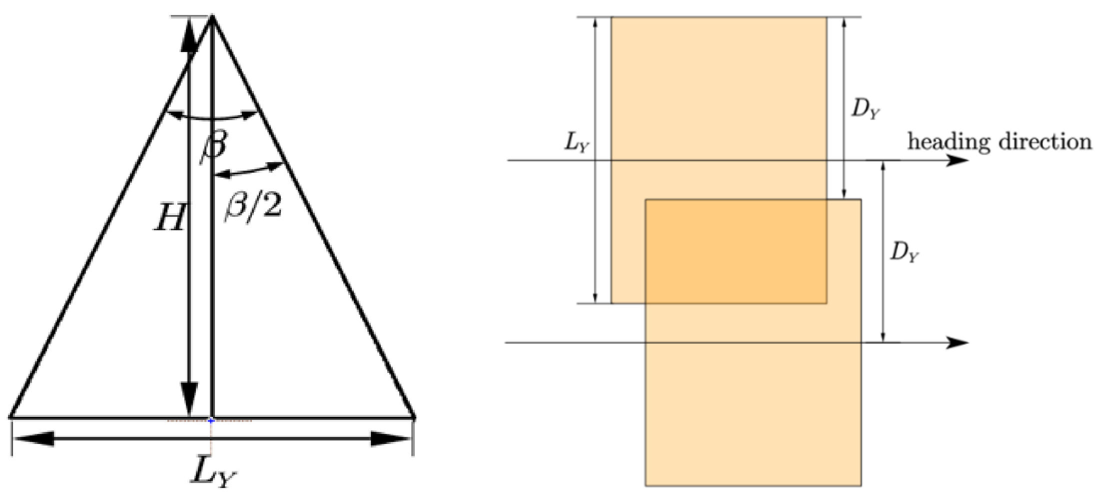
Table 4: The value comparison table between map scale and map resolution.

Taking into account the flight capability of SSA drones, the camera parameters and the resolution required for this mission, we finally select the value of H as 1000 m.

2) Set the route spacing It is known that the field of view β of the SSA thermal imaging camera has the following relationship with the flight height h and the actual length of the ground image L_Y(as shown in Figure 9).

   After investigating the common thermal imaging cameras in the market, we take β as 60° here.

   And the paraxial overlap rate q_Y is defined as formula 21.



(a) Schematic diagram of drone vision (b) Route spacing

Figure 8 The name of figure

$$L_Y = 2\tan\frac{\beta}{2} \cdot H$$

After investigating the common thermal imaging cameras in the market, we take β as $60°$ here. And the paraxial overlap rate q_Y is defined as formula 21.

$$D_Y = L_Y(1 - q_Y)$$

where D_Y is the route spacing as shown in ***Figure 8***.

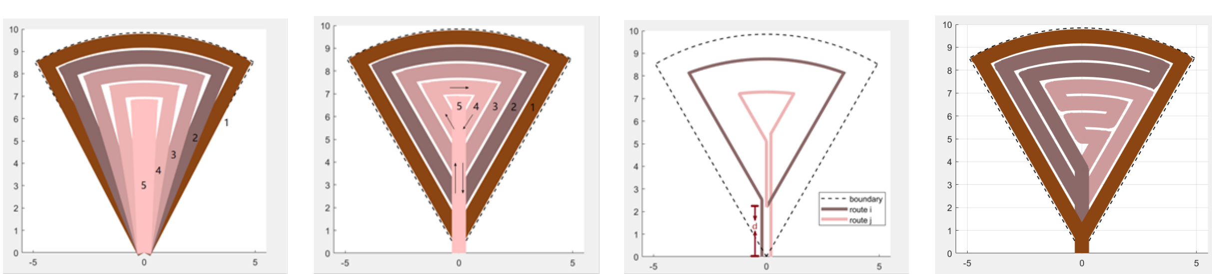
According to the "Low Altitude Digital Aerial Photography Specification", the parallax overlap of images is generally 461.88m9̃81.50m. In the following, we will take $D_Y = 730m$ as an example and discuss the cost that can be minimized by different planning schemes. (The bypass overlap rate $q_Y \approx 36.8\%$ when D_Y is 730 m, which meets the specification requirements.

