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Fighting Wildfires——Modeling of the largest central circle of signal reception

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Abstract: Fires, especially forest fires, occur in Australia every year. The size, frequency, and loss of its scale have bothered the authorities. And now, with the development of technology, drone technology can already be used in the field of fire warning. Therefore, proper planning for drone fire protection can allow the Australian government to reduce a lot of economic losses every year. We first gridded the map of Victoria and determined the area where the UAV detection system should be deployed based on Victoria's population distribution, fire location distribution, fire scale, fire frequency and other factors. Then, we used Monte Carlo simulation to calculate the probability that each reconnaissance UAV SSA fails to detect fires of different scales within the specified time. We control this probability to be as small as possible as one of the constraints and combine this with other constraints.

1. Introduction

Wildfires, more accurately referred to as bushfires in Australia, cause severe economic, ecological, and social damage to infrastructure, ecosystems, lives and properties around the world every year. Wildfires can be characterized in terms of several factors including the cause of ignition, their physical properties, the combustible material present, and the effect of weather on the fire.

Destructive wildfires have again swept across Australia during the 2019-2020 fire season, leaving every state in the country scathed, particularly in the eastern states of New South Wales and Victoria. This has alerted people to come up with a quick and effective solution to bushfires as soon as possible. Fortunately, with the development of signal transmission technology, drones carrying a variety of monitoring equipment have brought a boon to fire monitoring and data collection in Australia, providing a reliable protection for people to prevent bushfires from happening.

2. Model 1 — single UAV system

2.1 Grey predictions of the fire situation in Victoria, Australia in the next ten years

Firstly, we forecast the possible forest fire disasters in Victoria in the next ten years based on the collected data of forest fires in Victoria in the past 29 years.

We choose to use the GM (1,1) model in grey prediction to make predictions:
Then we get time response function of our fire prediction model as:

$$x^{(1)}(k+1) = \left(x^{(1)}(1) - 17769.79\right)e^{-0.0096k} + 17769.79, k = 1,2,\cdots n$$

