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Design of scheduling algorithms for UAVs to Detect Air Pollution Sources from Chimneys in Industrial Area

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***Abstract*—With the rapid development of Unmanned Aerial Vehicle (UAV), many related applications using UAVs is to monitor air quality in urban, rural or industrial areas. They often focus on how to monitor the propagation of air pollution, provided the pollution sources should be positioned with permanently placed wireless sensors. However, it is hard and time-consuming to identify pollution sources due to a number of chimneys in industrial areas. Therefore, to air pollution source detection in the minimum search time from the chimneys with fixed locations in an industrial park using one or more UAVs. In this paper, we propose two heuristics algorithms for air-pollution-source detection by UAVs including Interference-Graph- Based Algorithm (IGBA), and Extended Interference-Graph-Based Algorithm (EIGBA). As a result, the detection time by these proposed algorithms compared with that by the Traveling Salesman Problem (TSP) algorithm air pollution source detection time is significantly reduced.**

***Index Terms*—Gaussian Plume Model, Unmanned Aerial Vehicle, Air Pollution.**

I. Introduction

Today with the advancement of science and technology, human civilized life is increasingly prosperous, it is followed by the impact on human health and damage to the earth ecosystem far beyond the previous level [1]. Among them, air pollution has become an issue of global concern, in addition to the serious impact on the environment, it also affects human due to deteriorating air quality that humans have never faced before. Therefore, the issue of air quality has become a difficult problem that people face and measures need to be taken to solve today's environmental problems.

To monitor the air pollution source, in [2] they set up air quality monitoring stations, by placing sensors in the monitoring area and transmitting information about the base station for inspection and analysis. Traditional methods for air pollution measurement are expensive and have a spatial constraint. With these limitations, air pollution monitoring in a broader area is not feasible, the problem of using the modern low-cost multi-sensor node for air pollution measurement in conjunction with wireless sensor network (WSN) is to collect and aggregate real-time data from different locations and provide detailed pollution map proposed in [3]. This urban air pollution monitoring system is based on static locations, so this problem is limited by mobility. To overcome this limitation. In [4], that uses a combination of portable mobile sensor units, smart-phones, cloud computing, and mobile apps to measure air pollution information for individuals.

In recent years, UAV development and application have made great progress such as mobility, low cost, lightweight, and ease of use [5]. First, the UAV application is used in the military, with the aim of replacing large aircraft and humans with small UAVs for reconnaissance missions, which not only reduces the probability of casualties for humans but also increases the ability to conceal the quest [6]. Next, due to low cost, reduced job execution time and ease of use [7], package delivery services [8]. In the field of air environment detection, adding sensors to UAVs replaces permanently placed traditional wireless sensors, for collecting, and sending the collected data to the remote acquisition point [9]. That is useful for comprehending the impact of the local environment caused by air pollution.

The problem of adding sensors to the UAV, in addition to portability it also reduces the cost of environmental monitoring [10]. In [11], UAVs are equipped with off-the-shelf sensors to perform air pollution monitoring tasks, after transmitting data to the base station, it can draw pollution maps of the monitoring area. In critical areas [12], use UAVs to monitor air pollution in inconvenient traffic areas by focusing on areas with high air pollution to redraw the map polluted. . we noticed that, previous studies on air pollution focused on environmental monitoring, proposing solutions and improving, there have been no studies on pollution sources, and most pollution sources are diverse such as pollution sources in urban areas, rural areas, industrial areas, etc. In order to improve the air environment quality in the monitored area, it is necessary and timely to find the fastest and most accurate source of air pollution by the UAVs.

From the above problems. In this paper, we propose a model for air pollution source detection with reduced time in industrial areas by UAV. First, we propose TSP-based algorithm to solve flight scheduling problem. Second, we use the K-means clustering algorithm to divide the area into the number of sub-areas corresponding to the number of UAVs. Then we rely on the interference graph relationship to remove the positions that are not in the interference graph. The main contributions of this paper are as follows:

1) We propose the task allocation method for UAV based on clustering algorithm and mTSP-based flight scheduling

method.

2) We propose solution and experimental to the problem of optimizing the air pollution source detection time by the UAVs with the relationship of the interference graph.
3) Improved UAV features such as mobility, ease of maintenance, low cost, and being able to apply artificial intelligence (AI).