5.3.3 SSA path planning

After the previous discussion, we need to consider the following constraints when designing the optimal route plan.

Limited to a certain battery capacity of SSA drones, each trajectory is up to 30 km long, and its starting point and ending point are all located at point O. The width of the route interval, which is the part of the field length of the image captured by the drones that can be considered "valid", so all trajectories must cover the entire sector after widening $\dfrac{D_Y}{2}$ to each side. In the case of meeting mission requirements, our optimization goal is to minimize the number of SSA drones. Based on the idea of "going farther places from O point first", Through the discovering and solving of potential problems of our plan, we try the following three options and finally come up with the optimal path for SSA drones.

1. The first plan Due to power limitations, the farther the fire area is from O, the more expensive it is for the drones to reach it. Naturally, after the drone has penetrated a certain distance into the disaster area, we try to give priority to the area of the same depth, so as not to let the drones spend a long time to reach that distance in the future. As a result, we first obtain a scheme consisting of small fan-shaped paths with different central angles and the center of the circle at point O, as shown in Figure 10. Since the perimeter of the whole sector area fire is 30km, the length of each small fan-shaped path on the graph must be less than 30km. So minimizing the number of trajectories means trying to integrate multiple small sector paths into one. To facilitate the calculation, we approximate the arc portion of the fan-shaped path by the line segment between the two endpoints connected. Obviously, this approximation is smaller than the true value. The approximate lengths of the five fan-shaped paths are shown in the following Table **??**.



(a) Plan 1 (b) Plan 2-1 (c) Plan 2-2 (d) Plan 3

Figure 9

5.3.4 SSA path planning

After the previous discussion, we need to consider the following constraints when designing the optimal route plan.

- Limited to a certain battery capacity of SSA drones, each trajectory is up to 30 km long, and its starting point and ending point are all located at point O.
- The width of the route interval, which is the part of the field length of the image captured by the drones that can be considered "valid", so all trajectories must cover the entire sector after widening
$$\frac{D_Y}{2}$$
to each side.

In the case of meeting mission requirements, our optimization goal is to minimize the number of SSA drones. Based on the idea of "going farther places from O point first", Through constantly discover problems and improve our plan, we try the following three options and finally come up with the optimal path for SSA drones.

1) Due to power limitations, the farther the fire area is from O, the more expensive it is for the drones to reach it. Naturally, after the drone has penetrated a certain distance into the disaster area, we try to give priority to the area of the same depth, so as not to let the drones spend a long time to reach that distance in the future. As a result, we first obtain a scheme consisting of small fan-shaped paths with different central angles and the center of the circle at point O, as shown in ***Figure 10***. Since the perimeter of the whole sector area fire is 30km, the length of each small fan-shaped path on the graph must be less than 30km. So minimizing the number of trajectories means trying to integrate multiple small sector paths into one. To facilitate the calculation, we approximate the arc portion of the fan-shaped path by the line segment between the two endpoints connected. Obviously, this approximation is smaller than the true value. The approximate lengths of the five fan-shaped paths are shown in the following ***Table 2***.

   Table 2: Approximate lengths of the five fan-shaped paths

   It can be found that even for the sector trajectories No. 5 and No. 4 with the smallest radius, the combined approximate total length of 30.75 km exceeds the range limit of the drones of 30 km, and the approximate value is smaller than the true value, so paths 4 and 5 must not be combined into one path. Therefore, although the total length of these five paths is only 104.02 km<4*30km, at least five groups of SSA drones teams are required to be responsible for one trajectory each.

   The disadvantage of the first plan is that it is difficult to combine small sector trajectories with each other. But with a little observation, it can be found that trajectory 5 and trajectory 4 have a large area of overlap near the central axis position, and both route lengths have a lot of spare range from the upper limit of 30 km. This provokes a hypothesis: is it possible to make these two paths overlap completely at the central axis for some distance, so that the area responsible for the original two paths can be traversed in one long round trip?

