Acta Technica 62 No. 3B/2017, 149–158

Gas leakage source localization based on mobile sensor network[1]

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Abstract. Wireless sensor networks based gas leakage source localization (GLSL) has important significance in the fields such as environmental monitoring, security protection and pollution control. This paper proposed a GLSL algorithm based on mobile sensor networks to improve low performance of static sensor network. Maximum likelihood estimation method was used for the source location estimator based on the gas source diffusion model with the measured concentration information. Preliminary experimental results show that mobile sensor nodes can achieve an accurate source localization with a certain topology and environmental assumptions, through rational path planning.

Key words. Mobile sensor network, gas leakage source localization, maximum likelihood estimation..

1. Introduction

Wireless sensor network (WSN Wireless, Sensor Networks) could collect information with sensor nodes cooperation through sensing, computing and wireless communication function of the surrounding environment to complete environment monitoring, target positioning and tracking tasks [1]. Among them, the location and tracking of gas leakage sources is a hot issue in the environmental monitoring field [2]–[5]. Gas leakage source localization based on sensor networks is essentially a source parameter identification problem, which can also be regarded as an inverse problem of

[1]The authors wish to thank for the financial support of Natural Science Foundation of China(61573253, 61271321), Tianjin Natural Science Foundation (16JCYBJC16400), Tianjin Science and Technology Project (16YFZCGX00360, 16ZXZNGX00080), National Training Programs of Innovation and Entrepreneurship for Undergraduates (201610069007,201710069023). Tianjin University of Commerce Natural Science Nurturing Fund. The corresponding author is Professor Zhang Liyi.

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physical diffusion modeling, and usually implemented by probability estimation algorithm [6], [7]. At present, the localization of gas leakage source localization based on wireless sensor network is mainly realized through static sensor network, that is, the nodes in the network are fixed and the sensor node position is usually known. Michalis proposed a nonlinear least squares estimation (NLSE) method to detect and locate the source of gas leakage in the environment with the sensor node measurement of environmental information (gas concentration), and the study on the aspects of the source nodes numbers and the positioning accuracy and measurement threshold selection was focus to analyze. Vijayakumaran gave a maximum likelihood estimation (MLE) method to fulfill the gas leakage source localization problem [3], which was based on the gas source parameters and positioning estimation methods. In that, the gas concentration information collected on sensor nodes was binarization processing, and estimated by the fusion center to realize gas source position and time of the two parameters. This method could reduce the communication and information processing consumption in the implementation process by 0–1 value data optimization, however the 0–1 value processing method can also improve estimation error. Weimer studied the multi-gas leakage source detection and localization by using Bayesian inference method with sensor networks, a plurality of recognition rate and robust performance analysis are mainly studied the algorithm, and try to use the actual wireless sensor network monitoring platform to verify [4]. In [5] the static 3D wireless sensor network was using to realize the spatial location of the gas leakage source from the perspective of three-dimensional space. As for the gas leakage source localization with static wireless sensor networks, a large number of redundant information provided by sensor nodes should be needed to obtain high-precision positioning results involved in the calculation of the convergence center. This brings great difficulties to the actual networking, and it is also easy to cause topological unreasonable factors, such as local nodes too much or too little. At the same time, a large number of nodes participate in data communication can easily cause network congestion, which can also speed up network energy consumption and reduce network life. However, the actual conditions (such as funds and energy consumption, etc.) is usually limited, the deployment of nodes reducing will lead to too few nodes and not get accurate positioning results.

The gas leakage source localization with mobile sensor network have flexibility and mobility compared to the static sensor networks positioning methods, to some extent, can make up for its shortcomings, [8] mainly uses the mobile multiple sensor nodes localization based on heuristic search method to achieve the gas leakage source positioning through coordinated control the fusion center, and each mobile sensor node was independent for each other. In [9], a single mobile sensor node is adopted to realize the on-line estimation and localization of gas sources based on particle filter estimation algorithm. Based on the existing positioning problems of static sensor network method, and on the basis of the mobile sensor network methods in [8], [9], this paper proposes a new gas leakage source localization algorithm based on mobile sensor networks. In which, a gas leakage source was in a region environment, the use of multiple mobile sensor nodes have relatively fixed topology based on the real-time environmental information collected, the maximum likelihood estimation algorithm was used to complete the online gas source location estimation. The experiment shows that the method is constrained by some path and environment conditions, the path planning and dynamic topology of mobile sensor networks has good positioning effect to achieve a reasonable estimate of optimization of gas source localization.

