An Optimization of the Chlorine Gas Wireless Sensor Network Coverage and Leakage Model

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Abstract: In this paper, we focus on building a system of Chlorine gas monitoring wireless network, which the coverage optimized by artificial fish swarm algorithm. Based on this system, Gaussian leakage model was improved to estimate the location and damage of a leakage accident. The measurement resolution of the system was 1 ppm. Maximum measuring error was less than 5 %. The coverage of the system was 2 km. And the system power consumption reduced 40 % as well as the coverage of network was not less than 95 % by using artificial fish swarm algorithm. The improved model can accurately forecast the damage and diffusion path in a specific region. This research provided a method for designing wireless sensor network and forecasting leakage damage.

Keywords: Chlorine gas monitoring, Wireless sensor network, Artificial fish swarm algorithm, Coverage, Leakage model.

1. Introduction

Accidents of toxic gas leakages, which often occurred at the period of production, transport, storage and using, caused great human damage and property losses [1, 2]. Chlorine, which is a manufactured material of 60 % chemicals, is one of the highest rates of hazardous chemicals. If the leakage of Chlorine is more than 15 ppm, the damage will threaten human life. Chlorine gas monitoring devices currently was divided into two types, single-handheld and on-line devices. Using single-handheld devices, the operators directly touched the toxic gas and cannot continuous monitor. On-line monitoring devices had weak anti-jamming capability, complex laying lines, poor scalability and high cost [3]. Wireless sensor network (WSN) provided a new technical support for leaking monitor, and it can be the mainly method of toxic gas leakages monitoring [4, 5].

How to improve detection efficiency, which is assigned a minimum of detection nodes to get a maximum coverage, is the primary issue of WSN design [6]. At present, some researchers have applied the hybrid particle swarm optimization and the genetic algorithm to get the optimal solution. The average time of both analyses was too long and the rate of convergence was slow [7]. The artificial fish swarm algorithm had fast convergence rate and can solve real-time problem [8].

In this paper, the hardware and software of a WSN system for monitoring Chlorine was designed and experimentally testified. What is more, we got an optimal solution between the coverage and power...
consumption by artificial fish swarm algorithm. The designed system was applied in industrial field to build a leakage model of the small area. Thus, the model provided theoretical basis of accident prevention and rescue.


Fig. 1 shows the system was constituted by three levels: monitoring level, transport level and management level. The monitoring level was the section of perception and information processing. It determined the accuracy of system. The device was designed for measuring environmental parameters, such as concentration of Chlorine, temperature and humidity. Considering of coverage and scalability, a Wi-Fi independent network was built by a high power wireless bridge. The management level was a friendly interface of the system which operators can observe data changes directly in PC or Android cellphone.

The section of sensor (in dash-dotted line) measured gas concentration of Chlorine, temperature and humidity of environment, and transformed the sensor output (current signal) to standard voltage signal (1-3 V). Measurement of temperature and humidity was in order to compensate the Chlorine gas sensor. The Chlorine gas sensor was a three electrodes electrochemical sensor. Two stages of amplifier transmission circuit were designed for this based on single power supply [9]. As shown in Fig. 3, the circuit adopted 2.5 V as zero potential. The current output of sensor \( I \) turned into positive voltage signal \( V'_1 \) by low pass filter circuit. \( V'_1 \) and zero potential \( V'_2 \) input gain adjustable operational amplifier which was made up by A, B, C part of LM124. After two stages amplifications, MCU can read the signal \( V'_o \). \( R_1 \) is used to adjust the gain, and \( R_o \) is used to regulate the zero output voltage. The relationship between input and output is shown as formula (1).

\[
V'_o = \frac{(R_s + R_1 + R_o) - R_1}{(R_s + R_1) - R_o} \times \frac{(2.5 - IR_o) - 2.5 \times (R_s + R_o)}{R_s + R_o} (1)
\]

where \( V'_o \) is the output signal and \( I \) is the input signal.

