Application of RFID Technology in Urban Underground Comprehensive Pipe Gallery

Ye Tian¹ Bing Chen²

Correspondence author: Yali Wang¹

¹Zhonghuan Information College Tianjin University of Technology, Tianjin, China
²Tianjin Institute of Process Automation and Instrumentation CO., LTD, Tianjin, China

Abstract: This paper designs a kind of comprehensive pipe gallery patrol and positioning system based on RFID, in order to solve the problems of low work quality, poor reliability, easy loss of information and difficult to keep, etc. Firstly, many groups of RFID readers are installed on the patrol location and the route passed by the inspector. Based on the complex environmental factors of the comprehensive pipe gallery and the reliability of the positioning system, in this paper, an improved RFID location algorithm is designed, which is based on the VIRE algorithm and the nonlinear spline interpolation method. The dynamic threshold is introduced to obtain the coordinates of the target position. Several groups of target positions, which are satisfying the conditions, are recorded and the average value is calculated as the final result. The experimental results show that the proposed algorithm is compared with the VIRE algorithm. The improved algorithm can reduce the location error from 0.368m to 0.161m. It has better localization effect and can be used to track and locate the patrol personnel of the comprehensive pipe gallery.

1. Introduction
In order to ensure the running state and safety of the equipment, it is necessary for the inspector to inspect the important equipment regularly and record the data related to the equipment. The data should reflect the working performance of the equipment, and be used as the main basis for judging whether the equipment is in trouble. The RFID technology is simple and reliable. The system based on RFID can not only monitor the location information of patrol personnel but also write the equipment information of patrol into mobile terminal. The data is transferred to the management center via WiFi network to process the data, and the data is classified and stored, which is convenient for engineers and technicians to view. The location algorithm is one of the most important algorithms of RFID technology. How to improve the accuracy and practicability of RFID location algorithm has been a hot topic for scholars. In the traditional RFID positioning system, VIRE algorithm is regarded as the classical location algorithm. The algorithm has the advantages of low cost and high stability. However, the traditional linear interpolation algorithm can not meet the needs of the comprehensive pipe gallery inspection and location system because of the large positioning error.

In this paper, the advantages and disadvantages of existing RFID indoor location algorithm are analyzed. Then, an improved RFID location algorithm combining nonlinear spline interpolation is proposed to overcome the shortcomings of the existing algorithms. The experiment is analyzed and summarized.
2. Design of Comprehensive Pipe Gallery Patrol and Positioning system

The system consists of hardware part and software part. The hardware part mainly realizes the data acquisition and transmission, and stores the collected data into the database. It is mainly composed of RFID tags, RFID reader, WiFi module, mobile terminal, server and display device. The software mainly realizes the processing of data. It includes the upper computer and programming design of the inspection and positioning system. The overall scheme design of the comprehensive pipe gallery inspection and positioning system is shown in figure 1.

![System overall scheme block diagram](image1)

Install multiple sets of RFID readers at the location and route of the inspector, and ensure that each tag can be identified by the reader. When the inspector enters the reader's identification range, the system obtains the location information of the inspector by identifying the work card with RFID function, and sends it to the processor via the WiFi network. The processor records the location of the patrol and can display the name, the number, the location and the time of the patrol by the upper computer. The inspector inputs the data information of the device into the handheld mobile terminal, and the mobile terminal sends the patrol information to the server through the WiFi network. The server processes and saves the data.

3. Typical algorithm of VIRE based on RFID

As shown in figure 2, in general, there are several RFID readers and reference labels in the VIRE localization algorithm, which is proposed as optimization algorithm mainly based on the shortcomings of the LANDMARC algorithm. The main content of the VIRE is to improve the positioning accuracy by eliminating some impossible position points without adding additional reference labels.

![VIRE algorithm layout diagram](image2)

In the VIRE algorithm, all reference tags are regularly placed in two-dimensional regular networks,
while the ones to be located can be placed arbitrarily in the grid. In order to improve the positioning accuracy and reduce the interference, the algorithm uses "virtual reference tag" without adding reference tags. Each grid covered by four reference tags is divided into $N \times N$ virtual grid cells of the same size. The virtual tag coordinates are obtained by calculating the known reference tag coordinates. When the RSSI values of all tags are determined, the Vire algorithm sets a threshold value. Furthermore, the RSSI absolute difference of the label to be located and the virtual label is calculated, and the fuzzy map is established by comparing the threshold and the absolute difference to obtain the nearest neighbor reference label of the label to be located. Finally, some method is used to calculate the position of the undetermined tag. If there are $K$ readers, after obtaining the approximate map of $K$, the most likely region of the tag to be located can be obtained by the intersection operation between the approximate maps. If the final number of regions to be located is $t$, the coordinates of the tag to be located are:

$$\begin{align*}
(x, y) &= \sum_{i=1}^{t} w_i (x_i, y_i) \\
\end{align*}$$

where: weight is $w_i = w_{i1} w_{i2}$. $w_{i1}$ denotes the deviation of the virtual reference label and the located label. $w_{i2}$ is the correlation function of the density of the region. The advantage of VIRE algorithm is that it introduces the concepts of virtual reference tag and approximate map, so that the positioning accuracy can be improved without adding additional tags. However, in the traditional VIRE algorithm, the traditional linear interpolation algorithm is used to calculate the RSSI value of the virtual reference tag. Because the relationship between RSSI and distance is not a simple linear relationship, the traditional linear interpolation algorithm is bound to cause unnecessary errors. In order to reduce the unnecessary errors, the interpolation algorithm is improved in this paper. At the same time, a correction algorithm is used in calculating the coordinates of the tag to be located, which reduces the influence of the surrounding environment on the positioning accuracy of the system greatly.

### 4. Improvement of VIRE Algorithm

In order to solve the problem of unnecessary error caused by linear interpolation for virtual label interpolation in the VIRE algorithm mentioned above, in this paper, a nonlinear interpolation method is proposed to express the relationship between RSSI and distance. In a two-dimensional plane, if a series of points $(x_j, y_j)$ are given, and $0 \leq j \leq n$, we can find a polynomial of degree $n$ $T_n(x_j)$. Its expression is as follows:

$$T_n(x_j) = y_j, \quad 0 \leq j \leq n$$

If the given function is $y = f(x), a \leq x \leq b$, from the approximation theorem of Weierstrass polynomials, we know that for $\varepsilon > 0$, there must be a polynomial $T_m(x)$, such that:

$$f(x) - T_m(x) \leq \varepsilon, \quad a \leq x \leq b$$

When $n$ is very large or $\varepsilon$ is very small, the number of times of $T_n(x_j)$ and $T_m(x)$ will be higher, so that the calculation is very heavy. Secondly, because it is difficult to obtain $T_m(x)$, the interpolation polynomial is usually obtained for the function $f(x)$. However, when the degree of the interpolation polynomial is higher, it will cause the function to be not convergent or unstable. In order to solve this problem, a cubic spline interpolation algorithm is used.
\[ M(x) = M_0(x), x \in [x_0, x_1] \]
\[ M(x) = M_1(x), x \in [x_1, x_2] \]
\[ \ldots \]
\[ M(x) = M_n(x), x \in [x_{n-1}, x_n] \]

Can satisfy
\[ M(x_j) = f(x_j) \]
\[ M_{j-1}(x_j) = M_j(x_j) \]
\[ M'_{j-1}(x_j) = M'_j(x_j) \]
\[ M''_{j-1}(x_j) = M''_j(x_j) \]

Where, \( j = 1, 2, \ldots, n - 1 \).

If the number of times on the interval \([x_0, x_1]\) is not more than 3 by \( M(x) \), you can get:
\[ M(x) = \sum_{j=0}^{3} a_j x^j, x_0 \leq x \leq x_1 \]

Secondly, in the interval \([x_1, x_2]\), second consecutive derivation is obtained at \( x = x_1 \) by \( M(x) \), and the number of times is not more than 3. Such that:
\[ M(x) = \sum_{j=0}^{3} a_j x^j + b_1(x - x_1)^3 \]

It is now defined that when the value of \( M(x) \) is greater than 0, the value of \( M(x) \) remains unchanged. If the result is less than 0, then \( M(x) \) is 0, repeat the above steps, and get that there is:
\[ M(x) = \sum_{j=0}^{3} a_j x^j + \sum_{j=4}^{n+1} b_j (x - x_j)^3 \]

The interpolation function can be obtained from above. According to the layout of VIRE algorithm, there are \((n+1) \times (n+1)\) reference tags defined. Take the first row as an example, so that the RSSI value of each reference label of its interpolation function \( M_{h_1}(x) \) is recorded as \( f(x)_j \), \( j = 1, 2, \ldots, n + 1 \). Where the value of \( f(x)_j \) can be read out directly, there are:
\[ M_{h_1}(x_{j-1}) = f(x_j), j = 1, 2, \ldots, n + 1 \]