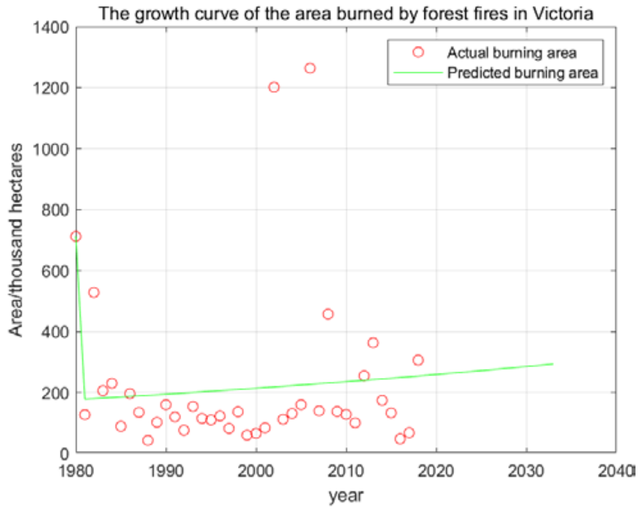


Figure 1. Fitting image of grey forecast and original data made by MATLAB

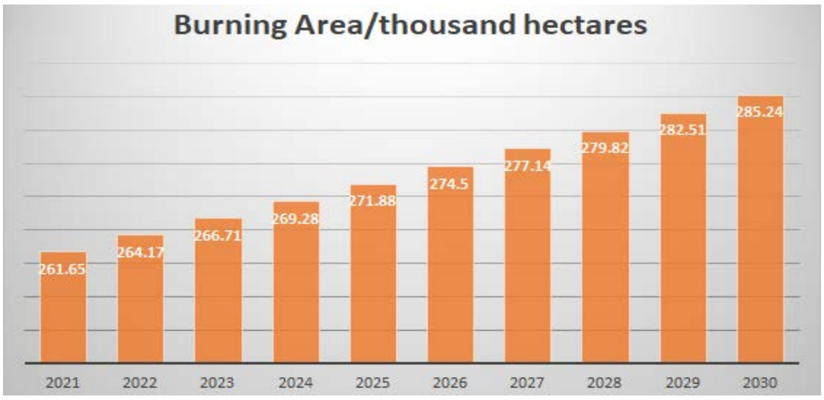


Figure 2. Figure of predicted burning area in Victoria

From the above figures, we can see that according to forecasts, the fires in Victoria will continue to expand in the next 10 years. Therefore, it is necessary to design a more efficient fire detection system to change this trend. In this case, it is the UAV detection system as outlined in the paper.

2.2 Single UAV system — Modeling of the largest central circle of signal reception

According to the topic request, to determine the SSA, the optimal number of drones, and radio repeater and combination, we have two aspects to analysis. One being the "boots on the ground" forward team how to use a radio repeater drones and eoc and how to establish contact SSA UAV reconnaissance of fire, and the other being for unmanned aerial vehicle (UAV) signal coverage combined with the research of Victoria and the circumstances.

In this section we introduce one of them. First of all, to be clear, the SSA UAV carries high definition and thermal imaging cameras and telemetry sensors for monitoring and reporting data from wearable devices for frontline personnel.

Two-way radio communication allows the "boots on the ground" advancing team to provide status reports to the leveling team and allows the leveling team to issue orders directly to the advancing team. Deployers carry hand-held bidirectional radios operating in the VHF/UHF band, and the signal can also be affected by urban areas, which could weaken the signal.

The repeater, transceiver, and automatic replay signal at higher power can expand the radio range. A repeater set in place can achieve the relay of radio signals to and forth between the EOC and the front.

Based on such consideration, we designed the scheme as shown in the Figure 1 below to simulate the signal range reception. The intention is to use the largest circular model as the basis for covering Victoria, i.e., the Single UAV System, to achieve full coverage of the range of multiple Single UAV Systems.

The repeater, as a signal increment station, will be placed at concentric points. As shown in Figure 3, repeater signal propagation range radius of 20 km, usually the ground holding a two-way radio (by people) with the signal range radius of 5 km, want to maximize the receiving range, will make the people-centered 5 km radius of circle and repeater as center, 20 km radius of circle tangent, but for the sake of signal stability, we will people-centric 4 km radius of circle and repeater 20 km radius of tangent circle for the center, then control SSA unmanned aerial vehicle (UAV) to carry on the exploration, check data, drone height from the ground 3.75 km, view Angle at 77 degrees, The signal transmission radius of 3km is calculated as below. Also, for reasons of signal stability and figure the definition, we provisions SSA unmanned aerial vehicle (UAV) distance of not more than 4 km, is made up of handheld radio and SSA radio signal receiving radius of 3 + 4 = 7 km, coupled with the repeater signal amplitude range, we can get up to 20 + 4 + 4 + 3 = 31 km signal coverage of the round, later called a unit circle — single UAV system.

This is the key basis for our regional plate planning in the next section.

Figure 3. The radius of SSA

2.3 Plate division and its causes

This subsection is to address the second point proposed in the first subsection, that is, the study of the coverage of drone signals combined with the specific situation of Victoria. We plan to use the circular model in the first section as a component to achieve full coverage monitoring of signals through the blocks in Victoria. Firstly, we checked the data and got the distribution of fires in Australia in the past 12 months.

We have collected data of records of fire from August 2019 to January 2020 and visualized the fire data with Tableau software (see Figure 4).