We adopted Wi-Fi as the communication mode which consumption was very high (>100 mA) [10]. In this paper, this problem was improved from two aspects. On one hand, the operating mode of wireless communication was changed from continuous to discontinuous which leaded to consumption decrease 80 %. On the other hand, the system used DS2438 to monitor the battery state parameters, such as voltage, current, working time and remaining capacity and to alarm. What is more, a circuit of charging battery and power supply automatic switching was designed. External power can charge battery if it switched on, at the same time, battery did not supply the system. The circuit is shown as Fig. 4.
The main functions of software platform were controlling working node, displaying measurement data, querying historical data, locating leakage position, building accident model and etc.

3. Experiment

3.1. Experiment Details

System test was carried out in a seal self-made test box (50L). There was a small fan in the box for accelerating the diffusion of gas. There was also a pump for exhausting. The test was conduct according to the following steps,
- Gas distribution: 50 ml 2 % Chlorine gas with Nitrogen gas as balance gas was prepared.
- Temperature compensation: humidity of 30 % RH in the test box was set. After the device was electrically stable (about 1 minute), injected 0.5 mL (10 ppm) gas into the test box, then, adjusted the temperature from -30 °C to 50 °C.
- Concentration calibration: Set humidity of 30 % and temperature of 20 °C. in the test box. After the device was stable, injected 0.1 mL (2 ppm) gas into the test box. The measured value and extracted the gas was recorded. we tested 10 times from 2 ppm to 20 ppm.
3.2. Temperature Compensation

Because electrochemical sensor was easily influenced by temperature, the device should be compensation at different temperature. Non-compensation test result shows in Table 1. The maximum relative error was 18 % which was out of requirement. We normalized the results measured under different temperature with the result under 20 °C. We used quadratic polynomial to fit the relationship between normalization coefficient and temperature, as expression (2). Fig. 5 shows the fitting curve. The sum of squares due to error (SSE) of the fitting was 0.001192, coefficient of determination ($R^2$) was 0.9739, Root mean squared error (RMSE) was 0.0141.

$$y = -5.065 \times 10^{-5}x^2 + 3.48 \times 10^{-3}x + 0.9474,$$  \hspace{1cm} (2)

where $x$ is the temperature and $y$ is the coefficient.

The compensated concentration was the actual measuring result divided by normalization coefficient $y$. The maximum relative error after compensated was descended to 4 %.

3.3. Correction of Gas Concentration

After the temperature compensation of the system, we tested the response of Chlorine according to experiment steps 3. As shown in the result of measurement (see Fig. 6 (a)), the curves of all testes showed the same trend. The response time of different concentration testes was all about 30s approximately. But the recovery time of high concentration was longer the low one. It was because the power of pump was constant and gas injected in the box of high concentration was more than the low one. The reason of curves jitter was that the fan in the test box blew the gas (density of Chlorine is greater than the air’s) result in the gas which the sensor contact with was unstable. When we injected 0.1 mL (2 ppm) and 0.2 mL (4 ppm) of gas, the result was 1.5 ppm and 3.6 ppm. The relative error was 25 %, 10 % which exceeded the system accuracy requirement (5 %). We used quadratic polynomial to correct the result. We can get the exact value by as formula (3), and SSE of the fitting was 0.3601, $R^2$ was 0.9989, RMSE was 0.2268.

$$x_2 = 0.00908x_1^2 + 0.797x_1 + 0.8687,$$  \hspace{1cm} (3)

where is $x_2$ exact value and $x_1$ is measurement result.

The corrected value is shown in Fig. 6 (b). From the Fig. 6 and Table 2, it is observed that the maximum relative error descended from 25 % to 5 % after the correction and the measure data was more close to the real value.

Table 1. Comparison result under different temperature (ppm).