2) The second plan As shown in the Figure **??**(the arrow in the figure that points to the drones' navigation process), we build the second trajectory planning model to answer the question above. Now the figure still has five small paths labeled from 1 to 5 in order from outside to inside, but this time each path extends deeper at the central axis first. We pass through a small sector with a circular angle also of 60 degrees but with a decreasing radius, then return to the central axis and finally return to the origin O along the central axis. This time, we use the program to calculate the length of each small path, and integrate it with Table **??** into Table **??**.

   It can be seen that the length of each minor path increases in plan 2 compared to plan 1. In fact, it is clear from the two illustrations above that this is inevitable according to the triangle inequality law.

   However, the advantage of plan II comes into play when we consider the combination between minor paths. When trying to combine small path i and small path j (i<j), path i and path j can meet at the position where path j turns away from the central axis, instead of having to meet only at the origin O as in model one, as shown in Figure 15 below. The drone starts from the origin O, passes through route i then route j, and finally returns to the point O.

   Therefore, this way of meeting saves two distances of length d. Further, we use the program to calculate that the new path length obtained after combining route 4 with route 5 is only 23.19 km, which can be completed by only 1 group of drones, i.e., the whole task can be arranged to be completed by 4 groups of drones.

   In addition, we need to discuss the possibility of 3 groups of drones to complete the mission. If the above 5 small paths are divided into the 3 groups, either one group is responsible for three small paths, or two groups are responsible for two small paths. If the former is the case, it is calculated that the shortest new path is 37.36 km > 30 km after the combination of 3 small paths (combining paths 3, 4 and 5), so it is excluded. If the latter is the case, path 1 should be handled by a separate group of drones, then path 2 must be combined with another path. But even if path 2 is combined with the shortest path 5, its combined path length is 36.63 km > 30 km, which is beyond the range limit, so it is also excluded.

   So is it the optimal plan?

3) The third plan The answer to the question above may be no. Once again, we try to implement the idea of "prioritizing the places farther away from point O". From the first two plans, path 1, which passes through the entire sector boundary, almost reach the range limit and there is no room for combining it with other paths. So path 1 in model 3 remains the same as in model 2. Next, to avoid overlapping with path 1, the first half of the next trajectory is also identical to path 2 of plan 2. However, when the drone in path 2 flies over the arc and is about to return to the center axis in a straight line, the second half path of model 3 chooses to traverse a parallel arc again in a serpentine manner. So we achieve the purpose of inspecting deeper points in priority before returning. For the remaining plane area, a third trajectory can be obtained by using a similar serpentine filling method. The final schematic diagram is as follows(Figure **??**). Since the analytic formula of the trajectory composition in this plan is more complicated, we directly give the numerical results of the trajectory length obtained by the procedure here in Table **??**.

   In model 3, trajectory 1 and trajectory 2 in particular make almost perfect use of the full range of drones, making the model capable of performing the mission with only 3 groups of drones in total.

5.4 Analysis of the result

In fact, the 3 plan have different performance for different route interval widths. Although each plan satisfies the inverse correlation property that the wider the route interval width D_Y, the smaller the number of drones k required, but k can only take integer values, so the 3 plans have different mutation point locations.

The total number of SSA required for each mission is $K_{SSA} = k_{SSA} * N_{\text{team}}$. In the above work, we have reduced the number of k by increasing the maximum data refresh interval t_0, and by planning the path coverage plan, it is concluded that at least $N_{\text{team}} = 3$ groups of drones are required to perform all monitoring tasks in the sector area. As a conclusion, we estimate K_{SSA} as 3 * 3 = 9.

6 Planning for the Future Budget

6.1 Planning for the Future Budget

Australia is the country with the most serious wildfire problem, with an average of more than 50,000 wildfires every year, and about 50 million hectares of forest and grassland are destroyed by wildfires. And due to global climate change, the risk of forest fires has increased significantly, especially in arid regions [4]. Therefore, from the overall trend, we need to estimate the future trend of fire occurrence in order to adjust the expenditure of fire-fighting equipment.

6.2 Notations

In this part, notation p is defined as the percentile specified.