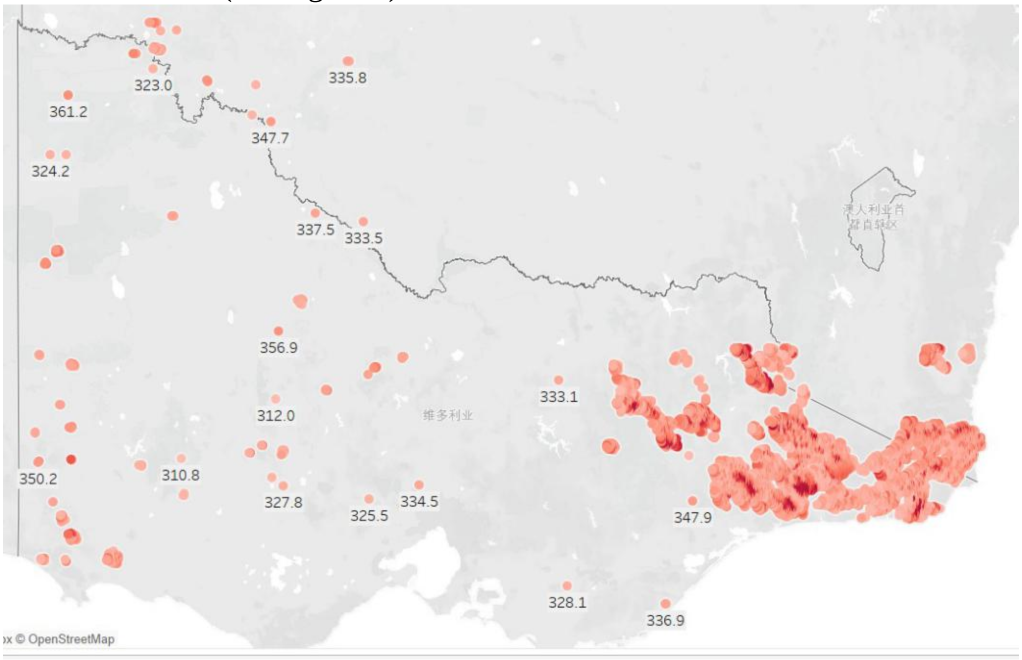


Figure 4. Fire data near Victoria recorded by satellite between August 2019 and January 2020 made by Tableau (The numbers in the figure indicate its fire thermodynamic values)

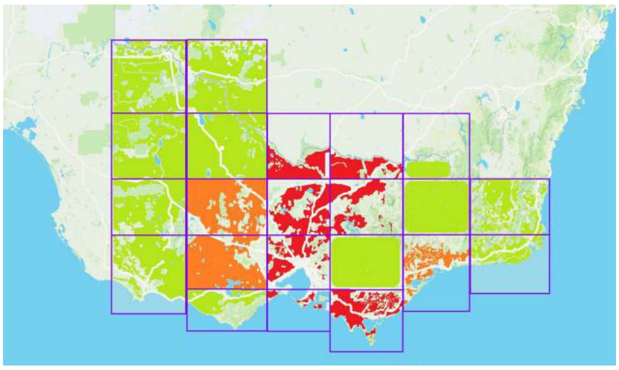


Figure 5. Population Distribution of Victoria (red means highly concentrated population, orange means small population, green means almost no permanent population)

Based on the principles of safety and economy (we have also made a reasonable statement for this decision in the hypothesis), we will not deploy UAV signals in urban areas with large population (large population, fewer urban fires, difficult to fly UAV, easy to detect fire, easy to reach firefighters, and slow fire spread). Next is the specific plate division as shown in the Figure 6.