II. SYSTEM MODEL AND PROBLEM DEFINITION

In this paper, our goal is to minimum search time air pollution source detection by UAVs. In Section II-A, we will talk about how the system model. In Section II-B, we generalize the Gaussian plume dispersion model. In Section II-C, we introduce a model of polluted chimney detection. In Section II-D, we will describe the problem definition of this paper.

A. System model

As illustrated in Fig. 1, We consider a system based on actual environmental conditions in a geographic area and it consists of a base station (BS), a set $U = \{U_1, U_2, ..., U_m\}$ of UAVs and a set $P = \{P_1, P_2, ..., P_n\}$ of the chimneys diffuse pollutant plume are distributed on the ground has a fixed position. The BS has responsibilities including air pollution source detection in the entire monitored surrounding area, providing chimney location coordinate information for UAVs, replenishing energy for UAVs, and planning a flight route for the UAV. The UAVs are equipped with air pollution sensors and have limited battery capacity. In our investigation, the UAV flight schedule is provided by the base station and to land at the initial position. When the BS air pollution source detection in the monitored area, the UAV will take-off at the initial position with the cruising speed u_v and the concentration value of the detected source of pollution u_c, assume the value of pollutant concentration threshold ξ. Initially, the UAV flew according to schedule to each chimney location to air pollution source detection. During the flying of the UAV, when the detected u_c concentration is found to be higher than ξ, a chimney search disperses pollution is performed. To shorten the search time for polluting chimneys. the UAVs will fly in search of chimneys in the wind direction, the chimneys that are not in the wind direction will be removed from the original schedule. When the UAV detects a pollution chimney location, the UAV will skip the remaining chimney locations and to return initial position.

B. Pollution source model

When we look at the atmosphere, we see that there are many factors that influence the behavior of a pollutant plume: wind speed, atmospheric stability, the occurrence of temperature inversion, plume temperature, plume exit speed, landscape, etc. To simulate the diffusion of the pollutant source, it is necessary to calculate quickly and accurately. In [13], [14] the Gaussian plume model can predict the surrounding concentration of a pollutant source. Assuming that the wind speed and direction are constant as shown in Fig. 2, we can observe a pollutant plume emitted continuously from the chimney mouth. When pollutant plume stain rises to a certain height, it will not continue to increase but it will remain motionless. If there is wind, from the chimney mouth the plume rise caused by the momentum of the plume as it leaves the stack or by the buoyancy as hot plumes are lighter than ambient air and stretches across the horizontal plane in the wind direction. Hence, in different weather conditions, then the instantaneous concentration a pollutant in a plume will be irregular. Set the air pollution concentration at the detection position to $C(x, y, z)$, the equation for pollutant concentrations in Gaussian plumes is as follows:

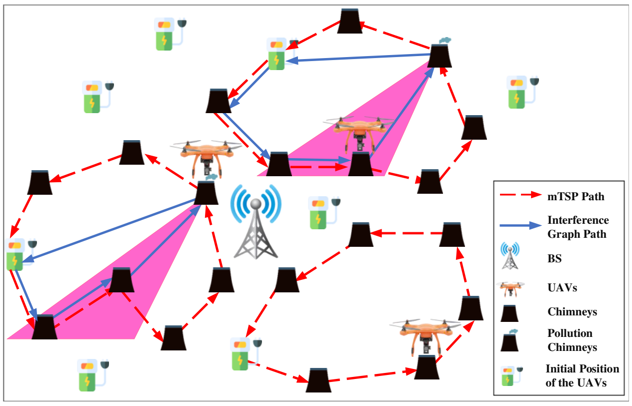

Fig. 1: System model to the air pollution source detection

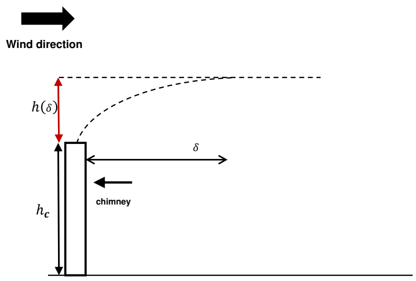

Fig. 2: The Gaussian plume dispersion model.

