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Research on Location Algorithm of Dangerous Gas Source in Chemical Industry Park based on ZigBee

Haibo Liu, Zhenfang Liu, Aining Li

Department of Electrical Automation, Hebei University of Water Resources and Electric Engineering, Cangzhou 061001, China
haibo696@126.com

With the development of people's society, the chemical industry has made great progress. In the industrial structure of developed countries, the chemical industry occupies a very large proportion. At the same time, chemical production is also the weakest link in the field of safety production. Hazardous gas is the most dangerous product in the process of chemical production, which means that it is necessary to monitor and locate the dangerous gas source in real time. In recent years, with the development of wireless communication technology, wireless sensor networks (WSN) have been applied in various fields. As a short-range wireless communication technology, ZigBee is widely used in military, environmental and industrial fields because of its low cost, low power consumption and multi-function. Gas source location is a method to predict the location of gas leak points by combining gas concentration detection and gas diffusion models, can help us to warn of the leakage of dangerous gas. According to the actual demand, this paper presents a gas source location algorithm based on the ZigBee communication mode. First of all, this paper gives a brief introduction to the composition and structure of ZigBee network. Secondly, the plume model based on turbulence is discussed in detail. Thirdly, aiming at the problem of large computational complexity of traditional model, an improved particle swarm algorithm for gas source location is proposed by combining force-directed algorithm. Finally, simulation experiments show that the improved gas source localization algorithm has better results.

1. Introduction

With the rapid development of the petrochemical industry, the production capacity of various enterprises is constantly expanding, which leads to more and more potential risks, especially the leakage of major chemical gases. Generally, through safety design, standardized operation, safety inspection and other measures, we can prevent accidents and reduce potential risks. Nevertheless, no measures can guarantee absolute safety. Once the leakage occurs, it not only pollutes the environment, but also causes a large area of human and livestock poisoning (Ampdiotis and Berberidis, 2010). Therefore, it is very important to establish a reliable and efficient monitoring system for hazardous gases. Through the real-time monitoring in the chemical industry park, we can deal with the accidents caused by the leakage of dangerous chemical gas immediately. In the monitoring system of dangerous chemical gas, the location of the source of leakage is the most critical link, which determines the efficiency of the subsequent emergency response (Fox, 2003). WSN is a new type of information acquisition system, which consists of multiple sensor nodes distributed in the monitoring area. The sensor nodes in the monitoring area use self-organizing networks to realize data communication, aggregation and processing, and this principle enables wireless sensor networks to be used for target location (Qin et al., 2013). First of all, we need to analyze the gas concentration data monitored by sensor nodes located in different positions. Secondly, based on the specific diffusion model and some algorithms, we can calculate the position of the gas source (Zhu et al., 2013).
In the location of gas leakage source, the location algorithm plays a decisive role. The performance of the localization algorithm directly determines the accuracy of the whole positioning system. Many research teams are trying to locate sources of chemical gas by using wireless sensor networks. Marques (2000) and his colleagues use a continuous concentration diffusion attenuation model to construct an inversion problem for

the location of gas source points. By solving the inversion problem, they successfully locate the gas source point. Michaelis (2005) and Christos use nonlinear least squares optimization to study the problem of gas source location. Experimental results show that the positioning algorithm has better accuracy for gas source localization in static environment. Xia (2008) tries to get location of the gas source according to the time difference of the gas monitored by different sensor nodes. Although the location accuracy is relatively high, the deployment cost and power consumption are also increasing. Aiming at the problem of chemical gas detection, Braun and Glina (2004) propose multi-sensor fusion and machine learning method. This method has good effects under the condition of no wind or steady wind speed. Zhu and Zhong (2013) use the strength of received signal (RSSI) to calculate the distance between nodes, which can be used in the Monte Carlo algorithm.

In this paper, we present a gas source location algorithm based on the ZigBee communication mode. First of all, this paper gives a brief introduction to the composition and structure of ZigBee network. Secondly, the plume model based on turbulence is discussed in detail. Thirdly, aiming at the problem of large computational complexity of traditional model, an improved particle swarm algorithm for gas source location is proposed by combining force-directed algorithm. Finally, simulation experiments show that the improved gas source localization algorithm has better results.

2. Basic theory and technology

There are many models about gas diffusion. After continuous development, there are several mature models of gas diffusion, and they are Sutton model, Gauss plume model, Gauss puff model, and FEM3 model. The Sutton model uses turbulent diffusion statistical theory to deal with turbulent diffusion problems. The model has a large error when simulating flammable gas diffusion. The FEM3 model is applicable to the diffusion of heavy gases for continuous source, and its simulation is more difficult because of the extensive calculation. Gauss model is relatively mature because of long-term theoretical proof and sufficient experimental data.