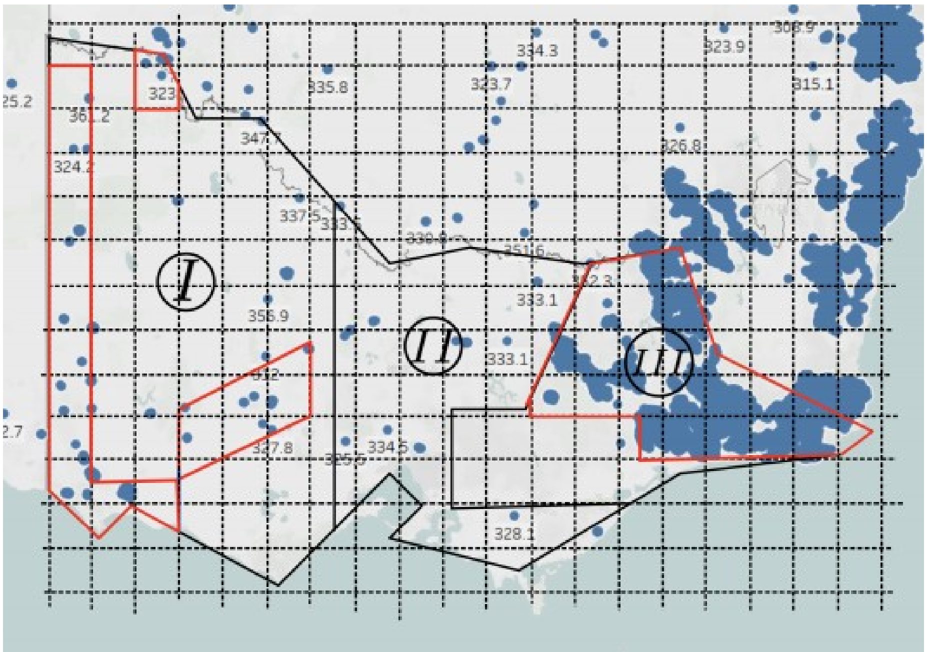


Figure 6. Victorian plate division

To begin with, we have carried on the grid to map of Victoria, the grid unit of Victoria 227000 km^2 treatment after carefully calculated in every 1900 km^2, for sure, a total of about 120 grid units. Then according to the population density of Victoria (Figure 5), we divide the map which Figure 5 describes into three black plates (Figure 6). From the above, the plate *III* red box area is the key deployment of unmanned aerial vehicle (UAV) area. For each grid unit within our radio coverage range, we use the unit circle model established in the first section to cover it. Here, we illustrate the feasibility of using a unit circle to cover a unit grid through calculation:
For the circumscribed circle, should satisfy:

$$\frac{S_{square}}{S_{circle}} = \frac{2}{\prod}$$

According to the data in the paper:

$$\frac{1900}{\prod \times 31 \times 31} < \frac{2}{\prod}$$

Which means that a unit circle can be covered.

2.4 The optimal quantities and combinations are based on the conclusions obtained from the previous sub-subsections

In the above two sections, we have solved the most basic exposition of the model, namely two problems: the first is the processing of the UAV signal circle model, the processing of the geographical location coverage and the combination of the two. In this section, we will deal with the details of the circle model with the relay station UAV as the center of the circle in the first section to complete the optimal number and combination processing of SSA UAV and radio repeater UAV. First, we consider the distribution of ground-based hand-held bidirectional radios (carried by humans, plus the SSA detection radius) within the great circle. We divide the great circle into inner and outer parts. By drawing, we can calculate the Angle formed by each peripheral circle and the center point to calculate how many peripheral circles are needed to cover. Similarly, we can also calculate the number of inner circles. Through the calculation of existing data, we finally get the conclusion that the outer circle needs 10 circles, and the inner circle needs 4.

Complete these our renderings as follows, we found that the outer circle and a small range between does not cover, but the adjacent unit circle will have overlap, which means blind area can be other SSA unmanned aerial vehicle (UAV) to detect the unit circle, therefore can be considered as direct coverage, for the radius of 3 km for the center with relay station has not been covered circle we proposed the following solution:

1. The SSA UAV hovering at the center of the unit circle to provide monitoring.
2. EOC is set at the center of the unit circle to be responsible for the control and charging of the repeater UAV and the SSA UAV in. Once a fire occurs at any place in the unit circle, personnel are selected from the EOC to form a mobile sub-EOC and go to the vicinity of the fire site to cooperate with the SSA UAV there to carry out further investigation and processing of the fire.

