STUDY AND IMPLEMENTATION OF A TUNNEL PERSONNEL AND MATERIALS MANAGEMENT SYSTEM BASED ON RFID TECHNOLOGY

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With the rapid development of cities, subway and other transportation infrastructure projects are growing in both number and scope. How to quickly, accurately, and efficiently find the basic situation and location of workers trapped in an accident is an important but difficult problem that researchers need to solve technically. To solve this problem, this paper designs a tunnel personnel and materials management system based on RFID technology, which can be used to manage the safety of tunnel workers and the distribution of materials. To track tunnel personnel and materials in real time and accurately locate them, this paper studies the factors that affect the system's positioning accuracy on the basis of LANDMARC and proposes an AVLS-LANDMARC algorithm also based on AdaNN and VIRE algorithms. The AVLS-LANDMARC algorithm uses Newton's interpolation method to insert virtual reference tags between actual reference tags and the AdaNN algorithm to find the optimal value of k. According to simulation results, the algorithm can reduce the system's mean positioning error to as low as 0.294 m, which enables the accurate positioning of the targets to be measured and will play an important role in improving the safety management of tunnel personnel and the distribution of materials.

Keywords: RFID technology, personnel and materials management system, LANDMARC algorithm, virtual reference tag, AdaNN

1. Introduction

With the development of computer technologies and communication technologies, a tunnel personnel and materials management system built on radio-frequency identification (RFID) technology will become a trend in tunnel positioning management thanks to advantages such as easy installation, support for real-time wireless communication, high positioning accuracy and low costs [2]. The system can not only track and locate the materials in a tunnel, but also allow for the real-time positioning of tunnel workers. Obtaining their locations and movement paths is critical to the rational allocation of resources, especially in a timely rescue for a tunnel accident. Given the aforesaid problems, this paper designs a tunnel personnel and materials management system based on RFID technology, which can help locate and manage tunnel personnel and materials in real time and provide

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remote decision-making services for the management of the safety of tunnel workers and the distribution of materials. In this system, the layout of the Location Identification based on Dynamic Active RFID Calibration (LANDMARC) positioning system is adjusted against the geographical characteristics of tunnels. After the determination of the factors that affect the positioning accuracy of the system, an improved positioning algorithm is designed based on some classical algorithms. The system will play an important role in ensuring safe underground operations and improving production efficiency.

2. Overall System Architecture Design

The tunnel personnel and materials management system designed in this paper is mainly composed of two parts. The part inside the tunnel mainly consists of active tags, readers, LoRa terminals, LoRa gateways, and an industrial Ethernet ring network. The part outside the tunnel consists of a core switch, Ethernet, a server, a standby server, and an upper computer. The overall structural block diagram of the system is shown in Fig. 1.

