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Simplified Atmospheric Dispersion Model and Model Based Real Field Estimation System of Air Pollution

Zheng Fu[#], Jingeng Mai, Lin Zhang, Fei Tao

School of Automation Science and Electrical Engineering, Beihang University, Beijing 100191, China

[#]Email: fu112358@163.com

Abstract

The atmospheric dispersion model has been well developed and applied in pollution emergency and prediction. Based on the sophisticated air diffusion model, this paper proposes a simplified model and some optimization about meteorological and geological conditions. The model is suitable for what is proposed as Real Field Monitor and Estimation system. The principle of simplified diffusion model and its optimization is studied. The design of Real Field Monitor system based on this model and its fundamental implementations are introduced.

Keywords: Atmospheric Dispersion Model; Simplified Dispersion Model; Real Field Monitor

1 INTRODUCTION

The Atmosphere is a complex of gaseous and natural factors co-reflected system, which is essential to support and protect the ecosystem on earth. The pollution of atmosphere could be the large-scale and long-lasting threat to human. And driven by the atmospheric circulation, the pollutants spread about could affect other ecosystems far from the release location. In order to forecast and estimate the degree of contamination once the dispersion occurs, agencies and countries have developed sorts of atmospheric dispersion models with regard to mountainous region, urban area, costal position and many other circumstances, ever since 1930s. The technical explanation of air pollution model in 1930s was a plume dispersion equation derived by Bosanquet and Pearson [1], which was not a Gaussian distribution, as is predominate and well known today, and did not include the effect of terrain types and other factors. Later in about 1950s, Sir Graham Sutton [2] derived an equation of atmospheric dispersion which assumed that the plume released in air is a Gaussian distribution in both vertical and crosswind directions, and it also concluded the ground effects. With the development of computer science and investment from government, more labs and agencies devoted to deriving air dispersion models, which leads to a better understanding of atmospheric dispersion. Models now become more complex and covers many practical circumstances of sorts of terrain types and weather conditions, and all could be implemented fast and accuracy with the help of computer science development [3]. There now have been developed about 100 types of complex models or model based platform to estimate and simulate atmospheric dispersion, such as AERMOD and CALLPUFF developed by U.S. Environmental Protection Agency (U.S. EPA), ADMS-3, sponsored by United Kingdom, and AEROPOL and ATSTEP developed by some continental European countries. According to those well-developed models, governments of countries are able to develop countermeasures to poisonous gas leak and radiation substance release, residents' evacuation beforehand and contaminants control. The Atmospheric Radiation Measurement (ARM) [4], supported by U.S. Department of Energy's (DOE's), created in 1989, is aiming to improve the treatment of atmospheric radiative and cloud processes with computer models, as well as prediction of climate change. It is complex combination of field measurements, atmospheric detection and corresponding climate models, which would be beneficial in case of atmospheric emergency.

In this paper, we proposed an application condition of Real Field Monitor and model based real-time dispersion prediction, with UAV remote monitoring and collecting data in need. This system, compared to other air emergency measures, is major superior in emergency quick response. Since the atmospheric dispersion technology has been well developed and widely applied in many cases, air pollution prediction is no more a difficult technical barrier. Though the more sophisticated the model become, the more reliable the simulation outcome could be, sometimes the complex model is too heavy to conduct for the device and a simple method like Gaussian model may be more suitable in condition of Real Field Monitor. The computational device used in Real Field Monitor conducting complex dispersion model cannot satisfy the requirement of real-time respond and data visualization. So the complex air dispersion model needs to be simplified, but not too simple to loss reliability and validation, which will be discussed in detail in Section 2. And next in Section 3, the mentioned above system, Real Field Monitor in air pollutants leak emergency, will be talk briefly with respect to structural design, essential monitor device and source tracing strategy.