At this point, we have achieved full coverage of the great circle.

Looking further, the transmission of signals between hand-held radios and SSA drones remains problematic. Because there is likely to be: in a certain period of time, the fire point now the SSA and people cannot reach "blind spots (Figure 7) "- although we realize the monitoring scope of the cover, but given the drone around speed and charging time, if the surrounding the unmanned aerial vehicle (UAV) is less may be found that fire time delay, lead to the spread of fire appeared great potential safety hazard.

So, we will discuss the quantity calculation around the SSA next. As the chart, the number 10 to discuss around SSA, we first known SSA surround path length for 8 km, and unmanned aerial vehicle (UAV) flight range of 30 km, maximum speed of 20 m s, the longest flight time of 2.5 h, and battery charging time is 1.75 h, need to be replaced in a timely manner. We now know that if there is only one SSA UAV around, there will inevitably be blind monitoring area in terms of time. The ideal state is to minimize the number of UAVs in a reasonable time and speed so that the rescue effect will not be affected when the fire is discovered and the charging time is exactly corresponding. For example, if the circling speed of SSA UAV is 4m s, then it can sail for 1.74h, which means that the cycle of charging and cruising can be approximately realized for two UAV. If the time of blind area corresponding to this speed is less than a domain value, then we believe that two UAV is the optimal circling solution. Therefore, we need to solve such domain value parameters based on the fire size and frequency relationship.

2.5 Parameters are solved based on the size and frequency of fire events.

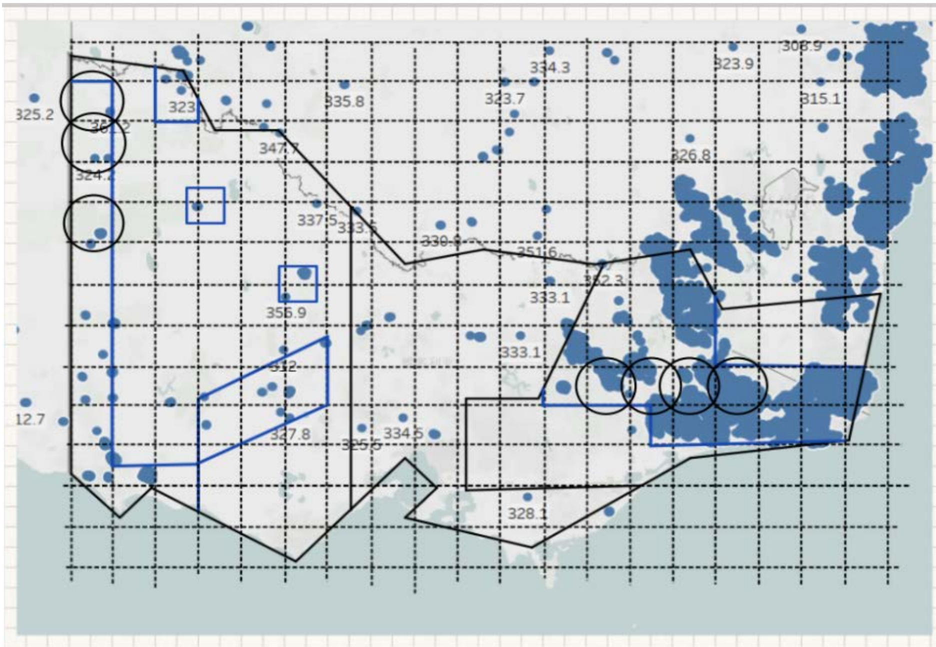


Figure 7. How does the drone detection circle effectively cover the detection area