Because there are \((n+3)\) unknown coefficients in cubic polynomial \( M_{h_1}(x) \) and \((n+1)\) \( f(x)_j \), in order to find these coefficients, we need to define the boundary.
\[ M_{h_1}(x_0) = M_{h_1}(x_n) = q \]

\( q \) is a constant, which is solved jointly by formula (8)–(10).
\[
\begin{bmatrix}
A \\
B
\end{bmatrix}
= \begin{bmatrix}
X_a & X_b \\
Y_a & Y_b
\end{bmatrix}^{-1}
\begin{bmatrix}
F \\
M
\end{bmatrix}
\]

Of which:
\[
X_a = \begin{bmatrix}
x_0^3 & x_0^2 & x_0 & 1 \\
x_1^3 & x_1^2 & x_1 & 1 \\
x_2^3 & x_2^2 & x_2 & 1 \\
\vdots & \vdots & \vdots & \vdots \\
x_n^3 & x_n^2 & x_n & 1
\end{bmatrix},
Y_a = \begin{bmatrix}
0 & 0 & 2 & 6x_0 \\
0 & 0 & 2 & 6x_n
\end{bmatrix}
\]

\[
X_b = \begin{bmatrix}
0 \\
0 \\
(x_2-x_1)^3 \\
\vdots \\
(x_n-x_1)^3 & (x_n-x_2)^3 & \cdots & x_n-x_{n-1}
\end{bmatrix}
\]

\[
Y_b = \begin{bmatrix}
6(x_n-x_1) & 6(x_n-x_2) & \cdots & 6(x_n-x_{n-1})
\end{bmatrix}
\]

\[
A = \begin{bmatrix}
a_0 \\
a_1 \\
a_2 \\
a_3
\end{bmatrix},
B = \begin{bmatrix}
b_1 \\
b_2 \\
\vdots \\
1
\end{bmatrix},
F = \begin{bmatrix}
f(x_0) \\
f(x_1) \\
\vdots \\
f(x_n)
\end{bmatrix},
M = \begin{bmatrix}
q \\
q
\end{bmatrix}
\]

When the unknown parameter of the first line of the interpolation function \( M_{hi}(x) \) is evaluated, the RSSI value of the first line from the left to the tag \( i \) is:

\[
H_i(i) = M_{hi} \left( x_0 + \frac{x_n-x_0}{nN} (i-1) \right)
\]

The same goes for the interpolation function \( M_{hi}(x) \) in line \( j \) and the line \( j \) for which the RSSI value of the tag \( i \) from the left is:

\[
H_j(i) = M_{bj} \left( x_0 + \frac{x_n-x_0}{nN} (i-1) \right)
\]

After calculating the RSSI value in the direction of the row, we know the RSSI value of the \( n \times N \) labels in each row, and on this basis, calculate the column according to the same method above, and get the interpolation function \( M_{hi}(x) \) of the \( j \) column and the RSSI value of the tag \( i \) from the top to the bottom in the \( j \) column:

\[
L_j(i) = M_{bj} \left( x_0 + \frac{x_n-x_0}{nN} (i-1) \right)
\]

The threshold \( \gamma \) is introduced in the definition of fuzzy map by VIRE algorithm, which can have a great influence on the acquisition of nearest neighbor reference tags. If \( \gamma \) is very large, there is more redundant information in the algorithm, and the number of places marked 1 on each fuzzy map increase. This will further increase the number of nearest neighbor reference tags in the intersection of various fuzzy maps. The proportion of the reference position with larger error increases, resulting in a large error in the calculation of target position. Similarly, if the selected \( \gamma \) is small, some effective nearest neighbor reference labels may be ignored, and the calculated target position error will be larger. Therefore, the selection of a suitable \( \gamma \) value is an effective measure to improve the positioning accuracy. In the simulation, we can dynamically select \( \gamma \) value and detect the number of nearest
neighbor reference tags. When the number of reference tags is 4 ~ 6, several groups of calculated values are selected, and the final results are obtained by taking the average value.

The improved VIRE algorithm is shown in figure 3.

5. Algorithm Simulation and Analysis
In the plane of 8 × 8, the location destination label is simulated. The initial γ value is 1 and the initial q value is 0. The coordinates of the four RFID readers are as follows: A(0, 0), B(0, 8), C(8, 0), D(8, 8). The location of the given 10 tags to be located is as follows: (4.692, 2.091), (3.30, 6.19), (6.70, 1.34), (4.641, 5.819), (5.928, 2.633), (2.738, 1.692), (6.347, 1.833), (6.53, 3.67), (2.429, 7.59), (0.123, 5.976).