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>-30</th>
<th>-20</th>
<th>-10</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Measuring</td>
<td>8.2</td>
<td>8.6</td>
<td>9.1</td>
<td>9.5</td>
<td>9.8</td>
<td>10.1</td>
<td>10.4</td>
<td>10.2</td>
<td>9.9</td>
</tr>
<tr>
<td>Relative Error (%)</td>
<td>18</td>
<td>14</td>
<td>9</td>
<td>5</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Compensation Measuring</td>
<td>10.3</td>
<td>10.0</td>
<td>10.0</td>
<td>10.0</td>
<td>10.0</td>
<td>10.1</td>
<td>10.3</td>
<td>10.1</td>
<td>9.6</td>
</tr>
<tr>
<td>Relative Error (%)</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

Fig. 5. Fitting of temperature compensation.
Fig. 6. Comparison correction result under different Chlorine concentration.

Table 2. Comparison of correction results under different Chlorine concentration (ppm).

<table>
<thead>
<tr>
<th>Theoretical Value</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
<th>12</th>
<th>14</th>
<th>16</th>
<th>18</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured Value</td>
<td>1.5</td>
<td>3.6</td>
<td>6.2</td>
<td>8.1</td>
<td>10.2</td>
<td>12.0</td>
<td>14.6</td>
<td>16.1</td>
<td>17.7</td>
<td>19.6</td>
</tr>
<tr>
<td>Relative Error (%)</td>
<td>25</td>
<td>10</td>
<td>3.33</td>
<td>1.25</td>
<td>2</td>
<td>0</td>
<td>4.29</td>
<td>0.63</td>
<td>1.66</td>
<td>2</td>
</tr>
<tr>
<td>Corrected Value</td>
<td>1.9</td>
<td>3.9</td>
<td>6.3</td>
<td>8.1</td>
<td>10</td>
<td>11.7</td>
<td>14.3</td>
<td>15.9</td>
<td>17.8</td>
<td>20.1</td>
</tr>
<tr>
<td>Relative Error (%)</td>
<td>5</td>
<td>2.5</td>
<td>5</td>
<td>1.25</td>
<td>0</td>
<td>2.5</td>
<td>2.14</td>
<td>0.63</td>
<td>1.11</td>
<td>0.5</td>
</tr>
</tbody>
</table>

3. Coverage Optimization Based on Artificial Fish Swarm Algorithm

The coverage optimization of Chlorine WSN was to get the greatest coverage using least sensor nodes in the premise of keeping the network flow. Thus, it reduced the energy consumption of the system and increased the working time. The primary target of optimization was to keep the coverage as large as possible. Each sensor node had monitoring range, and Chlorine concentration can be measured in this area probably. Monitoring region A was assumed to be two-dimensional plane, and divided into m×n parts which the area of each was 1. There were N same sensor nodes in region A. The probability $p(s_i, m)$ which the target $m(x_m, y_m)$ was measured by sensor node $s_i(x_i, y_i)$ can be calculated by formula (4).

$$p(s_i, m) = \begin{cases} 1, & d(s_i, m) \leq d - d_e \\ e^{-\frac{(d - d_e)^2}{2 \sigma^2}}, & d - d_e < d(s_i, m) < d + d_e \\ 0, & \text{otherwise} \end{cases}$$

where $d(s_i, m)$ is distance between sensor node $s_i$ and target $m$, $d$ is theoretically monitoring range of sensor, $d_e$ is reliably monitoring range of sensor,
\( \lambda_1, \lambda_2, \beta_1, \beta_2 \) are all specific parameters of the sensor node.

The joint probability which the target was measured by the set of sensor nodes was calculated by formula (5).

\[
p(s_{all}, m) = 1 - \prod_{i=1}^{n} (1 - p(s_i, m))
\]

where \( p(s_{all}, m) \) is the joint probability.