We collected the data of the average number of fires per hour of *III* in Eastern Victoria (Figure 6), and according to the grid statistics in the above figure (Figure 7), *III* accounts for about 20 grid units, which means that *III* occupies 38000km^2 according to the proportion. Since fire is a typical accidental event, we put it into a Poisson distribution probability for solving. By the above list data, in December 4.8375 for example has proportion:

$$\frac{4.8375}{\lambda} = \frac{S_{square}}{S_{east}} = \frac{49\prod}{38000km^2}$$

Get for λ value is within a circle, λ is the average per hour within a circle of fire occurrence frequency, according to Poisson distributed:

$$P = \lambda e^{-\lambda}$$

To calculate the corresponding probability. In the same way, we can now calculate the probability of risk associated with the "blind spot". The area corresponding to the blind area is S S_0 S_1, then λ calculated by the same method is the average number of fires occurring in each hour in the risk "blind area", and then the risk probability p.

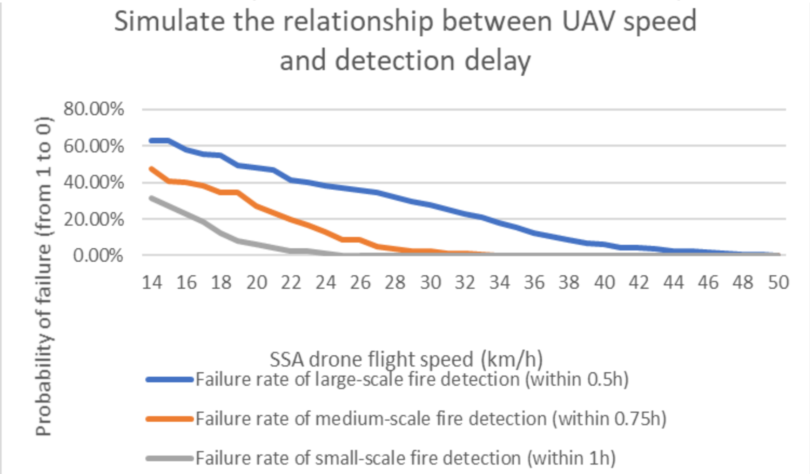
Based on the size and frequency of fire, after consulting the information and sorting out, we made the thermal value as the standard to judge the size of fire and the probability diagram of the occurrence of fire and determined the following table (the corresponding probability of small and medium sized fire), and calculated the probability of P_1, P_2 and P_3 under small and medium sized fire. Next, we also contend with the above idea and collate the data to get the tolerance time T_1, T_2 and T_3 under the small and large fires.

Through data collection and sorting, simulation, and algorithm design, we complete the simulation implementation and can calculate the probability P1, P2 and P3, i.e., the probability of t being greater than the above time, respectively, at the speed v of any desired aircraft, namely the risk probability.

3. Goal planning model

In the second part, this paper presents the composition of the UAV reconnaissance system. However, it is worth mentioning that due to the characteristics of the UAV itself, within each detection unit circle, the SSA reconnaissance UAV is not always able to achieve detection coverage for all areas. In theory, the faster the drone flies, the lower its detection error rate will be. In the following text, we will study this situation. In addition, the flying speed of the SSA drone is limited by its own manufacturing quality. On the other hand, increasing the speed of the drone may also affect its power consumption speed and other factors. Ultimately, to significantly increase the flying speed of the drone means an increase in its cost. In this regard, this article proposes to use the target planning model to optimize the flight speed of the SSA UAV in a single reconnaissance system in order to achieve the strategy with both safety and economy, of which safety is at priority.