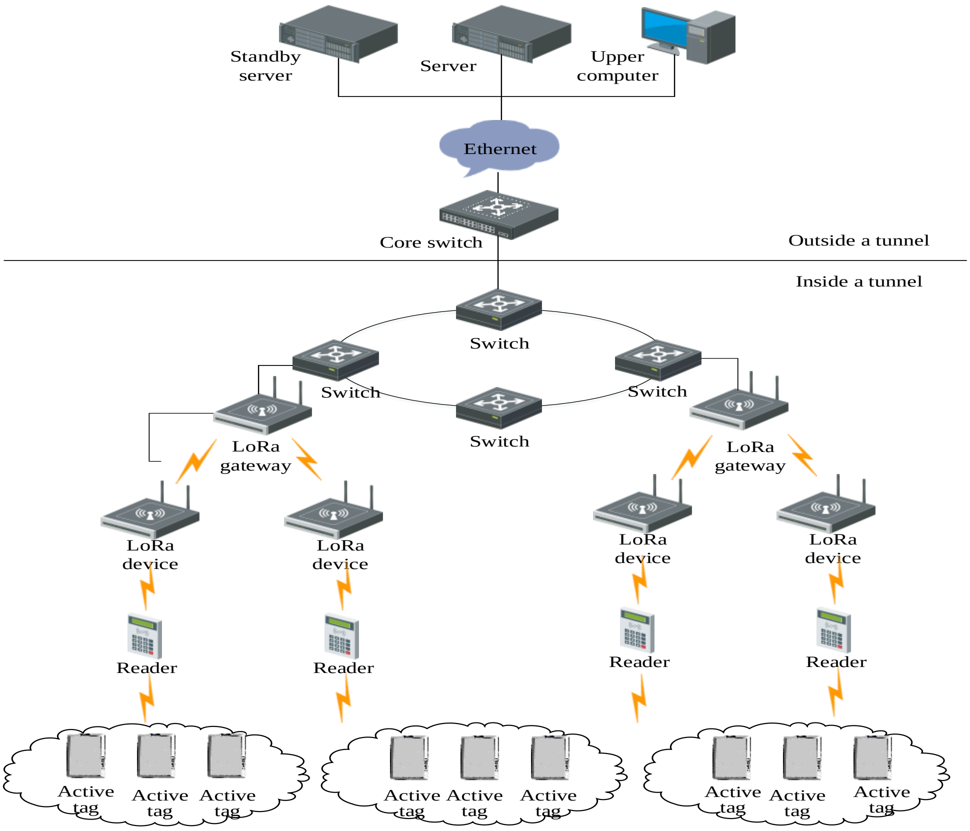

Fig. 1. Overall structural block diagram of the system

The system is designed to mainly control personnel and materials in tunnels. In terms of its main functions, the system is divided into a personnel management platform and a material management platform. The overall functional diagram of the system is shown in Fig. 2. In addition to being widely used in tunnel construction companies, the system can also apply to places that require the real-time and precise control of production materials and staff in industrial production, e-commerce warehousing, and other scenarios and will bring good economic results [3].

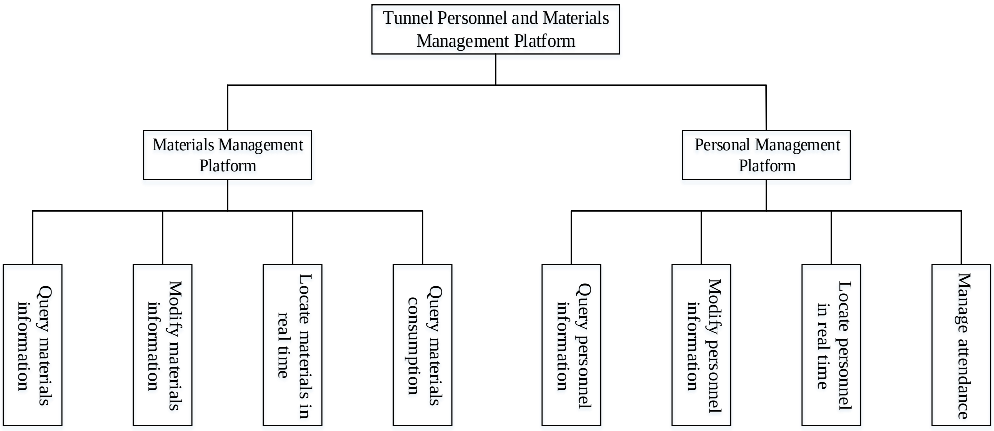

Fig. 2. Overall functional diagram of the system

3. System Hardware Design

3.1 Reader Hardware Design

A reader mainly consists of an STM32F103VE main control chip, an SX1278 LoRa 433 MHz wireless module, an nRF24L01 2.4 GHz radio-frequency (RF) module, a DS1302 clock module, an LCD12864 liquid crystal display (LCD) module, keys, a power management module, and an external memory module. The structural block diagram of the reader is shown in Fig. 3.

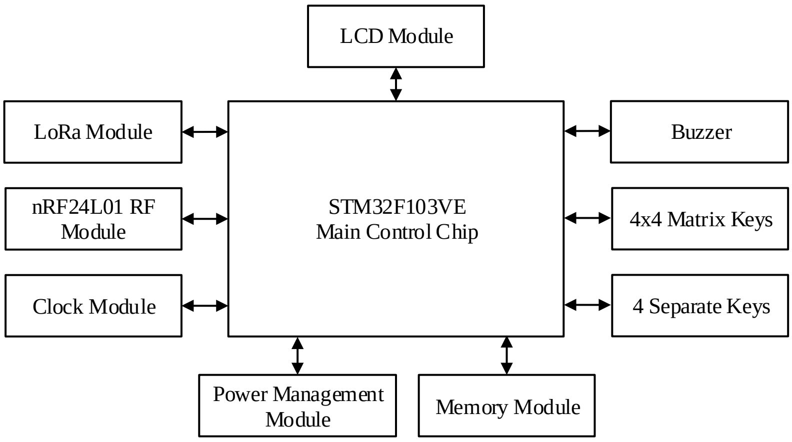

Fig. 3. Structural block diagram of the reader

(1) Main controller

As the core of the entire reader design, the main controller uses a low-power STM32F103VE 32-bit microcontroller as its main control chip. The smallest system of the main control chip mainly consists of a 3.3V power supply circuit, crystal oscillator circuit, and reset circuit [4].