2.1 ZigBee network

ZigBee is a two-way wireless communication technology which has the characteristics of short distance, low complexity, low power consumption, low rate and low cost. It is mainly used for data transmission between various electronic devices in a certain area. At present, it has been widely used in public utilities, agriculture, medical care, petrochemical and other fields. ZigBee divides nodes into three different roles, and they are coordinator, router and terminal.

Coordinator

The coordinator is the first device in the network, which is responsible for the initialization of the entire network. Firstly, the coordinator selects a channel and a network ID. Then, the coordinator begins to enable the entire communication network. What is more, the ZigBee coordinator can also be used to help establish the binding of the security and application layers in the network. The coordinator mainly involves the initiation and configuration of the network. Once the initialization and configuration of the network are complete, the role of coordinator will convert to a router.

Router

Router is responsible for data storage, forwarding and routing discovery. Usually, the router is always active, so its power consumption is faster than other nodes. When the ZigBee network is deployed in a tree topology, the routing interval is allowed to be operated periodically, so that the battery can be powered by the battery, which can save power consumption.

Terminal

The terminal can only act as a data collector. The terminal device has no specific responsibility to maintain the network structure, so it can sleep or wake up at any time. In general, the terminal has a low requires on storage space. Owing to the single function, its energy consumption is the lowest compared with coordinator and router. The network structure of ZigBee is as follows.

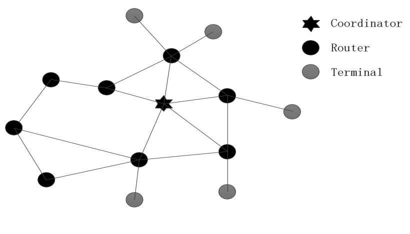

Figure 1: The network structure of ZigBee

2.2 The plume model based on turbulence

We assume that there is a horizontal wind in the monitoring area, and in order to obtain the attenuation model of gas concentration for gas source location, we set the following conditions.
(1) The gas travels around in a monitoring area at a certain rate, and there is no sudden change in environmental factors during the diffusion process.
(2) The influence of temperature variation and barrier occlusion on diffusion process is not considered.
(3) A stationary gas source with a constant mass release rate is distributed in the monitoring area, and its position is (x_0, y_0).
(4) The gas concentration released by the gas source point remains constant during the positioning process, and we use T to represent the gas concentration.
(5) There are N sensors randomly located in the monitoring area, and their locations are already known.
(6) Only when the gas concentration measured by the sensor node exceeds the threshold R, the presence of a gas source can only be detected.
We assume that there are N sensor nodes which can detect the presence of gas sources in the monitoring area and the gas concentration collected by sensor i can be represented by a formula.

$$c_i = \frac{T}{4\pi k \mid \vec{p}_i - \vec{p}_0 \mid} \cdot \exp\{\frac{\mid \bar{v} \mid \cdot [(x_i - x_0) - \mid \vec{p}_i - \vec{p}_0 \mid]}{2k}\} + n_i \tag{1}$$

In the formula, $\bar{v}$ and n_j means wind speed and measurement noise respectively. At the same time, $\mid \vec{p}_i - \vec{p}_0 \mid$ represents the distance between sensor i and the gas source. We define C as follows.

$$C = (c_1, c_2, c_3 \ldots c_n) \tag{2}$$

Then, we can get the joint probability density function as follows.

$$p(H \mid \vec{p}_0) = \sqrt{\frac{1}{(2\pi)^N}} \cdot \prod_{i=1}^{N} (\frac{1}{\rho_i}) \exp\{-\frac{1}{2} \sum_{i=1}^{N} \frac{h_j - u_i - \frac{T}{4\pi k \mid \vec{p}_i - \vec{p}_0 \mid} \cdot \exp\{\frac{\mid \bar{v} \mid \cdot [(x_i - x_0) - \mid \vec{p}_i - \vec{p}_0 \mid]}{2k}\}^2}{\rho_i^2}\} \tag{3}$$

And $p(H \mid \vec{p}_0)$ satisfies the following relation.

$$p(H \mid \vec{p}_0) \propto \exp\{\frac{N_s}{4\gamma^4} \sum_{i=1}^{N} (h_j - u_i - \frac{T}{4\pi k \mid \vec{p}_i - \vec{p}_0 \mid} \cdot \exp(\frac{\mid \bar{v} \mid \cdot [(x_i - x_0) - \mid \vec{p}_i - \vec{p}_0 \mid]}{2k})^2)\} \tag{4}$$