$$C(x, y, z) = \frac{Q}{V} \frac{1}{2\pi\sigma_y\sigma_z} \exp(-\frac{1}{2}\frac{y^2}{\sigma_y^2}) \exp(-\frac{z^2}{2\sigma_z^2}) \quad (1)$$

$$\sigma_y = \frac{ax}{(1 + bx)^{0.5}} \quad (2)$$

$$\sigma_z = \frac{dx}{(1 + ex)^{0.5}} \quad (3)$$

where

C = concentration at a given point (gm^3)
Q = emission rate (gs^1)
V = wind speed (ms^1)

σ_y = dispersion parameter in the horizontal (lateral) direction (m)

σ_z = dispersion parameter in the vertical direction (m)

The coordinate axes in Gaussian plume dispersion modeling are illustrated in Fig. 3 as follows:

x = direction of the wind (x = 0 at the source; x >0 downwind).

y = horizontal direction perpendicular to the wind (y = 0 at the center of the plume; positive on your left when you look downwind).

z = vertical direction (z = 0 at the surface and positive above the surface).

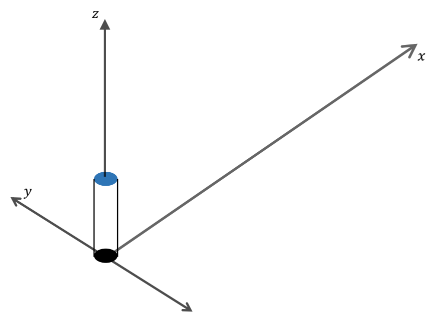

Fig. 3: Coordinate system in simple Gaussian dispersion model

From Eq 1 and Fig. 4, the wind speed depends on height, the wind speed at the effective source height h should be used for V and the spread parameters depend on the distance from the source and on weather conditions.

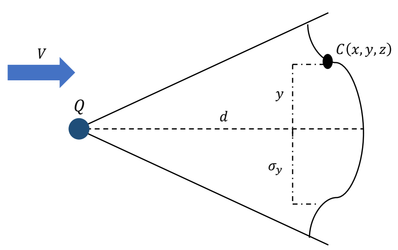

Fig. 4: Horizontal plume dispersion in the wind direction

C. Model of detecting pollution chimney

To detect whether a chimney is a source of air pollution, by easiest intuition is that the UAVs fly to the chimney to check, but the chimney emits stack of pollutant at very high temperatures can lead to the UAV malfunctioning. Hence, we set up the UAV to fly about an δ distance away from the chimney mouth to ensure that the UAV will not fail. As shown in Fig. 2, effective source height h of the UAV is the sum of source height h_c and plume rise $h(\delta)$. The chimney diffuses the plume do not rise indefinitely but stabilize at a certain height, the final plume rise height. The height equation of plume rise $h(\delta)$ achieved at a distance δ from the source is as follows:

$$h(\delta) = \frac{1.6F_b^{\frac{1}{3}}\delta^{\frac{2}{3}}}{V} \quad (4)$$

where, F_b is the floating force parameter, this parameter is related to the gravitational acceleration and the temperature difference.

As shown in Fig. 5, when the UAV flies to the chimneys to detect the source of air pollution, the UAV flies in a $semicircle$ from point $p^{'}$ to point $p^{''}$. If the concentration values of the pollutant plume diffuse u_c are found greater than the value of the concentration threshold δ, it means that the chimney being detected is a source of pollution, otherwise, the chimney being detected is not a source of pollution.

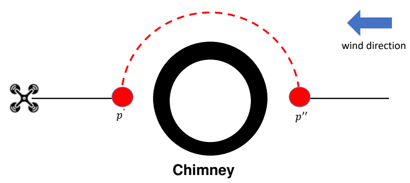

Fig 5: Semicircle diagram

D. Problem definition

In this section, the main issue discussed is that when the UAV gets the necessary information from the BS provided. The ideal situation is that the UAV can air pollution source detection and flies back to its initial position with excess energy. Assuming the search time is T, our goal is to minimize the search time for T as short as possible. Therefore, the problem of flight planning and flight time of the UAV to air pollution source detection is carried out. The search time of multiple UAVs is calculated based on the calculation of the first UAV that air pollution source detection and flies back to its initial position. Accordingly, Minimum-SearchTime Air Pollution Source Detection Problem (MSTAPSD) is proposed.