(2) Wireless forwarding module

The wireless forwarding module is mainly responsible for forwarding the information encapsulated by a reader to a gateway. Since a reader is powered by a battery and gateways cannot be arranged very densely in a tunnel, power consumption and distance must be considered at the same time. The SX1278 LoRa module is characterized by a long transmission distance, low power consumption, strong transmission capability, and high penetration, thereby meeting communication requirements for tunnels.

(3) RF module

An RF module is mainly responsible for wireless data communications between a reader and an electronic tag to ensure their reliability even in harsh environments. The RF module should not cost much as it has to connect to a large number of electronic tags and readers. Given this, a 2.4 GHz RF module adopts a relatively cost-effective nRF24L01 chip.

(4) LCD module

In addition to scanning and forwarding electronic tag information, a reader should also be able to display tag information, so that materials managers can check materials and perform inbound and outbound management. The LCD12864 module that can display data clearly is therefore selected as the LCD module.

(5) Clock module

The data packed and uploaded by a reader must contain time information, so a clock chip should be there to provide real-time clock information. In this design, the clock module adopts a DS1302 clock chip.

(6) External memory

A reader must store information about the currently scanned electronic tag in case of network crashes during information upload. If this happens, the reader will re-upload the stored information to the LoRa gateway when the network recovers. Given this, FM24CL64B ferroelectric memory is selected as an external memory.

(7) Power module

Given special conditions in tunnels, we use an intrinsically safe lithium iron phosphate battery. The power module mainly consists of a CN3058 battery USB charger circuit, a TPS63031 3.3V voltage regulator circuit, and a one-key boot circuit built with discrete components.

(8) Keyboard input module

In this design, besides reading and forwarding electronic tag information, a reader should also be able to modify such information. We also use a matrix keyboard to scan keys.

(9) Reader PCB

The two-layer PCB shown in Fig. 4 is designed with Altium Designer's PCB routing tool.

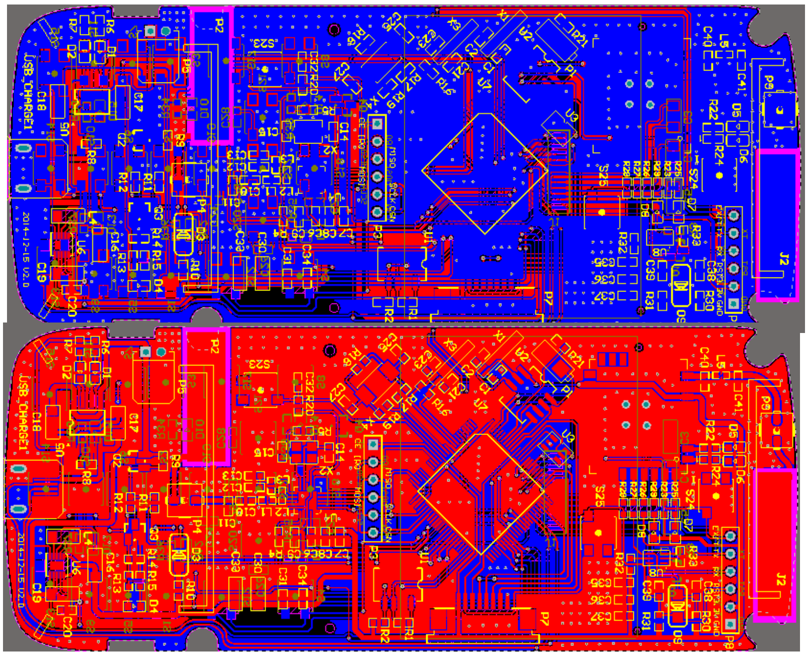

Fig. 4. PCB design of a reader

3.2 Electronic Tag Design

An electronic tag mainly consists of a main control chip module, RF module, and key module. The tag is small and consumes ultra-low power. Fig. 5 shows the structural block diagram of the electronic tag.