2. System and observation model

2.1. Gas diffusion model

The mobile sensor nodes constructed the networks with star topology construction based on the Zigbee protocol in mobile sensor networks, which can instead of the static sensor network to the diversity of information real time acquisition in different time and locations. The gas concentration information measured by each node in the mobile sensor network is usually consistent with the gas diffusion model. Among the existing gas source position estimation studies, the Gauss model and the turbulence diffusion theory are most widely used. In fact, the latter is also a class of Gauss model [10]. In this paper, the flow field of indoor environment is considered to be consistent with Gauss distribution and statistical stability for a long time. The turbulent gas diffusion model is applied to study.

In this paper, a gas turbulence model is used and the following assumptions are made:

1. the positive direction of X is considered as the direction of the wind, without considering the influence of the obstruction of the obstacle, and so on, it is assumed that the interior is a steady and uniform airflow field;
2. a single gas source prediction and location is studied. The location of the gas source is randomly distributed as $(x_{\mathrm{s}}, y_{\mathrm{s}})$; $(\hat{x}_{\mathrm{s}}, \hat{y}_{\mathrm{s}})$ is the prediction and location;
3. the gas release rate q of the gas source is constant;
4. the N mobile sensor nodes are distributed in the square area by simple dynamic topology, and the nodes position (x_i, y_i), $i = 1, 2, 3, \cdots, N$ are known; The surface averaged gas concentration can be derived from the following equation

$$R(x_i, y_i) = \frac{q}{2\pi K} \frac{1}{x_i} \exp\left[-\frac{U}{2K}(d - (x_i - x_{\mathrm{s}}))\right]. \tag{1}$$

In the formula, R_i is the gas concentration measurement of the sensor node i in the sampling period t; q is the gas diffusion rate, K diffusion coefficient, U turbulent wind speed, $d = \sqrt{(x_i - x_{\mathrm{s}})^2 + (y_i - y_{\mathrm{s}})^2}$ for any point to the gas source distance, (x_i, y_i) for the current position of the sensor node i.

As shown in Fig. 1, it is the gas source diffusion model generated in Matlab, the region $1000\,\mathrm{cm} \times 400\,\mathrm{cm}$ is in the direction of the positive X axis as the wind

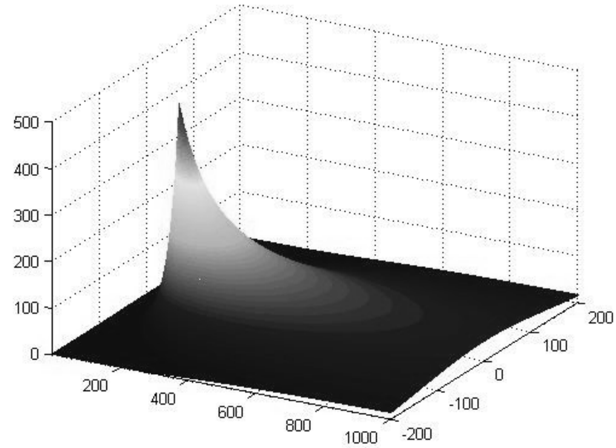

Fig. 1. Turbulent diffusion model of gas source.

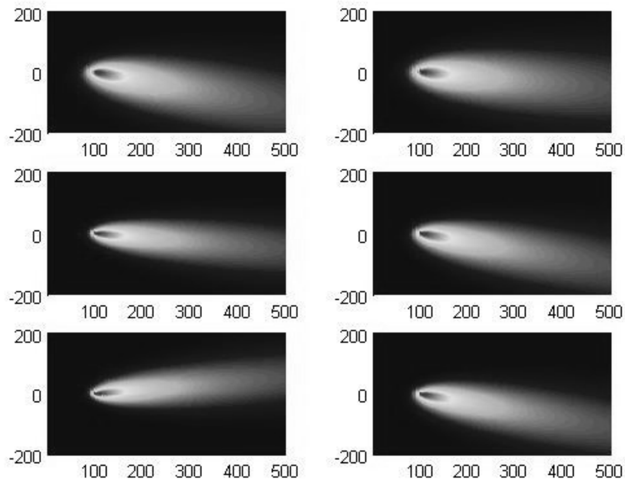

Fig. 2. Diffusion model under different wind speed and direction.

direction, the wind speed is a constant value, the gas source coordinate is $(100, 0)$ cm, and the Z axis is the concentration information.