2 SIMPLIFIED ATMOSPHERIC DISPERSION MODEL

As is mentioned in last section, models of atmospheric dispersion have now become a complex combination of climate & terrain information and dispersion equation. Some consist of series of sophisticated equations about meteorology, geology and etc. However, no matter how well the model is developed or sophisticated to cover all the conditions, the based on basic models are simple but effective. They are the sophisticated combination of basic mathematic models and corresponding optimization of terrain and climate. Those basic models could be summarized to four basic types: (1) Box model, the simplest model type. It assumes that the gas is in the shape of a box where it homogeneously distributed [5]. This model using the assumption to estimate the average concentration is too simple and unavailable for our requirement. (2) Gaussian model, the oldest and most popular used model. It assumes that the pollution gas dispersed in air is a Gaussian distribution. The model has other modified type for different gas and environment conditions, and is usually used for predicting different type of release, such as non-continuous plumes, continuous dispersion and long-time release (3) Lagrangian model is usually used for mathematical concentration evaluation in hydromechanics. The model uses Lagrangian coordinate system, focusing on the puff released form the source and following its trajectory [6]. (4) Eulerian model, same as the Lagrangian model for mathematical evaluation, uses Eulerian coordinate system and evaluates the released puff from a fixed point as a frame of reference. This model and the above are not suitable for long-time continuous release, as well as dispersion prediction.

According to the basic mathematical models and its own characteristics, it is better to choose the widely used Gaussian model that is superior in both small amount of computation and data visualization. It is not the kind of model calculating partial differential equations, but by means of probability formula, Gaussian distribution, to describe the probability distributions while a plume diffuses in air. The basic equation [7] is derived as:

$$\mathrm{C(x,y,z)} = \frac{Q}{2\pi \mathrm{u} \sigma_y(s)\sigma_z(s)} \cdot exp\left[-\frac{y^2}{2\sigma_y^2(s)}\right] \cdot exp\left[-\frac{z^2}{2\sigma_z^2(s)}\right] \tag{1}$$

Where C (mg/m^3) is the ground level distributed concentration of source substance Q (mg/m^3). u is the mean wind speed, σ_y and σ_z are dispersion coefficients (m) of cross wind and vertical direction respectively. The dispersion coefficients are standard deviation of the Gaussian distribution, which could be derived from Vogt or Briggs formula [8]. The calculated distribution of this equation is shown in FIG. 1.

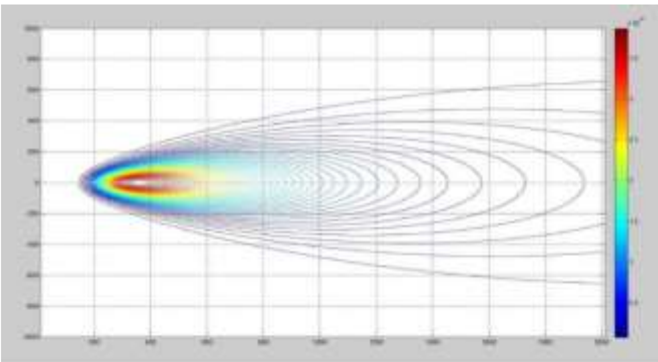

FIG. 1 CONCENTRATION DISTRIBUTION DERIVED FROM BASIC GAUSSIAN DISPERSION MODEL

The model is widely used as basic equation of Gaussian dispersion that is too simple to be applied to practical conditions. It has two defects that its wind speed is limited to constant wind direction and speed, and it is lack of time component in the equation. To improve reliability, the Gaussian equation is split to series of two-dimensional Gaussian distribution puff, and each could be described as:

$$\mathrm{dC}_{k+1} = \frac{dQ(x_k, y_k,, z_k, t_k)}{(2\pi)^{3/2}\sigma_{x,k+1}\sigma_{y,k+1}\sigma_{z,k+1}} \times exp\left\{-\frac{\left[x-x_k-u_{x,k+1}(t-t_k)\right]^2}{2\sigma_{x,k+1}^2} - \frac{\left[y-y_k-u_{y,k+1}(t-t_k)\right]^2}{2\sigma_{x,k+1}^2}\right\}$$

$$\times\left\{exp\left[-\frac{(z-z_k)^2}{2\sigma_{z,k+1}^2}\right] + exp\left[-\frac{(z+z_k)^2}{2\sigma_{z,k+1}^2}\right]\right\} \tag{2}$$

The equation describes that a continuous release is split into a series of instantaneous puffs release, and each one diffuses driven by different wind of its location [9]. $u_{x,k+1}$ and $u_{y,k+1}$ represent the mean wind speed of number k+1 moment in x and y directions respectively, so that the model can be controlled by the wind fields [10]. The model also introduced time component. The concentration in region could be described as superposition of each instantaneously released puff. x_k and y_k is the puff's coordinate point of number k moment, and are expressed as:

$$\mathrm{x}_k = u_{x,k-1}(t - t_{k-1}) + \sum_{i=1}^{k-2} u_{x,i}(t_i - t_{i-1}) \tag{3}$$

$$\mathrm{y}_k = u_{y,k-1}(t - t_{k-1}) + \sum_{i=1}^{k-2} u_{y,i}(t_i - t_{i-1}) \tag{4}$$