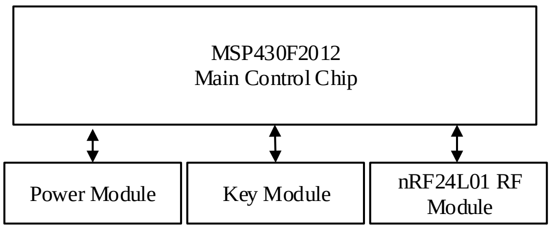

Fig. 5. Structural block diagram of an electronic tag

(1) Main controller

Since the main principles of selection of an electronic tag main controller are (i) low power consumption; (ii) small size; and (iii) high reliability, this design selects an MSP430F2012 16-bit main control unit (MCU).

(2) RF module

The RF module of an electronic tag is mainly designed to communicate with a reader. Like in a reader, an nRF24L01 chip is selected as the RF module.

(3) Electronic tag PCB

According to the schematic diagram, the PCB of an electronic tag is designed with a length of 42 mm and a width of 22 mm. This small size can meet design requirements. Fig. 6 and Fig. 7 show the PCB routing diagram and the electronic tag, respectively.

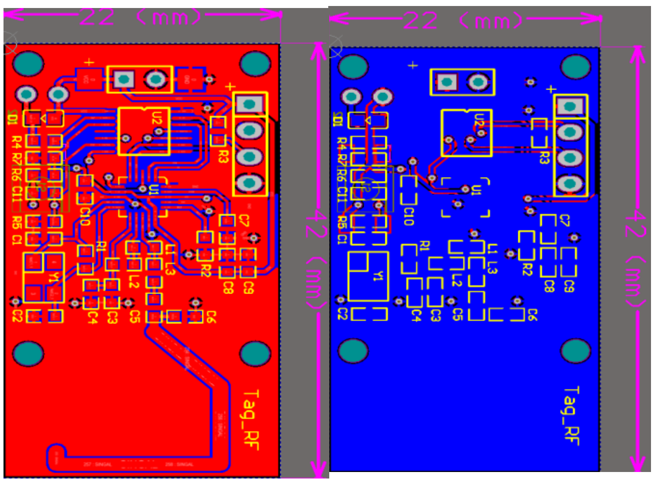

Fig. 6. PCB design of an electronic tag

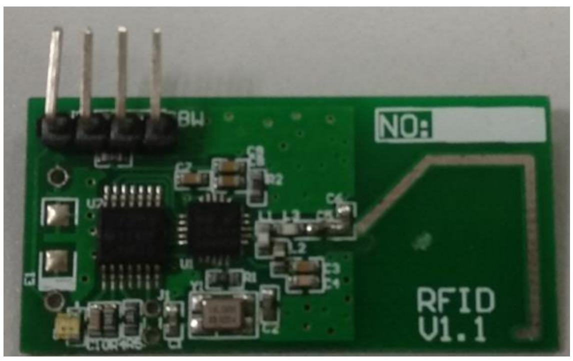

Fig. 7. Electronic tag

4. System Software Design

4.1 Software Design for a Reader

The software design of a reader mainly covers system initialization, broadcasting of a card reading instruction, running of a collision avoidance algorithm, data packaging, and data forwarding. Fig. 8 shows the workflow chart of a reader.