Notations	Description
λ	Parameters of the Poisson distribution
S_f	Fire area per day during the fire season
S_0	Sector work area that can be handled by one EOC
N_{need}	Number of EOCs required for a fire department
N_{possess}	Number of EOCs available in a fire department

Table 5: Notations C

6.3 Model Preparation

6.3.1 Problem analysis

In the previous work, we have determined that under normal circumstances, the number of SSA drones required for each Emergency Operations Center is $K_{\text{SSA}} = 9$ and the number of RRepeater drones $K_{\text{rep}} = 6.75$. To determine a budget, we only need to plan the number of EOCs that Victoria should be able to establish at the same time, which will be referred to as "EOC numberN_{EOC}"

6.3.2 Data collection and processing

We obtain data on the number of fires started per day between 2003 and 2019 and concluded that CFA should assign an EOC to each fire. In statistics, a percentile is a score below which a given percentage of scores in its frequency distribution fall [This sentence is from Wikipedia]. This means that if we prepare an EOC at 90% of the percentile value, then it will be able to resist fires for 90% of the days in a year. Using a year as the period of consideration, we calculate the 90% percentile for the number of fires started per day, and then take the 90% percentile for each year. Finally the results are obtained in Table 9.

Since the occurrence of a large fire is aggregated in nature in the time series, producing a continuous period with a high number of fires per day, the 90% percentile can help us ignore those very large fires that CFA tends to leave alone and consider small and medium-sized fires more economically. Based on the results in the table, we recommend that CFA equip Victoria with 69 EOCs needed to withstand more than 90% of the fires in 90% of the years past. In fact, after rechecking our data, 69 EOCs would have been able to resist 93.46% of the fires in the last 17 years.

6.4 Budget Forecast Over the Next Decade

6.4.1 ARIMA model

An autoregressive integrated moving average (ARIMA) model is a generalization of an autoregressive moving average (ARMA) model. It is fitted to time series data either to better understand the data or to predict future points in the series. The AR part of ARIMA indicates that the evolving variable of interest is regressed on its own lagged values. The MA part indicates that the regression error is actually a linear combination of error terms whose values occurred contemporaneously and at various times in the past. The I (for "integrated") indicates that the data values have been replaced with the difference between their values and the previous values. The purpose of each of these features is to make the model fit the data as well as possible. The flowchart of the ARIMA algorithm is shown in Figure 10. Based on the 90% percentile series of daily fire starts between 2003 and 2019, we used the ARIMA algorithm to predict the trend of this value in the next ten years, as shown in Figure 10 (note 2003 as the first year)

6.5 Analysis of the result

According to the previous budget plan with 69 EOCs and the ARIMA forecast results, we can see that the forecast value for the next ten years will never exceed 69 except for the 23rd year. The forecast value for the 23rd year is 70, which shows that the current capacity can still deal with fires in most cases. What's more, we have the 85% confidence that the maximum of the 90% percentile over the next decade will not exceed 90, which means that we could increase the budget up to 90 EOCs to ensure safety.

7 Sensitivity Analysis

In the above analysis, we believe that it is reasonable to use p=90% percentile of the number of fire points in a year to estimate the amount of EOC required. Next, we will perform a sensitivity analysis on the factor p. We set the value of p to be 85% and 95%, and re-calculate the data. According to the process described above, the recommended number of EOCs we got is 29 and 215 respectively.

The results obtained after ARIMA time prediction are shown in the following Figure 10.

It can be seen that the p percentile of daily fire points in the next ten years will still hardly exceed 2006. And the recommended number of EOCs is also applicable to the corresponding predicted time series. This shows that our model is almost stable.

8 Strengths and Weaknesses

8.1 Strengths

On the basis of the initial model, we gradually take important impact factors into consideration, and tested it with actual data to optimize the model. Reflects the thought of gradual progress.

The planning area we selecte is fan-shaped, which facilitates the combination and expansion according to the actual terrain. In practice, the budget can be further optimized by optimizing the combination of sector areas.

8.2 Weaknesses

In the drons' path planning process, we do not consider small operational times such as battery changes, which actually exist.

When considering the budget, we do not consider the cost of equipment maintenance and scheduling and the loss due to equipment worn out.