Due to the different fire scales, we set 0.5h, 0.75h, and 1h as the maximum detection time for large, medium, and small fires respectively. If the moving drone fails to detect a fire within the specified time, it will for a failure. So, according to Monte Carlo simulation, we got the following figure:



From the above figure, we can see that when the drone speed is high (greater than 40km/h), the detection failure rate of fires of various scales has dropped to around 0, which is fully in line with our expectations. Now that the data has been obtained, we will then fit the functional relationship between UAV speed and detection failure rate so that we can put it in the next planning model. Using MATLAB for interpolation fitting, we obtain the following functions between the flight speed v of the SSA UAV and the failure rate of large-, medium-, and small-scale fire detection y_1,y_2,y_3, respectively:

$$y_1 = 198.43v^{-2} - 11.84v^{-1} + 0.1681$$

$$y_2 = 116.94v^{-2} + 0.29v^{-1} - 0.0812$$

$$y_3 = -219.67v^{-2} + 32.69v^{-1} - 0.5943$$

We then reduced the function of the number of drones and the speed v mentioned in the above paper into the simplest form:

$$y_4 = \frac{v}{8\pi}$$

The function of drone charging frequency and y_5 speed v is transformed into the simplest form:

$$y_5 = \left\lceil \frac{0.21875v}{\pi} \right\rceil + 1$$

According to the weight coefficient, different constraints are given different priority factors (priority levels). For this, we first stipulate that the signs of the positive and negative deviation variables in the model are:

d^+, d^-

Above all, we have obtained a complete target planning model for the optimal flight speed of the SSA UAV.

Our Objective function and Restrictions:

$$\min z = 1000d_1^+ + 70d_2^+ + 30d_3^+ + 7(d_4^+ + d_4^-) + 3(d_5^+ + d_5^-)$$

$$\begin{cases} y_1 + d_1^- - d_1^+ = 0.2(p_1) \\ y_2 + d_2^- - d_2^+ = 0.1(p_2) \\ y_3 + d_3^- - d_3^+ = 0.01(p_3) \\ y_4 + d_4^- - d_4^+ = 1(N_1) \\ y_5 + d_5^- - d_5^+ = 4(N_2) \end{cases}$$

4. Sensitivity analysis

There is a large number of environmental variables in the target planning model for determining the flight speed of reconnaissance drones, including the probability of UAVs detecting large fire delays P1, the probability of detecting medium fires delay P2, the probability of detecting small fires delay P3, and the UAV charging frequency N1 and variables such as the number of SSA reconnaissance drones in a drone system N2. Their initial values are: P1=0.2, P2=0.1, P3=0.01, N1=1, N2=4. Let these variables fluctuate continuously 5 %, using MATLAB software to draw a schematic diagram of the five parameters between the decision variables and the flying speed v of the surveillance drone.

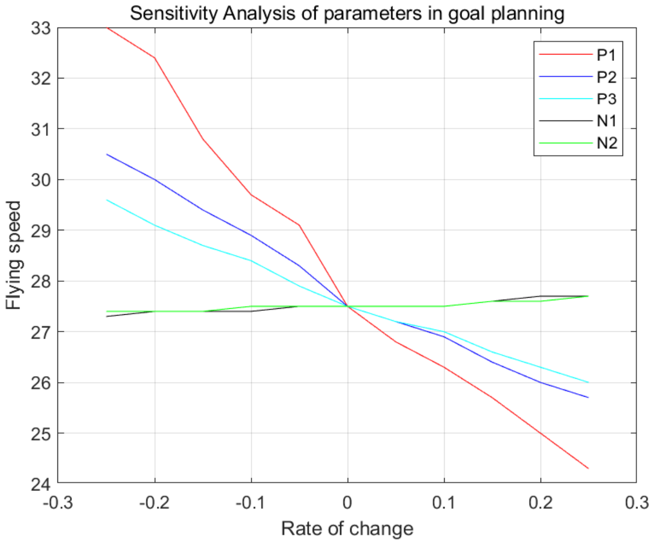


Figure 8. Figure of sensitivity analysis

The solution model of the flying speed of the reconnaissance drone in question 1 is more sensitive to the three parameters P1, P2, and P3. The change of P1 will have a greater impact on the speed of the drone. (Figure 8) Therefore, in actual application of our model, users should also pay special attention to the values of the above parameters.

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