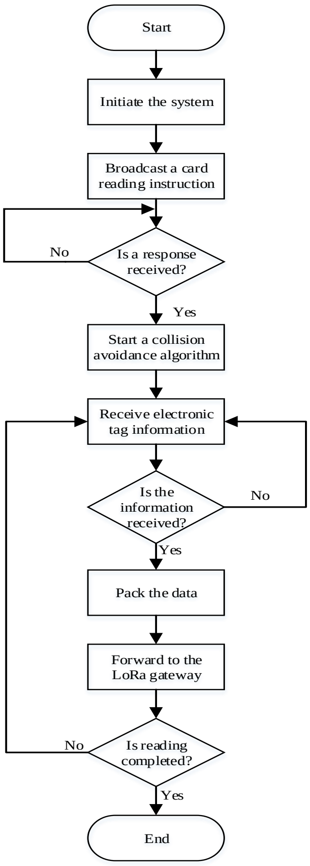

Fig. 8. Workflow chart of the reader

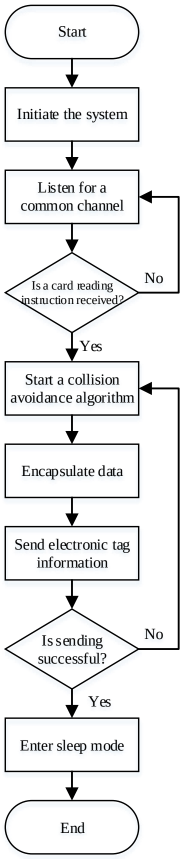

Fig. 9. Workflow chart of an electronic tag

4.2 Software Design for an Electronic Tag

An electronic tag is mainly used to send useful information in the memory to a reader after the reader sends a card reading instruction. The main steps taken by an electronic tag include initializing the system, running a collision prevention algorithm, and sending tag information. Fig. 9 shows the workflow chart of an electronic tag.

4.3 Software Design for the Upper Computer

The software on the upper computer adopts the browser/server mode with the architecture shown in Fig. 10. The web technology based on Struts 2 calls data from the database and converts it into the JSON data format[5] in the background. At the front end, EasyUI and ECharts front-end display technologies are used to display the processed data to users.

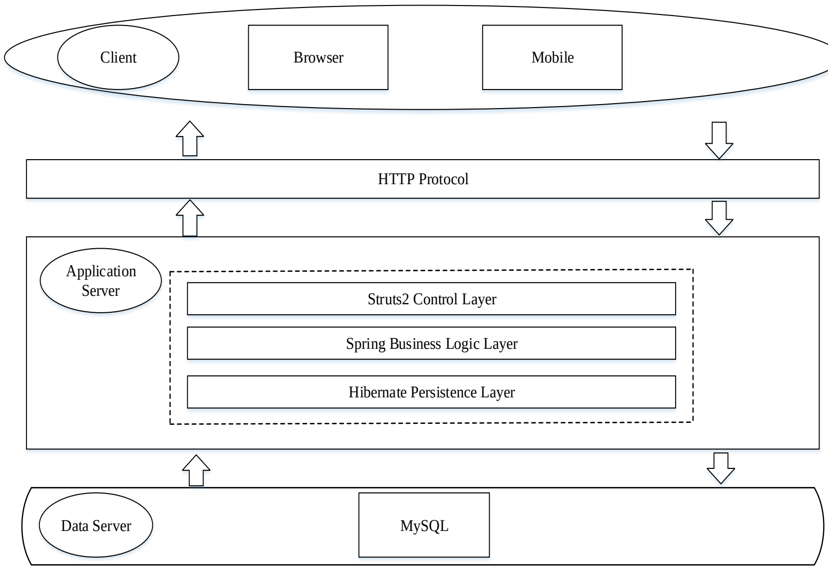

Fig. 10. Architectural diagram of the upper computer

5. Study and Improvement of LANDMARC Algorithm for Tunnel Applications

5.1 Introduction to LANDMARC Algorithm

The key to LANDMARC, an indoor positioning system, is to infer the coordinates of a tag to be measured based on the known fixed coordinates of reference tags. A reader can obtain the signal strength values of both the reference tags and the tag to be measured and calculate the relevance between the tags with a certain method. Finally, the reader will select k suitable reference tags to calculate the location of the desired tag[6]. Fig. 11 shows the schematic diagram of the LANDMARC algorithm, while Fig. 12 shows the core flow of the k-nearest neighbors (k-NN) algorithm.