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Track number	1	2	3	4	5
The approximate $length/km$	27.89	24.51	20.87	17.06	13.69

Table 6

Track number	1	2	3	4	5
Length of $plan1/km$	27.89	24.51	20.87	17.06	13.69
Length of $plan2/km$	28.40	25.12	21.47	17.52	14.89

Table 7

track number	1	2	3
Track length/km	28.40	29.17	22.78

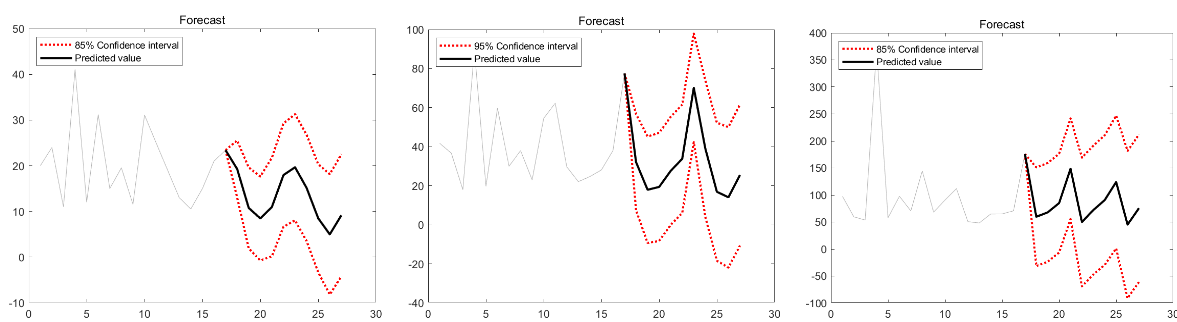
Table 8

2003	2004	2005	2006	2007	2008	2009	2010	2011
41.7	36.7	18	89.7	19.7	59.7	30	38	23
2012	2013	2014	2015	2016	2017	2018	2019	**90% Percentile**
54.5	62.3	29.7	22.1	24.7	28.1	38	77.6	68.42

Table 9

Radius	Randomly Distributed	4-Cluster Distributed
2	17	11
3	8	8
4	6	5
5	3	3

Table 10



(a) 85% (b) 90% (c) 95%

Figure 10

[4] H. Jing, "Vulnerability assessment and influencing factors analysis of urban flood disaster in yangtze river delta city cluster," *Journal of Hohai University(Philosophy and Social Sciences)*, pp. 39–45+110–111, 2020.

Appendices

Globally, especially in Australia, we are facing a greater risk of forest fires. In order to deal with it, we need to make more adequate preparations. The following is the Budget Request provided by our team to CFA.

Taking into account the range of drones, we have developed a sector planning area strategy for your Emergency Operations Center. The actual number of drones is related to the frequency, size, and topography of the fires. The higher the frequency and scale of fires, the shorter the period that SSA drones need to scan regularly, and the larger the number of SSAs required. The more undulating terrain or the more obstacles, the smaller the signal radius of handheld radios, and the more repeater drones are needed. After careful calculations, in order to ensure the safety of your firefighters, the drone-system in an EOC is mathematically expected to be equipped with 9 SSA drones and 6.75 repeater drones.

According to our plan for you, for each fire point, one EOC will be able to extinguish a fire area of up to 50 km^2 per day. Combining the fire data of the past 17 years, we believe that if you want to hold enough EOC to handle 90% of the disaster, you should buy 69 units of drone-systems. If you want to deal with 85% or 95% of disasters, you should purchase 29 or 215 units of drone-systems respectively. In addition, we also used these data from previous years to predict the extent of future fires. The results show that we have 85% confidence that there will be no more fires in the next ten years than in 2006. However, there is still a possibility of a large fire in 2025. If you want to extinguish it with a 90% probability, you need to purchase 19 more sets of equipment. Otherwise, you will have a 50% chance of not being able to extinguish it.

Finally, we once again sincerely recommend that you purchase 69 drone- systems.

Thank you for your consideration of our team of consultants. We're looking forward to working with you again.

Sincerely yours,

Your friends