The standard deviation components σ of three directions are due to distance travelled from source, local meteorological and geological conditions. To get the concentration at (x, y, z) at moment t, the equation is described as series of puffs superposition:

$$\mathrm{C(x, y, z, t)} = \sum_{i=1}^{n} C(x_i, y_i, z_i, t_i) \tag{5}$$

Where n is the number of puffs released to represent a continuous release in a certain period of time t. The larger n is set, the bigger calculation pressure of computer will be. While a puff diffuses far enough that it had little effect on the whole concentration in region, there is no need to track this puff anymore which could be omitted. It is better to set a concentration threshold to control the number of puffs in scene. The test result is shown as FIG.2, where consists of 10 puffs in period of 10 minutes and it releases from a point source [11]. The deviation components derived from Briggs.

According to the real various conditions of meteorology and geology, the simplified model needs optimization to ensure reliability. Since it is restricted by real computing capacity while applied in real field system, the optimized simply model still could not be compared to developed complex air dispersion model. But it could satisfy the demand of real time result visualization under low computation capacity, and somehow reflect the real situation after optimization. The major optimizations would be about meteorological conditions, terrain and substance type.

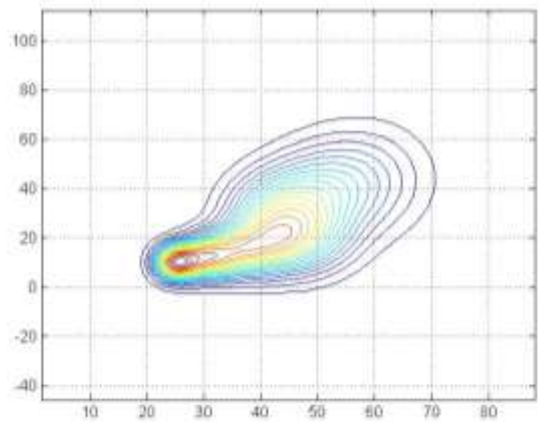

FIG. 2 TEST RESULT OF SIMPLIFIED GAUSSIAN DISPERSION

The meteorological conditions mainly constrain the boundary of puff dispersion and concentration loss while raining. The earth's atmosphere consist from ground of the troposphere, stratosphere, mesosphere, thermosphere, exosphere and magnetosphere, where the pollutants dispersion mainly in the layer of troposphere. The air is warmer near ground and cooler above it, thus the temperature decreases with increasing the altitude. But under some conditions, the air gets hotter from certain altitude and above. The layer between ground and warmer altitude is called inversion layer, and the altitude where the air starts get warmer is mixing layer height [12]. The diffused puff will be trapped in this layer due to the temperature inversion, so the concentration near ground gets larger [13]. It is optimized in vertical direction as:

$$g = \sum_{n=-k}^{n=k}\left\{exp\left[-\frac{(2nL-H_e)^2}{2\sigma_z^2}\right]+exp\left[-\frac{(2nL+H_e)^2}{2\sigma_z^2}\right]\right\} \tag{6}$$

Where g represents the vertical part of a puff and L is the mixing layer height. The puff is split into several slices and superpose the concentration as the puff is trapped under L.

After the puff is release in air, it is mainly driven by wind, the diffusion component σ is a minor factor compared to wind convection. Under the certain terrain conditions, wind direction and speed changes along with terrain, then changes the puff dispersion [14]. And also, when a puff float in air bumps into a mountain, it would be pushed aside and keep floating by wind [15]. For example, it is set a terrain that has a little mountain in region, northeast wind, as is shown below. The source point is near the mountain and release pollutants continuously. The wind changes while coming across the mountain and the puffs are pushed aside and keep diffusing.