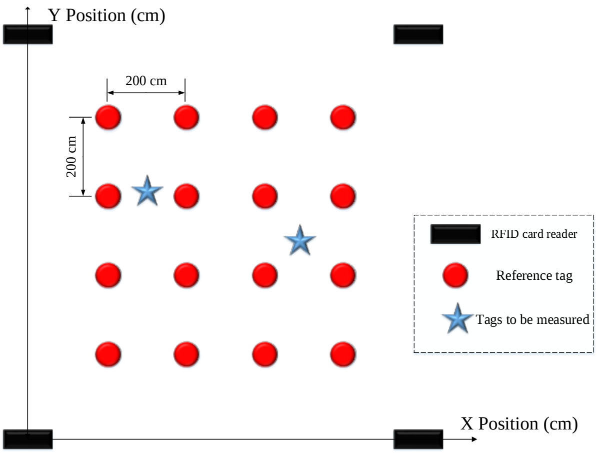

Fig. 11. Schematic diagram of the LANDMARC algorithm

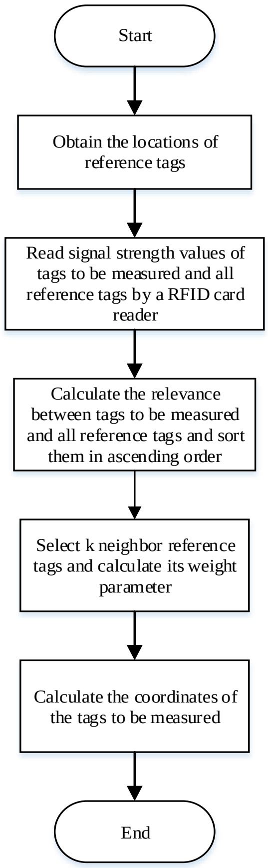

Fig. 12. Flowchart of LANDMARC k-NN algorithm

5.2 Influence of the Number of Readers on the Positioning Results of the System

A tunnel is horizontally short and vertically long, and a special track is built in the middle of the tunnel for vehicles to transport materials. The look of a tunnel is shown in Fig. 13.

The positioning system is arranged according to the actual situation of a tunnel, as shown in Fig. 14. The Y-axis represents the transverse direction of a tunnel, while the X-axis represents the longitudinal direction of the tunnel. Since no tags can be placed on its track, reference tags are spaced 1.5 m apart and RFID readers are placed at four vertices.

Fig. 13. Picture of a tunnel

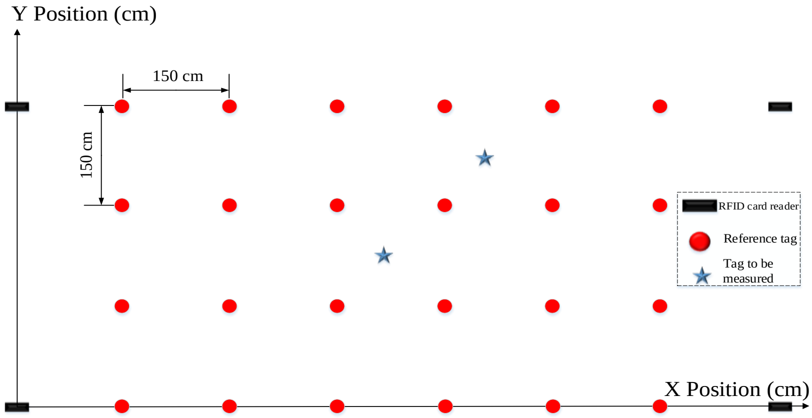

Fig. 14. Layout of a positioning system designed for tunnels

The LANDMARC positioning system uses readers to read the received signal strength values of reference tags and the tag to be measured. During the locating of a target tag, the received signal strength will fluctuate sharply due to the harsh environment and the factors of a device itself. Since the signal strength received by a single reader at a certain point in time may vary from case to case, the positioning accuracy of the system will also be greatly affected, leading to huge errors. The number of readers can be appropriately increased to improve the positioning accuracy of the system. To study how the number of readers affects the positioning results of the system, 2 to 6 readers are set up, as shown in Fig. 15. The k value is set to 4, and 1,000 coordinates to be measured are randomly generated within the scope of the reference tags. After simulation with MATLAB, the cumulative distribution of errors is graphed in Fig. 16.