III. PROBLEM STATEMENT

A. Schedule

In this phase, since all chimney locations are known. If the expected flight path is given in advance for the UAV, the UAV can avoid having to calculate the flight path by itself, which will reduce power consumption and computation time for the UAV. Hence, UAV path planning can be divided into two different formats.

In the first one, uses single UAV to air pollution source detection in the minimum search time. First, the UAV take-off from initial position, then the UAV flies to the positions of all the chimneys by the shortest path, at each position of the UAV chimney flying in a semicircle. Obviously, the minimum flight time problem is similar to Traveling Salesman Problem (TSP) [15]. TSP forms the basis of the problem we're facing and considered as one of the most popular NP-complete problems where TSP can be defined as visiting all cites for the UAV in the environment once in a time.

The second format uses multiple UAVs to air pollution source detection in the minimum search time. Hence we cut down the area of responsibility for the UAVs using the K-means clustering algorithm [16], in each cluster has a UAV which corresponds to air pollution source detection. Definition 2 and Definition 3 in section II-D is a variation of multiple traveling salesman problems (mTSP), which is to minimize the maximum distance traveled by any UAV (min-max mTSP) [17], [18] , Compared with minimizing the total distance by all the UAVs.

B. Interference Graph

During the flight schedule of the UAV to the air pollution source detection. When the UAV hovered along the flight path and detected the pollution location. Then the UAV must know which source of air pollution is coming from the chimney. Hence, our goal at this stage is to establish a relationship diagram for the chimney locations, i.e. in which direction the UAV will fly, which fly to the next chimney location, and remove which chimney positions were in the original flight schedule. We use the following two as requests during this phase. 1) Wind direction: Know the wind direction that the source of pollution can affect; 2) Pollution source formula: Knowing the spread of the pollution source and being able to know which source of pollution affects the chimney positions as shown in Fig. 6.

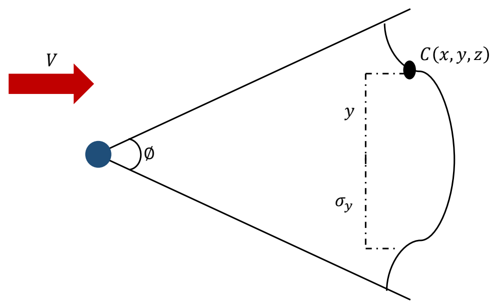

Fig 6: The air pollution source interference graph

IV. PROPOSED ALGORITHMS

In this section, algorithms that optimize the air pollution source detection time are based on flight schedules, interference graph. The details of this algorithm are as follows.

A. Interference-Graph-Based Algorithm (IGBA)

Combining the two problems presented in Part III including the UAV flight schedule and the interference map. First, the UAV take-off at the initial position and flies according to a flight schedule based on the TSP algorithm in Section III-A with using all chimney positions. Then during the flight of the UAV, the UAV detects the pollutant plume in the air. According to the air pollution source interference graph mentioned in Section III-B, the UAV determines where the chimney locations can cause the source of air pollution and deletes the chimney locations that do not cause pollution in the interference map. Therefore, the time to find the air pollution source of UAV will decrease compared to the original schedule.

Algorithm 1 IGBA(C,u,p, θ, δ)

$(V_{G_r}, E_{G_r}) \leftarrow$ constructInterferenceGraph (C)
Let R be the routing path $(u, r_1, r_2, \ldots, r_n, u)$ constructed by the Ant Algorithm [17, 18] to visit $\{u\} \cup C$
$psrc \leftarrow NULL$
Remove the first node from R
while $R \neq \emptyset$ **do**
  Let x be the node pop up from the first item of R
  Let pos' and pos'' be the checkpoints obtained by x, θ, δ
  if the UAV detects the air pollution at pos' **then**
    Move UAV to pos''
    if the UAV detects the air pollution at pos'' **then**
      Let Y be the set of nodes y for all $(y, x) \in E_{G_r}$
      for each r in R **do**
        if $r \notin Y$ **then**
          pop up r from R
        end if
      end for
    else
      $psrc \leftarrow x$
      $R \leftarrow (u)$
    end if
  end if
end while
return $psrc$

B. Extended Interference-Graph-Based Algorithm (EIGBA)

In this algorithm, the implementation problems are similar to the IGBA algorithm in Section IV-A. But the difference is that more UAVs are used to air pollution source detection, each UAV is responsible for a corresponding area. The first stage is clustering, we based on the number of UAVs to divide into the number of corresponding clusters using K-mean algorithm. Then, we scheduled the flight using the multiple traveling salesman problem (mTSP). Finally, the relationship diagram is implemented similar to the IGBA algorithm after mTSP has been computed. EIGBA proceeds as follow.