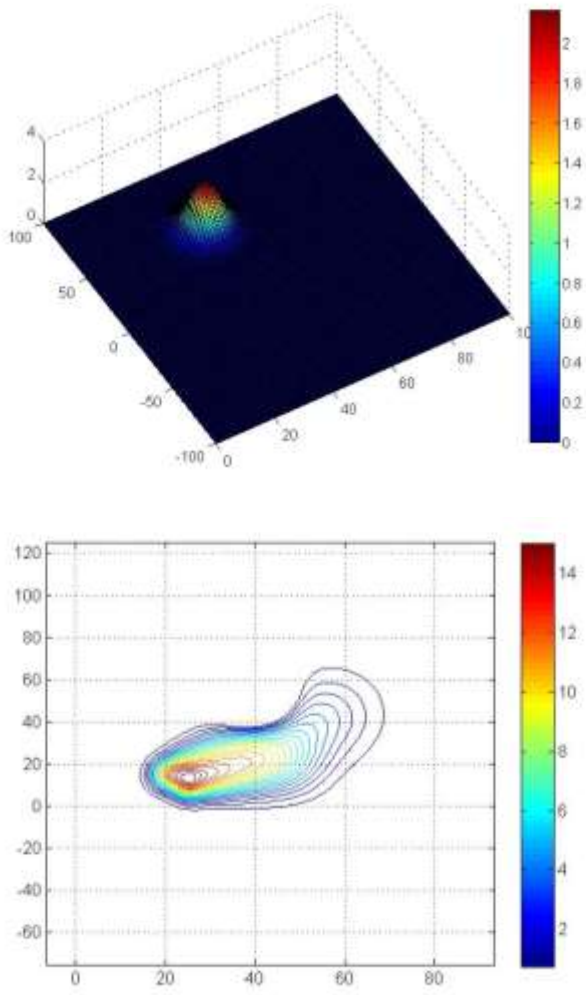

FIG. 3 SAMPLE OF TERRAIN FACTORS OF AIR DISPERSION

Considering the actual situation, the dispersion substances are poisonous gas such as sulphur oxides and nitrogen oxides, or radioactive particles. The poisonous gas concentration decreases in rain or high humidity and the source component Q in model could be optimized [16]. The radioactive particle substance decays while in dispersion. The source part in model will be introduced in correction factor [17] as is the formula below, where λ is the exponential decay constant, representing the degree of decay.

$$f = \exp(-\lambda t) \tag{7}$$

3 REAL FIELD MONITOR SYSTEM

3.1 Structural Design

In consider of a burst of atmosphere pollution, the Real Field Monitor system could be superior in mobile monitor and real-time dispersion forecast. The strategy of it should have the characteristic of mobility, efficiency and accuracy. So it is proposed an assessment framework consists of remote UAV monitor and ground basement consist of simplified computer model of air dispersion, database and visualization platform. The monitoring is a mobile unmanned detector which is controlled by the ground basement, in responsible for monitoring and collecting the pollution data and some related information. The ground basement is a comprehensive terminal of data reception, data storage, data processing with dispersion model and data visualization. The platform displays the polluted region and make a forecast of the polluted area and level ahead of time, as well as some treatment suggestion provided for users to make a better emergency measurements [18].

In the framework (shown as FIG. 4), two important parts are UAV monitor and ground basement. The former detects and collects data to send to the later part, and the basement give orders to the UAVs to comply self-destruction or source siting operation. The data received from UAV will be stored in database and processed by air dispersion model, and the optimized outcome is displayed on the visual platform, as well as some related information. Users could take measures in advance with the help of the information on screen. In this framework, two significant matters are the combination of dispersion model and data to make the forecast reliable, and how to design the flying route of UAVs to get required information. The two matters are co-related. Only that the monitoring station receives the required information, will the model functions well and make a reliable forecast, which is the matter of the combination.

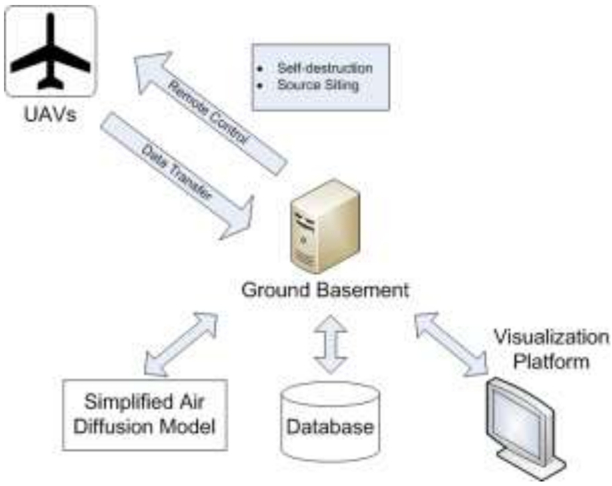

FIG. 4 STRUCTURAL DESIGN OF REAL FIELD MONITOR SYSTEM.