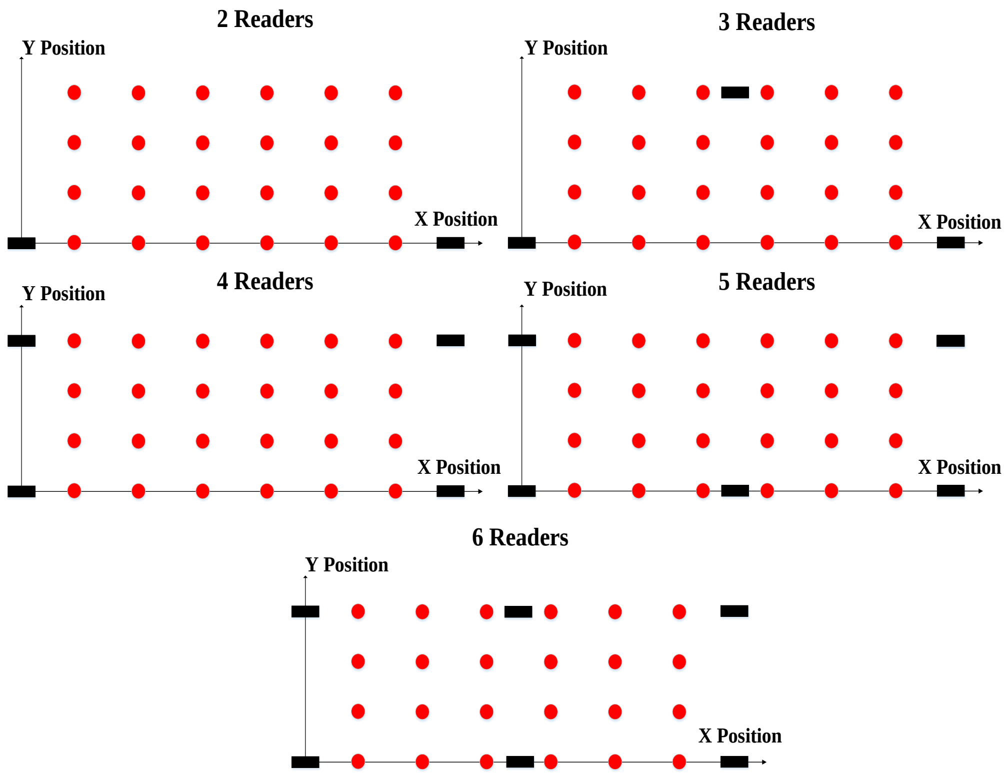

Fig. 15. Schematic diagram of reader layout

Fig. 16 shows that when there are 2 or 3 readers, the probability of a positioning error of less than 1 m and less than 1.8 m is 50% and 90%, respectively; when there are 4 readers, the probability of a positioning error of less than 0.8 m and less than 1.5 m is 50% and 90%, respectively; when there are 5 readers, the probability of a positioning error of less than 0.56 m and less than 1 m is 50% and 90%, respectively; when there are 6 readers, the probability of a positioning error of less than 0.5 m and less than 0.78 m is 50% and 90%, respectively. According to the data in Table 1 and considering the efficiency and costs, the number of RFID readers is set to 6 in the positioning subsystem of this design.

Table 1

Algorithm results with different numbers of readers

Number of Readers	Average Error (m)	Maximum Error (m)
2	1.074	2.942
3	1.056	2.618
4	0.805	3.323
5	0.565	1.651
6	0.499	1.371