Algorithm 2 EIGBA(C,U,p, θ, δ)

Let $\mathcal{C} = \{C_1, C_2, \ldots, C_{|U|}\}$ be the set of groups constructed by K-means, where $C = C_1 \cup C_2 \cup \ldots \cup C_{|U|}$ [16]
$psrc \leftarrow NULL$
for each $u \in U$ **do**
    Let c be the chimney closest to u
    Let C_i be the group that contains c
    $psrc \leftarrow$ IGBA(C_i,u,p, θ, δ)
    if $psrc$ **then**
        return $psrc$
    end if
    Remove C_i from $\mathcal{C}$
end for

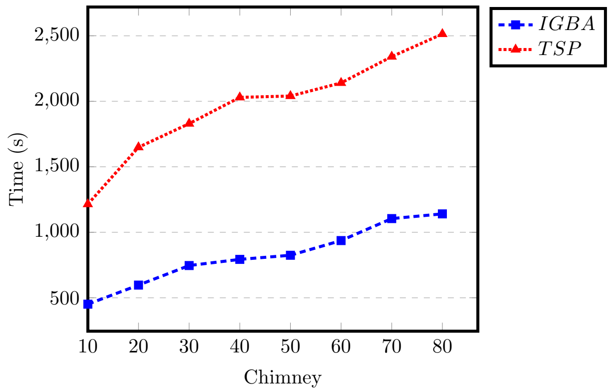

Fig 7: Compare the air pollution source detection time with single UAV when the number of chimneys increases.

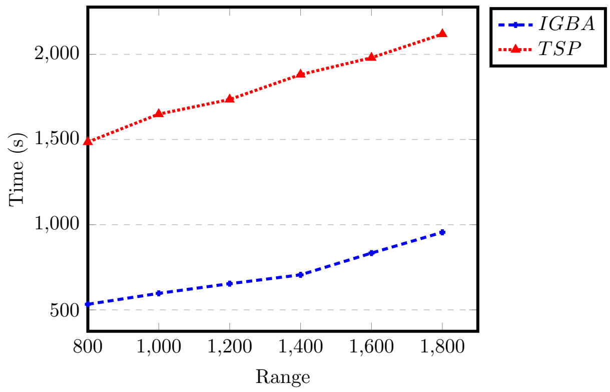

Fig 8: Compare the air pollution source detection time with single UAV when changing area.

V. SIMULATION RESULTS

In this section, we present simulation results to demonstrate performance of our Minimum-SearchTime Air Pollution Source Detection algorithms. We consider a UAV-enabled model air pollution source detection in industrial area that consists of UAVs, chimneys, and wind direction. The position of the chimneys is randomly placed in a squareshaped area from $800m^2 \times 800m^2$ to $1800m^2 \times 1800m^2$, the number of UAVs and chimneys will increase or decrease according to the simulation scenario, and the number of clusters corresponds to the number of UAVs. In each flight schedule, the UAVs were dispatched to air pollution source detection along the flight trajectory with the velocity v set as $10m/s$.

The (TSP, mTSP)-based algorithm optimizes the air pollution source detection time proposed and compared with the IGBA, EIGBA algorithms subverted by the original (TSP, mTSP) algorithm.

A. Comparison of search problems with single UAV

In this subsection, to air pollution source detection with single UAV, the TSP-based algorithm is compared with the IGBA algorithm.

1) **Comparison the number of the chimneys** In Fig. 7, we compare the air pollution source detection time of the UAV in each flight schedule corresponding to the number of chimneys increased from 10 to 80. We noticed that as the number of chimneys increased, the TSP-based algorithm with UAV hovering around all the chimney locations. Therefore, UAVs perform a longer flight schedule, because many chimney positions are not required for the UAV to fly over. Our proposed IGBA algorithm is combined with the interference graph. Hence it has the relationship of obtaining information from the air pollution source information and it is used to remove unnecessary chimney positions, resulting in a significantly reduced flight time of the UAV on a schedule. So the IGBA algorithm results in shorter flight times than the TSP-based algorithm.