Where, N_S represents the number of sample points which can detect gas concentration and γ represents the background noise.
By taking the logarithm of the joint probability density function, the log likelihood function can be obtained.

$$L(H \mid \vec{p}_0) = -\ln(p(H \mid \vec{p}_0)) \tag{5}$$

At the same time, $L(H \mid \vec{p}_0)$ meets the following conditions.

$$L(H \mid \vec{p}_0) \propto \sum_{i=1}^{N} (h_j - u_i - \frac{T}{4\pi k \mid \vec{p}_i - \vec{p}_0 \mid} \cdot \exp(\frac{\mid \bar{v} \mid \cdot [(x_i - x_0) - \mid \vec{p}_i - \vec{p}_0 \mid]}{2k})^2 \tag{6}$$

The process of finding the maximum of the above formula can be converted to the following formula.

$$\min_{\vec{p}_0} (l(H \mid \vec{p}_0)) = \sum_{i=1}^{N} (h_j - u_i - \frac{T}{4\pi k \mid \vec{p}_i - \vec{p}_0 \mid} \cdot \exp(\frac{\mid \bar{v} \mid \cdot [(x_i - x_0) - \mid \vec{p}_i - \vec{p}_0 \mid]}{2k})^2 \tag{7}$$

Finally, by solving the minimum value of the above formula, we can obtain the optimal solution of the source location.
On the whole, this algorithm has a high demand for the surrounding environment. At the same time, this algorithm not only has great computational complexity, but also has poor positioning effect.

3. Improved particle swarm algorithm for gas source location

Force-directed algorithm has attracted much attention because of its strong global searching ability, which can solve the coverage problem of sensor networks effectively. In this paper, an improved particle swarm algorithm for gas source location is proposed by combining force-directed algorithm. In order to find the location of gas sources more precisely, we use virtual forces to guide particle evolution, which eventually accelerates the convergence of the algorithm.
Suppose that in a certain region, the sensor node exerts gravitational or repulsive force on any particle in the region. We use $\overrightarrow{F_{ij}}$ to represent the force exerted by the sensor node s_j on the particle i in direction $\overrightarrow{x_i}$. Then, the resultant force of the particle i in direction $\overrightarrow{x_i}$ is as follows.

$$\vec{F}_i = \sum_{j=1}^{N} \vec{F}_{ij} \tag{8}$$

We use Φ to represent the set of sensor nodes which can detect the presence of the gas source, and use Φ_i to represent the set of sensor nodes which can detect the presence of the gas source in direction $\vec{x}_i$. Suppose the estimated value is $[\hat{\vec{p}}_{0i}, \hat{T}_i]$, and $\hat{\vec{p}}_{0i}$ meets the following formula.

$$\hat{\vec{p}}_{0i} = (\hat{x}_{0i}, \hat{y}_{0i}) \tag{9}$$

Then, we can get Φ_i by the following formula.

$$\Phi_i = \left\{ s_j \mid \frac{\hat{T}_i}{4\pi k \mid \vec{p}_j - \hat{\vec{p}}_{0i} \mid} \cdot \exp\left(\frac{\mid \bar{v} \mid \cdot [(x_j - \hat{x}_{0i}) - \mid \vec{p}_j - \vec{p}_{0i} \mid]}{2k} + n_i > R \right\} \tag{10}$$

According to the principle of force-directed algorithm, we can get that when $s_j \in \Phi$ and $s_j \notin \Phi_i$, the node generates a gravitational attraction to the particle. On the contrary, when $s_j \notin \Phi$ and $s_j \in \Phi_i$, the node produces repulsion to the particles.
So, in the polar coordinates, $\vec{F}_{ij}$ is defined as follows.

$$\vec{F}_{ij} = \begin{cases} \eta_a \cdot d_{ij}^2, w_{ij} + \pi & s_j \in \Phi, s_j \notin \Phi_i \\ \dfrac{\eta_c}{d_{ij}^2}, w_{ij} & s_j \in \Phi, s_j \notin \Phi_i \\ 0 & \end{cases} \tag{11}$$

Where, η_a and η_c represent the coefficients of gravitation and repulsion, respectively, and w_{ij} represents the direction angle of the sensor node to the source point. Since the force applied to each particle can lead the particle to move to the optimum direction, the position of each particle need to take into account the influence of the virtual force.