3.2 UAV Monitor

Just like the UAV used in ARM, the basic facility of air pollution estimation like burst of poisonous or radioactive gas, should be characterized by the following points: (1) Unmanned and remotely controllable. The region in danger is usually human prohibited, so that the monitoring station remotely-controlled from safe area is essential. (2) Mobile and applicable to a variety of terrain. (3) Sensors for monitoring and sorts of data collection are equipped on a stable operation platform [19], which guarantees that sensors works properly without much disturb. (4) Self-destruction available in order to prevent secondary pollution in safe area. The monitoring station returned from the polluted region, can carry toxic or radical substance to region in safe. So it has to be self-destroyed right in polluted area after finishing the operation. Considering that the disposability of the monitor device, the cost of it should not be too high.

According to those constrictions above, the UAV is design to be a remotely-controlled unmanned airship [20]. The airship is advantageous in stability and big load, which can be designed to have enough loads to equip essential observers and fly smoothly. Also airship is more easily controllable with the cost of relatively low speed and mobility [21], which causes the inefficiency in large area observation and monitor. However, airship used as UAV monitor device has two major advantages compared to hard-wing airplane [22]. First one is stability. The airship is mainly composed of large gasbag providing buoyancy and guidance equipment, which makes it low fuel consumption but long flight time. The airship could also be applied in severe weather conditions with better control algorithms [23], and is capable of variety of terrain type. Second one is low cost. Because of it simply structure compared to hard-wing airplane, the material cost of an airship is much lower, just suitable for self-destruction constriction in monitor operation.

In general, the airship could guarantee adequate sampling time for sensors thus reduce the burden of signal processing. Several airships are controlled by a remote manage basement, where the data got from UAVs will be processed and stored in database, and then displayed intuitively on screen of the software platform [24], combined with map information and user-defined details.

3.3 Ground Basement

The ground basement is an integrated platform of data storage and modification, information display and forecast. Data received from the monitoring are stored in offline database. Considering that the monitoring collects one streamline of information per second at most, the amount of data is not so big that normal My SQL could be a compatible option. The data stored will be optimized to display with related information on map of the software, with the technology of data visualization [25].

With the integration of atmosphere dispersion model, the software could use the collected data to make forecast, telling the users what position and area of the pollution region will be ahead of time [26]. The data of terrain type and other Geographic Information shown on the visualization platform uses the Geographic Information System (GIS). The collected data from UAVs are real-time displayed on GIS. The problem of developing this visual platform is how to make a better combination of the simplified air dispersion model and variety of terrain and climate information. According to development work so far, the platform of Real Field Monitor system is now temporarily designed as shown below.

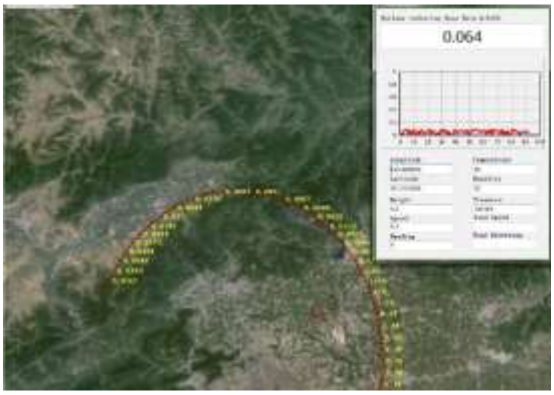

FIG. 5 INITIAL DESIGN OF VISUAL PLATFORM IN GROUND BASEMENT (A)

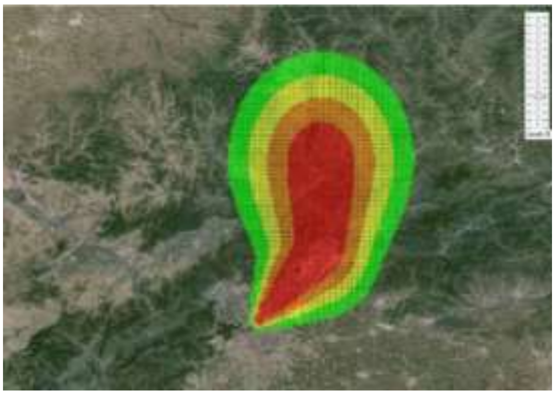

FIG. 6 INITIAL DESIGN OF VISUAL PLATFORM IN GROUND BASEMENT (B)

3.4 Source Searching Strategy

In practice, one special circumstance has to be taken in consideration that we only know there happens gas leak but not the exactly position where the source point is located [27]. As the feature of real time estimation, the Real Field Monitor can satisfy this sort of condition. Here proposes an algorithm called Simplex Method. After confirming the approximate region where pollution source is in, a remote carpet-research will get a full image of distribution. Then the release source can be spotted considering its circumstance condition. Firstly, given the condition of single airship monitor, and complexity of terrain and atmosphere condition, it needs to propose a specific way of searching, in order to get it spotted as quickly and accurately as possible.