2) **Comparison areas of change in size** With the number of chimneys maintained at 50. we noticed that the search time increases gradually as the range expands from $800m^2$ to $1800m^2$. When the range is enlarged, the positions of the chimneys will be further apart, so the distance between the chimneys will increase. Since the maximum diffusion range of the air pollution source is constant, the diffuse pollution source is only detected within a certain range. The results are shown in Fig. 8, the air pollution source detection time of the IGBA algorithm is shorter than that of the TSP-based algorithm.

B. Comparison of search problems with multiple UAVs

In this subsection, to air pollution source detection with multiple UAV, the mTSP-based algorithm is compared with the EIGBA algorithm.

1) **Comparison areas of change in size** With the number of chimneys maintained at 50. we noticed that the

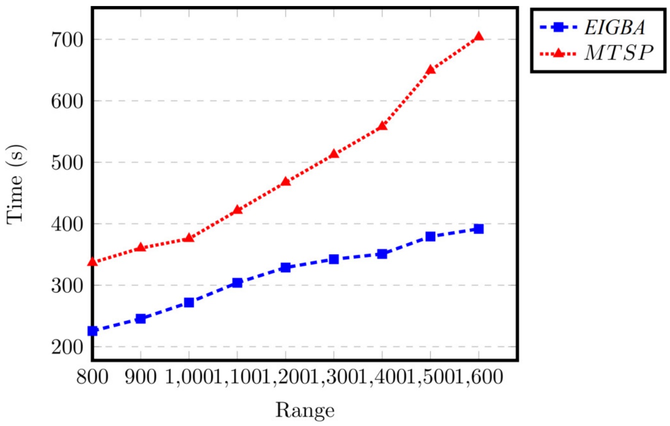

Fig 9: Compare the air pollution source detection time with multiple UAV when changing area.

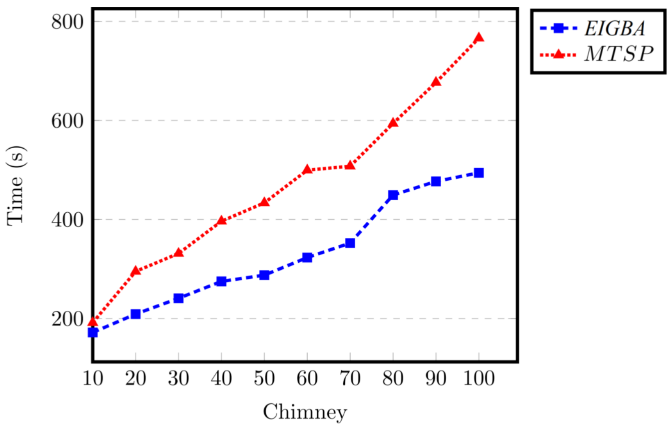

Fig 10: Comparison of the number of chimneys that minimize the detection problem of multiple UAV.

air pollution source detection time of the EIGBA and TSP algorithms gradually increases as the area increases from $800m^2$ to $1600m^2$. Due to increased position and distance between chimneys. In Fig. 9, the air pollution source detection time of EIGBA algorithm is shorter than that of mTSP algorithm.

2) **Comparison the number of the chimneys** In this subsection we compare the change in the number of chimneys shown in Fig. 10. As the number of chimneys increased, leading to more and more chimney positions in the flight path, so the flight distance of the UAVs also increased. Since the EIGBA algorithm benefits from the air pollution source interference graph reflected at this time, the flight path removes unnecessary chimney locations. Therefore, the air pollution source detection time of the EIGBA algorithm has a shorter flight schedule than the mTSP algorithm.

VI. CONCLUSIONS

In applications using sensors to detect air quality is the mainstream. These applications often focus on monitoring the spread of air pollution when the source of the pollution is known, resulting in deficiencies and failure to meet actual needs. To overcome the above limitations. In this paper, we use UAVs to the air pollution source detection with low cost and high efficiency. First, we flight schedule for the UAVs to monitor respective areas. Next, based on the position where the UAV detected the pollutant plume to construct the interference graph. Finally, remove chimney locations that are not in the interference graph. Through simulation experiments, with the use of the interference graph method. Our proposed algorithms have a shorter air pollution source detection than the (TSP, mTSP)-based algorithm.

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