$$P = \phi \cdot Pb_{id} + (1-\phi) \cdot Gb_d + \phi \cdot \gamma \cdot D_{id} \tag{12}$$

In the formula, ϕ is a random value which satisfies the formula.

$$\phi \in [0,1] \tag{13}$$

Suppose that in the dimension d of the particle i, D_{id} is dynamically updated through $\vec{F}_i$.

$$D_{id} = \begin{cases} \cos(w_i) \cdot D_{\max} \cdot e^{-\frac{1}{F_i}} & \text{d=1} \\ \sin(w_i) \cdot D_{\max} \cdot e^{-\frac{1}{F_i}} & \text{d=2} \end{cases} \tag{14}$$

Where, $D_{\max}$ represents the maximum move step size.

In order to prevent the instability of the algorithm into the local extreme, we need to revise the extreme value of the individual. We choose an individual extreme $Pb_j(t)$ from other extremes, and the new individual extreme is calculated as follows.

$$Pb_i(t) = \varepsilon \cdot Pb_{i0}(t) + (1-\varepsilon) \cdot Pb_j(t) \tag{15}$$

The flow chart of algorithm is shown in figure 2.

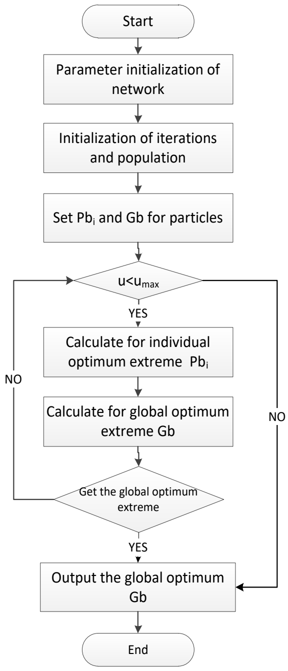

Figure 2: The flow chart of improved algorithm

Since the force-directed algorithm is directly derived from real physical phenomena, it can better reflect the source location problem. The virtual force method can enhance the global searching ability, which can speed up the convergence of the algorithm. To some extent, this virtual force makes particles move more purposeful and reduces the number of iteration.

4. Simulation experiment and result analysis

The localization algorithm for gas source proposed in this paper is mainly aimed at two dimensional situations. This experiment is carried out in the area of 80m*80m. In the experimental area, we deployed 81 sensors which are evenly distributed and their location is known. The measurement noise in the positioning process can be modelled by nonzero Gauss noise.

Root mean square error (RMSE) is a key performance index to evaluate the accuracy of location algorithm. The calculation method of RMSE in two-dimensional space is as follows.

$$RMSE = \sqrt{\frac{1}{m}\sum_{1}^{m}\left(\left(x_i - x_0\right)^2 + \left(y_i - y_0\right)^2\right)} \tag{16}$$

In the above formula, m means the number of experiments. And (x_i, y_i) is the position of gas source obtained by simulation experiment, while (x_0, y_0) is the true location of the gas source. The experimental results are shown in table 1 and figure 3.

Table 1: The average time consumption of the two algorithms

	Improved algorithm	Original algorithm
Time	0.0852	0.0631

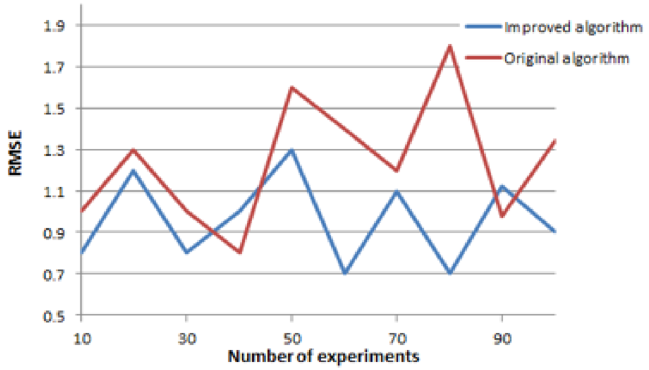

Figure 3: RMSE of the experimental results

Through the experimental results, we know that the improved algorithm has good performance both in accuracy and speed. That means that the new algorithm has better applications in more and more fields.

5. Conclusion

In this paper, we make a study on the gas source location algorithm in wireless sensor networks based on the gas diffusion model. By combining particle swarm optimization and force oriented algorithm, the global search ability of improved algorithm is improved. At present, the research of gas source localization is mainly aimed at two-dimensional space, so the application in three-dimensional space needs further study.

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