The network coverage of the system \( f_1 \) was calculated by formula (6).

\[
f_1 = \frac{\sum_{x_i=1}^{n} \sum_{y_j=1}^{m} p(s_{all}, m)}{m \times n}
\]

The other optimization target was using sensor nodes as few as possible. The less sensor nodes there are, the less consumption of system there will be. We defined dormancy \( f_2 \) to show the consumption. If there were totally \( S \) monitoring points, where \( S_0 \) nodes was working, the dormancy \( f_2 \) is shown as formula (7).

\[
f_2 = \frac{S_0}{S}
\]

So, the optimization model of Chlorine WSN was established, considering the coverage \( f_1 \) and dormancy \( f_2 \). In the formula (8), we considered that \( \eta_1 \) was 0.9 and \( \eta_2 \) was 0.1.

\[
f = \eta_1 f_1 + \eta_2 f_2
\]

Artificial fish swarm algorithm is an algorithm that can quickly find the optimal solution by simulating behavior of a fish [11]. A fish got food by foraging, bunching, followership and comparison. The position of the fish was \( x_i \), right now. The status of the fish was \( X_i \), and the food in the position was \( iN \).

1. Foraging. The fish moved to an area for a fixed distance \( \text{Step} \) which the food was more than where it was in the visible region. After the movement the status of the fish was \( X_j \). If the fish cannot meet the condition after several selections, it will move to a random area. \( N_i \) was the food at the status \( X_j \).

\[
\begin{align*}
\text{if } & N_j > N_i, \quad X_j = X_i + \frac{1}{||x_j - x_i||} \cdot \text{Step} \\
\text{end if}
\end{align*}
\]

2. Bunching. The number of partners of the fish was \( m \) in the visible region, and the central location of them was \( x_c \). If the food in \( x_c \) was more than \( x_i \) and the crowd density in \( x_c \) was less than \( x_j \), the fish will move to the partners. After the movement the status of the fish was \( X_c \).

\[
\begin{align*}
X_c = X_j + \frac{1}{||x_c - x_j||} \cdot \text{Step} \\
N_c > N_j \& N_c / m > \delta N_j
\end{align*}
\]

3. Followership. There was a fish in \( x_{max} \) where the food was maximum in the visible region, and the crowd density in \( x_{max} \) was less than \( x_j \). The fish will move to the fish in \( x_{max} \). After the movement the status of the fish was \( X_{max} \).

\[
\begin{align*}
X_{max} = X_j + \frac{1}{||x_{max} - x_j||} \cdot \text{Step} \\
N_{max} > N_j \& N_{max} > \delta N_j
\end{align*}
\]

4. Comparison. The fish compared the food and the crowd density to choose an area to move and recorded. If the new selection was better than the record, it will be replaced.

According to the food density, the fish chose bunching or followership and refresh the record. The optimization solution was obtained by repeat this. Using this algorithm, we adopt the wireless sensor node in the system as the artificial fish and set them random in area square area of \( 100 \times 100 \) m. The number of artificial fish was 30. The visible distance was \( 20 \) m, the fixed displacement distance was \( 3 \) m. When the coverage rate reached \( 95 \% \), the average time of iteration was \( 63 \) s operated in MATLAB 2009. Coverage was lifted from the random distribution of \( 63.2 \% \) to \( 96.4 \% \), and the work of sensor nodes was decreased to \( 13 \) which the energy consumption reduces by \( 56.7 \% \).

4.4. Field Test and Chlorine Leakage Model

4.1. Field Test Details

According to the terrain and artificial fish swarm algorithm, we fitted the system of Chlorine WSN in a waterworks for testing. The waterworks was located in the suburbs of open area and it covered 15000 square meters. Fig. 8 shows a schematic drawing of waterworks and monitoring point. In the period of monitoring, the leakage of Chlorine happened accidentally due to staff’s mistakes of conveying waste. The accident details are shown as Table 3.
4.2. Results and Analysis

Workers started to rescue after 3 minutes when the accident happened. In the period of time, the leakage of Chlorine was without manual intervention. We adopted the monitoring data during this period to establish the model. Fig 9 shows the monitoring data of each test point. Which not shown in Fig. 9 is that the concentration of them is 0 all the time.

4.3. Analysis of Location

The measuring range of monitoring point was 0-20 ppm. Although the measurement of high concentration was not precise, we still can use the data to alarm and analysis of leakage. As shown in Fig. 9, the data of No. 3 node increased fast, and stayed at maximum range stable, the No. 8 node increased soon afterwards. According to weather conditions at the time of the accident, we considered that the accident happened in the west of No. 3 nodes.