When the wind direction is fixed as the positive direction of X and the wind speed, the model can be improved as shown in the formula (2).

$$R(x_i, y_i) = \frac{q}{2\pi K}\frac{1}{x_i}\exp\left[-\frac{U}{2K}(d - \Delta x)\right]. \tag{2}$$

In the model, the wind speed U varies randomly between 3 cm/s $\sim$ 8 cm/s, and the wind direction angle fluctuates at random between $(-30°, 30°)$ with the center of X axis, $\Delta x = (x_i - x_\mathrm{s})\cos\phi + (y_i - y_\mathrm{s})\sin\phi$. Figure 2 is a 2D diffusion model under different wind speed and wind direction. As for the static model of turbulent diffusion theory based on the introduction of the wind, it is more in line with our simulated environmental conditions, so the gas source search algorithm is mainly based on the model. Various localization algorithms will be studied on the basis of the above model.

2.2. Sensor model

The concentration $C(x_i, y_i)$ measured at (x_i, y_i) of the gas sensor can be expressed as

$$C(x_i, y_i) = R(x_i, y_i) + \omega(i)\,. \tag{3}$$

In the formula, $R(x_i, y_i)$ means the ideal output value of the sensor localized(x_i, y_i), which is shown in the formula (2), and the noise $\omega(i)$ satisfies the normal distribution $N(0, \delta^2)$.

In this paper, metal oxide semiconductor gas sensor MICS-5135 is applied. This gas sensor is very sensitive to alcohol vapor, and alcohol concentration changes were shown in sensor resistance R verity, i.e., the smaller the resistance, the higher the gas concentration. Because of the different parameters of each sensor, the drift of the sensor has great influence on the measurement results under different temperature and humidity conditions. If the relationship between the output voltage and the concentration of the sensor is calibrated [10], when the environment changes slightly, the measurement of the sensor will be invalid.

3. Gas leakage source localization algorithm with mobile sensor networks

3.1. Maximum likelihood estimation algorithm

In [11], the maximum likelihood estimation algorithm was used in the application of sound source localization. In this paper, a maximum likelihood estimation algorithm for gas leakage source localization was proposed based on the transform of the gas concentration attenuation model, which could easily to fulfill the gas leakage source location positioning problem through the maximum likelihood function directly solving. According to formula (2), the concentration collected by sensor node i can be expressed as

$$C_i(x_i, y_i) = \frac{q}{2\pi K}\frac{1}{x_i}\exp\left[-\frac{U}{2K}(d - (x_i - \hat{x}_\mathrm{s}))\right] + \omega_i\,. \tag{4}$$

In the sensor, C_i is the actual measured concentration, $(\hat{x}_\mathrm{s}, \hat{y}_\mathrm{s})$ is the desired position. ω_i means environmental background noise, it is known to satisfy the normal distribution $N\left(\mu, \delta^2\right)$. While the two sides of the equation are standardized at the same time, there are

$$\frac{C_i-\mu_i}{\delta_i}=\frac{q}{2\pi K\delta_i}\frac{1}{x_i}\exp\left[-\frac{U}{2K}(d-(x_i-\hat{x}_{\mathrm{s}}))\right]+\frac{\omega_i-\mu_i}{\delta_i}\sim$$
$$\sim N\left(\frac{q}{2\pi K\delta_i}\frac{1}{x_i}\exp\left[-\frac{U}{2K}(d-(x_i-\hat{x}_{\mathrm{s}}))\right],1\right). \quad (5)$$

Here, the $\frac{\omega_i-\mu_i}{\delta_i}$ satisfied the standard normal distribution $N(0,1)$. Assume

$$Z_i=\frac{C_i-\mu_i}{\delta_i}, \quad (6)$$

$$G_i=\frac{q}{2\pi K\delta_i}\frac{1}{x_i}\exp\left[-\frac{U}{2K}(d-(x_i-\hat{x}_{\mathrm{s}}))\right], \quad (7)$$

$$\varsigma_i=\frac{\omega_i-\mu_i}{\delta_i}, \quad (8)$$

So $Z_i-G_i=\varsigma_i$ satisfied $N(0,1)$.

When the maximum likelihood estimation algorithm is used, the joint probability density function can be expressed as follows

$$f(Z-G\,|\theta\,)=(2\pi)^{-(N/2)}\cdot\exp\left[-\frac{1}{2}(Z-G)^T(Z-G)\right]. \quad (9)$$

The unknown variable θ is the prediction of the source location ($\hat{x}_{\mathrm{s}}$, $\hat{y}_{\mathrm{s}}$), and the log likelihood function is the logarithm of the joint probability density function

$$L\left(\theta\right)\sim-\frac{1}{2}\sum_{i=1}^{N}\left\|Z_i-G_i\right\|\sim$$
$$\sim-\frac{1}{2}\sum_{i=1}^{N}\left(\frac{C_i-\mu_i}{\delta_i}-\frac{q}{2\pi K\delta_i}\frac{1}{x_i}\exp\left[-\frac{U}{2K}(d-(x_i-\hat{x}_{\mathrm{s}}))\right]\right)^2. \quad (10)$$