The problem of source tracing can be reduced to the model of finding the point of maximum in a two-dimensional plane. The boundary condition is linear search in a large region, where the direction of linear search is optional. It also needs to take into account of its real circumstance, where the wind is changeable and terrain varies a lot. So considering those conditions above, the basic searching procedures could be as follows (shown as FIG. 7).

Step.1. Setup an original straight searching route (route 1) randomly in the pollution region. Go and detecting the value of pollution concentration, and record the position and wind direction of the maximum point (point A).

Step.2. Set next route (route 2) going through the last max point A and be parallel or vertical to the wind direction of point A. Go and search in region, find the max point (point B) on this route and record its wind direction.

Step.3. Repeat Step.2 and setup the straight searching routes No.3, 4 and 5, and the max points C, D and E respectively. Each route is vertical to its last one.

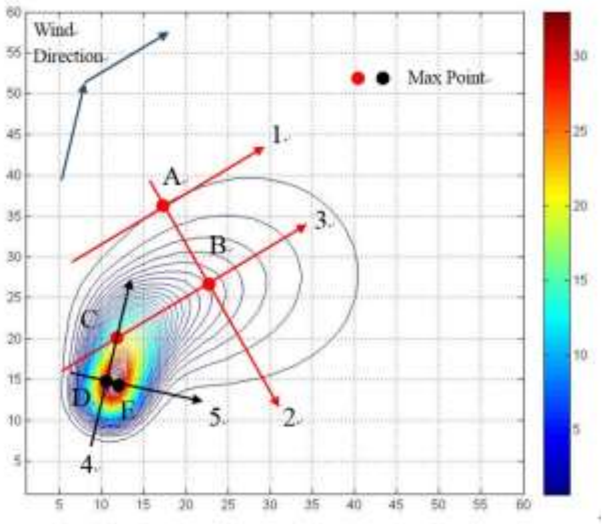

FIG. 7 SEARCHING PROCESS UNDER THE PRINCIPLE DESIGNED

Step.4. Search until we got the position of the max point is nearly the same as the last one. It means that the max point on the latest route could be the max point of the partial pollution region.

Step.5. Reset the original search route and go over Step.2 to Step.4, until we find another max point in region, in order to reduce errors caused by environmental factors.

After several times of search according to the procedures above, it could be reduced to the maximum of the pollution plane. Meanwhile, it guarantees the sampling time at each point on the searching route of the airship, in order to get a more accurate value. Even though, the validation and reliability of Simplex Method is still far from satisfactory degree. As is strongly infected by complex terrain and varied atmospheric condition, the airship monitor may get to the point where the partial derivative is zero but not the maximum position of the whole region [28]. So it's necessary to change the original search route and direction for several times, making comparison and data optimization, in order to get a better result and conclusion. Note that the Simplex Method is used for one airship. There could be a better result controlling several airships simultaneously searching the suspicious region, which makes the region search quick and efficient and somehow compensate the unreliability of single search algorithm.

4 CONCLUSION

In this paper, it is proposed a simplified atmospheric dispersion and its corresponding optimization about meteorology and geology, based on the previously studied sophisticated air dispersion models. And the Field Time Monitor and Estimation of air pollution system is proposed, which is consist of remote controlled UAVs and integrated ground basement. The diverse data collected by UAVs is processed using the simplified model to estimate pollution degree and make prediction. The UAVs could use Simplex Method to site search in source missing situation. This system is superior in real-time estimation, mobility and low cost. The simplified model is suitable under the constriction of low cost computing capacity and real-time visual performance.

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AUTHORS

Zheng Fu, born in 1990, master student in Academy of Automation Science and Electrical Engineering, Beihang University. Currently he is engaged in research on environmental modeling and simulation.

Lin Zhang, born in 1966, professor of Academy of Automation Science and Electrical Engineering, Beihang University, major in modeling and simulation theory and technology. He is currently engaged in research of cloud manufacturing, cloud computing and intelligent systems, high-performance simulation, parallel computation and visualization, etc.