<table>
<thead>
<tr>
<th>Spillage</th>
<th>15 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leakage rate</td>
<td>50 g/s</td>
</tr>
<tr>
<td>Height of leakage point</td>
<td>1.5 m</td>
</tr>
<tr>
<td>Height of monitoring point</td>
<td>1.5 m</td>
</tr>
<tr>
<td>Temperature</td>
<td>27 °C</td>
</tr>
<tr>
<td>Humidity</td>
<td>51 %</td>
</tr>
<tr>
<td>Wind direction(angle with north wind)</td>
<td>117°</td>
</tr>
<tr>
<td>Wind speed</td>
<td>2 m/s</td>
</tr>
<tr>
<td>Atmosphere stability degree</td>
<td>B</td>
</tr>
</tbody>
</table>

Table 3. Accident details.

Fig. 7. Comparison of Optimization result.

Fig. 8. Schematic drawing of waterworks.

Fig. 9. Monitoring data of each testpoint.
4.4. Analysis of Leakage Model

The expression of Gaussian model [12] is shown as formula (12). If \( H \) is 0 then we get an expression as formula (13).

\[
C(x,y,z,H) = \frac{Q}{2m\sigma_x\sigma_y\sigma_z} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \left\{ \exp\left[-\frac{(z+H)^2}{2\sigma_z^2}\right] + \exp\left[-\frac{(z-H)^2}{2\sigma_z^2}\right] \right\}
\] (12)

where \( C(x,y,z,H) \) is the concentration degree of a certain downwind point \((x,y,z)\) which the height of leakage is \( H \). \( Q \) is the leakage rate. \( u \) is the average wind speed. \( \sigma_x, \sigma_y, \sigma_z \) are respective coefficient of diffusion on X, Y, Z three direction.

\[
C(x,y,0,0) = \frac{Q}{m\sigma_x\sigma_y} \exp\left(-\frac{y^2}{2\sigma_y^2}\right)
\] (13)

In the analysis, we considered that height of leakage was 0 approximately. According to the condition of leakage, we get the theoretically two dimension equidensity curve based on Gaussian model as shown in Fig. 10.

For convenience of the analysis, we established two-dimensional coordinate that the accident point was origin, the direction of wind was the direction of X axis and the direction perpendicular to downwind was Y axis. Fig. 11 compares the theoretically model and improved model. We put the theoretically curve and condition of waterworks on the coordinate (see Fig. 11 (a)), and the Chlorine concentration of A area was greater than or equal to 200 ppm, the B region was greater than or equal to 80 ppm, the C region was greater than or equal to 40 ppm, the D region was greater than or equal to 20 ppm, the E region was greater than or equal to 8 ppm. The theoretical Chlorine concentration of No. 5 test point was 7.2 ppm, but the measuring data was changed from 0 to 10 ppm after 1 minute. For the No. 9 and No. 11 test point, the theoretical Chlorine concentrations were greater than 40 ppm and 8 ppm respectively, but the stable measuring data were 6 ppm and 8 ppm ultimately. The reason for deviation between the actual and theoretical was that building prevented the gas diffusion. The building not only reduced the concentration of Chlorine gas, but also declined the diffusion rate. We connected the points which measuring concentration was same, and made up the high concentration measurement problem by Gaussian model. Then we can get a new model that more fit for the real situation. Fig. 11 (b) shows the improved model. If the accident happened, people should escape from the color area.
5. Conclusions

This paper completed the design of the wireless monitoring network of Chlorine leakage based on Wi-Fi. Its characteristic was that wireless self-organizing network was designed based Wi-Fi. Thus, it increased the communication range and had good scalability. It will be the direction of industrial automation in future. The maximum error of the system was less than 5%, the coverage radius was larger than 2 km. The working time of the system was prolonged at the same time the coverage was not decreased by using artificial fish-swarm algorithm. According to improved Gaussian model, we can know the location of accident and the evacuation routes after the accident. This system can be widely used in the field of data acquisition and monitoring system.

Acknowledgements

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