The maximum likelihood of the log likelihood function can be equivalently converted to the minimum in the lower form

$$\min l\left(\theta\right)=\sum_{i=1}^{N}\left(\frac{C_i-\mu_i}{\delta_i}-\frac{q}{2\pi K\delta_i}\frac{1}{x_i}\exp\left[-\frac{U}{2K}(d-(x_i-\hat{x}_{\mathrm{s}}))\right]\right)^2. \quad (11)$$

Seeking the partial conductance for X and Y respectively and equal to zero.

$$\frac{\partial l\left(\theta\right)}{\partial\hat{x}_{\mathrm{s}}}=0;\ \frac{\partial l\left(\theta\right)}{\partial\hat{y}_{\mathrm{s}}}=0. \quad (12)$$

By solving nonlinear equations of equation (12), the expected position ($\hat{x}_{\mathrm{s}}$, $\hat{y}_{\mathrm{s}}$) is obtained while the minimum is satisfied with $l(\theta)$.

3.2. Mobile sensor network gas leakage source localization algorithm

In this paper, the gas leakage source localization process using mobile sensor networks can be described as follows:

1. We assumed that each mobile sensor node activated in an intermittent cycle Δt, so the n numbers measurements data needed $n\Delta t$ cycles and transmitted to the mobile sensor node data fusion, which was only because that the mobile sensor nodes could not work continuously with the restriction of environment and technology.

2. Assume that the gas source position estimation error $\boldsymbol{\Delta\theta} = [\Delta x, \Delta y]$ is a vector, in which $\Delta x = \hat{x}_{\mathrm{s}} - x_{\mathrm{s}}$, $\Delta y = \hat{y}_{\mathrm{s}} - y_{\mathrm{s}}$. The object of the proposed optimal algorithm is that the error between the estimated position $(\hat{x}_{\mathrm{s}}, \hat{y}_{\mathrm{s}})$ and the actual location $(x_{\mathrm{s}}, y_{\mathrm{s}})$ of the gas source to achieve a prescribed value in as possible as least time, it means that $\|\boldsymbol{\Delta\theta}\| \leq \varepsilon$ should be reached after n times measurement. When the range error ε to achieve, some methods can be used to the gas source.

3. On the basis of known location and sampling time of mobile sensor nodes, a coordinate estimation $[\hat{x}_{\mathrm{s}}(n), \hat{y}_{\mathrm{s}}(n)]$ of gas source can be obtained after sub measurement and prediction positioning algorithm.

4. the vector coordinates $r_i(n) = [x_i(n), y_i(n)]$ means the mobile sensor nodes localization moved in a period, the position set $s_i(n+1)$ means the sensor nodes can reach of movement under some certain conditions, then choosing a point $r_i(n+1) = [x_i(n+1), y_i(n+1)]$ from the set $s_i(n+1)$ that can reach the least positioning error, and then let the mobile sensor node has a fixed topology structure moved to the point, then do the next step and measure.

5. The next measurement information of mobile sensor node i depends on its current position $r_i(n)$, the mobile sensor nodes usually moved to the position which can further reduce the positioning error. With the iterative processing continuously, the gas leakage source localization could be achieved in a shorter period of time with the predetermined error $\|\Delta\theta\| \leq \varepsilon$ meeting a required range.

In the algorithm of point sets $s_i(n+1)$ in the two-dimensional space environment is actually a circle located in $r_i(n)$, the radius of circle depends on the movement speed and cycle of the mobile sensor node i, and the next point $r_i(n+1)$ of the sensor node arrivaling can be found in this circle.

4. Experimental result analysis

As shown in the Fig. 3, the solid square indicates that the gas leakage source location coordinates (100, 0) cm; dots represent 6 sensor nodes, and distributed in the radius of 50 cm ring with the center of coordinate (400, 100) cm as a circular topological uniform. The estimated position is expressed in large solid circles. The background noise satisfied $N(0, 1)$ distribution. The maximum likelihood estimation method was adopted, and the other conditions are unchanged in the simulation environment. The estimated result will be obtained at each time step, the sensor network should be rearranged with the estimated result as the new center of the circle, and a new round of estimation is carried out. From left to right, from top to bottom, the four iteration process of sensor network is shown. It can be seen that the localization results of the mobile sensor network can roughly reflect the trend of gas source direction and concentration when the gas source is not surrounded. Previously, the estimated position is a new initial coordinate, and the method can be used to locate the gas source better after several times of movement.