The experimental layout of VIRE algorithm is shown in figure 4. The distance between adjacent reference labels is 2m. The VIRE algorithm and its improved algorithm are simulated, and the simulation results are shown in Table 1. Table 1 shows that the average error of each point of the traditional VIRE algorithm and the improved algorithm is 0.368m, and the average error of the improved algorithm is 0.161m. From the comparison of the error curves of the two algorithms in figure 5, it can be seen that the accuracy of the improved algorithm at each point is much higher than that of the traditional VIRE algorithm.
Figure 3. Improved algorithm flow chart

Start

Initialize each parameter

Determine the RSSI value for all tags of each reader

Dynamically selecting threshold and detecting the number of nearest neighbor reference tags

The number of nearest neighbor reference tags is between 4 and 6?

Y

Find out the location of the target under this condition and record

Three sets of target coordinates are selected and the average value is used as the final result

End

N
Figure 4. Experimental layout of VIRE algorithm

Table 1. Experimental simulation results

| Target tag | Actual position of tag to be tested | Traditional algorithm | Traditional algorithm error | Improved algorithm | Improved algorithm error |
|------------|------------------------------------|-----------------------|-----------------------------|--------------------|--------------------------|
| 1          | (4.692, 2.091)                     | (4.749, 2.245)        | 0.164                       | (4.711, 2.125)     | 0.039                    |
| 2          | (3.30, 6.19)                       | (3.355, 6.068)        | 0.190                       | (3.258, 6.138)     | 0.079                    |
| 3          | (6.70, 1.34)                       | (6.501, 1.499)        | 0.255                       | (6.76, 1.374)      | 0.07                     |
| 4          | (4.641, 5.819)                     | (4.744, 5.750)        | 0.124                       | (4.736, 5.74)      | 0.124                    |
| 5          | (5.928, 2.633)                     | (5.998, 2.859)        | 0.238                       | (5.945, 2.759)     | 0.127                    |
| 6          | (2.738, 1.692)                     | (3.001, 1.511)        | 0.323                       | (2.944, 1.623)     | 0.227                    |
| 7          | (6.347, 1.833)                     | (6.019, 2.241)        | 0.535                       | (6.249, 1.87)      | 0.115                    |
| 8          | (6.53, 3.67)                       | (6.176, 3.659)        | 0.354                       | (6.559, 3.507)     | 0.183                    |
| 9          | (2.429, 7.59)                      | (2.498, 7.011)        | 0.593                       | (2.681, 7.466)     | 0.281                    |
| 10         | (0.123, 5.976)                     | (0.989, 5.766)        | 0.903                       | (0.437, 5.786)     | 0.367                    |
| Average    |                                    |                       | 0.368                       |                    | 0.161                    |

Figure 6 shows the relationship between the value of N and the accuracy of the two algorithms. It can be obtained from the diagram that the value of N is between 1 and 4, the localization error of both algorithms is obviously reduced, and the speed of reduction is very fast. When the value of N is between 4 and 10, the localization error of the two algorithms is basically unchanged, and the accuracy of the improved algorithm is always higher than that of the VIRE algorithm. It can be seen from figure 7 that the error of the two algorithms is not changed much when the threshold value is taken near 1, but the accuracy of the improved algorithm is obviously higher than that of the VIRE algorithm, and when the threshold value is 1 the accuracy is the highest.
6. Summary
In this paper, we first put forward a kind of comprehensive pipe gallery patrol location system based on RFID, which can accurately understand the location of patrol personnel and avoid the occurrence of missed inspection. At the same time, the patrol data of the device is sent directly to the server via the WiFi network through the mobile terminal. Compared with the traditional way of recording the patrol personnel with pen, it has the advantages of convenient operation, uneasy to lose data and easy to manage the data uniformly. In order to ensure the reliability of the positioning system, an improved location algorithm based on RFID is designed on the basis of VIRE algorithm. The improved algorithm adopts nonlinear interpolation and dynamic threshold, which effectively solves the problem of unnecessary error caused by traditional linear interpolation. The experimental results show that the improved localization algorithm has higher positioning accuracy than the traditional VIRE algorithm, and it can better meet the needs of the patrol personnel in the complex environment of the comprehensive pipe gallery, and has higher theoretical and practical application value.

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