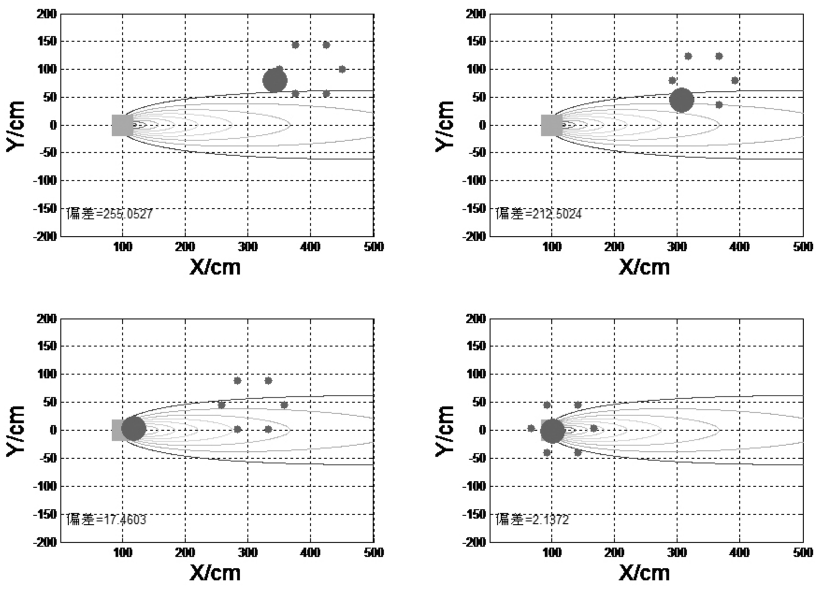

Fig. 3. Positioning results with initial coordinate (400, 100) cm and 50 cm circle radius.

In order to improve the localization accuracy, the dynamically changing the range of the sensor network method is adopted without considering the increase of the number of sensors, it is means to combine the high adaptability of the large scale distribution with the advantages of the high positioning accuracy of the small range dense distribution. As shown in Fig. 4, the sensor network starts from the environment boundary (400, 150) cm, the radius will be reduced after each estimate with the 90 cm initial radius, and the radius of the final sensor network is 40 cm. Figure 5 is the final positioning results. It can be seen that the positioning effect of this method is very satisfactory. It has good adaptability and positioning precision. High positioning accuracy can also be obtained from the environment boundary.

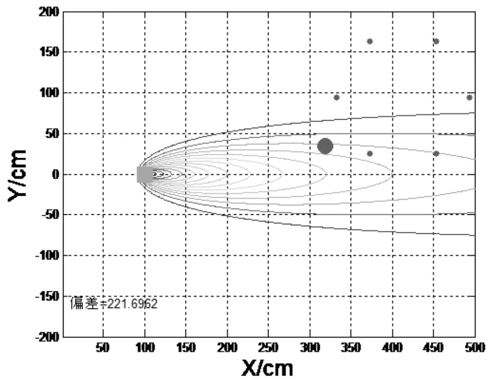

Fig. 4. Localization with 90 cm radius dynamic shrink radius.

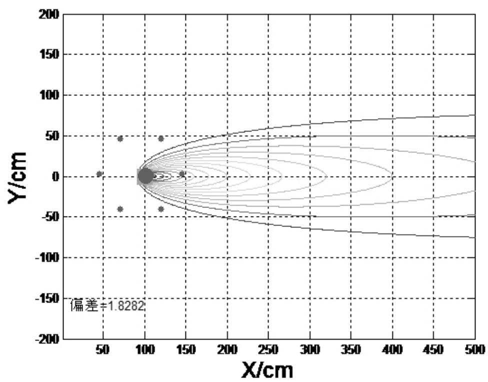

Fig. 5. Dynamically radius reducing finally results.

5. Summary

To solve the problem of gas source localization in static sensor networks, a gas leakage source localization algorithm with mobile sensor networks is proposed to fulfill the gas sources positing. The feasibility of this method is verified by simulation experiments, the results show that the mobile sensor nodes could achieve reasonable gas source location estimation in a certain topological structure and environmental conditions, the optimal path planning can help to research the best positioning effect. This method can be used as the carrier of the limited mobility micro robot as the carrier to locate the gas source in the area where the current gas source localization method can not reach. In the future, it will consider increasing the number of nodes and according to the concentration value and position change of real-time topology to overcome the limitation of the method of the actual wind direction, and the real experiment platform for the method to verify the analysis.

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Received September 12, 2017