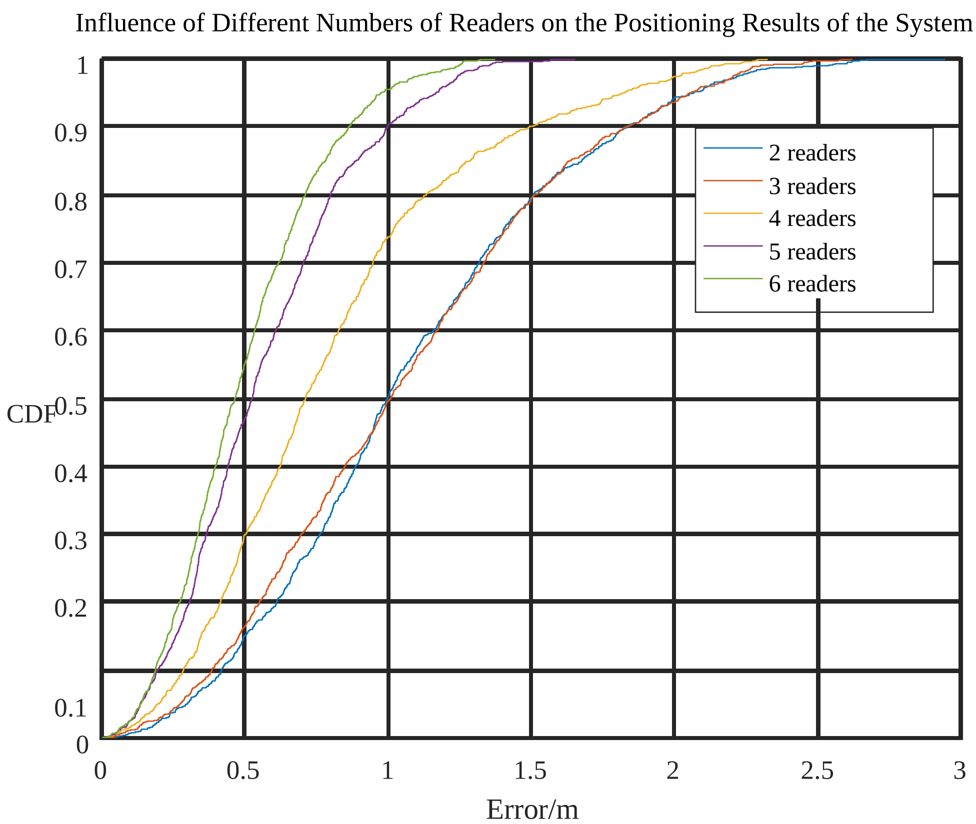

Fig. 16. Cumulative distribution of positioning errors with different numbers of readers

5.3 Influence of the k Value on the Positioning Results of the System

The selection of the k value is particularly important to the k-NN algorithm as selecting an appropriate k value can improve the positioning results of the system. In the simulation for this paper, k is increased from 1 to 8, and 1,000 coordinates to be measured are randomly generated within the scope of reference tags. After simulation with MATLAB, the cumulative distribution of errors is graphed in Fig. 17 and the average errors and other indicators are calculated as listed in Table 2.

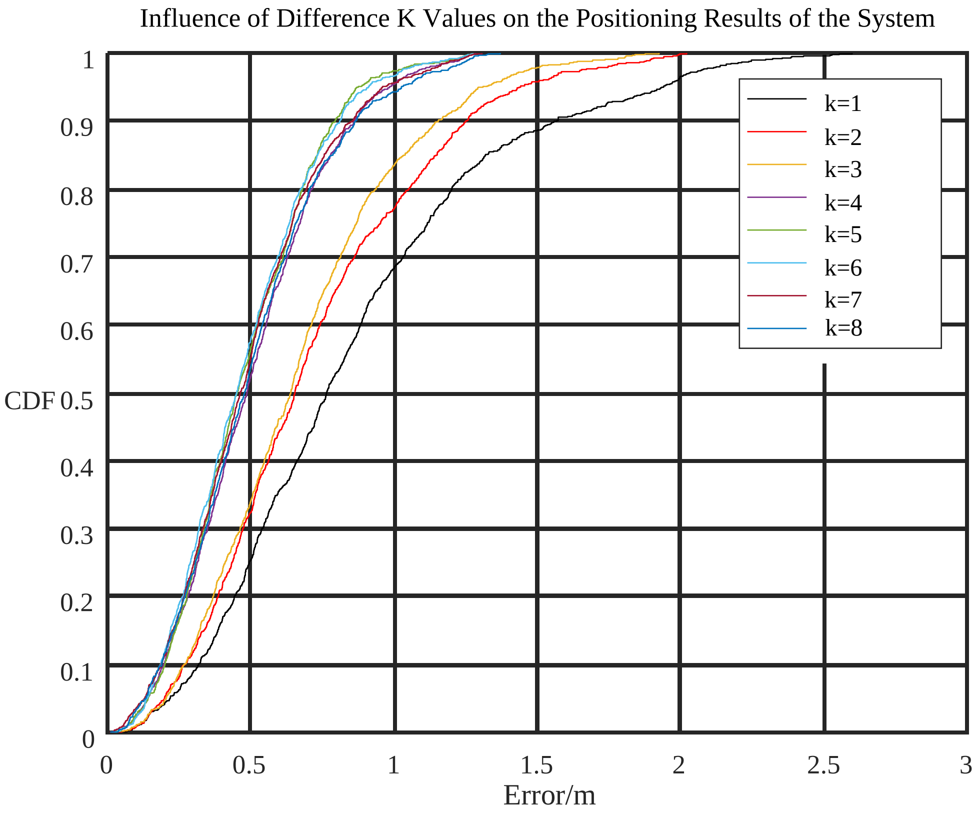

Fig. 17. Cumulative distribution of positioning errors under different k values

Table 2

Algorithm results under different k values

K Value	Average Error (m)	Maximum Error (m)
1	0.857	2.598
2	0.717	2.021
3	0.672	1.925
4	0.507	1.254
5	0.482	1.275
6	0.476	1.276
7	0.491	1.306
8	0.504	1.370

According to the above experimental results, the system positioning error decreases significantly and system accuracy improves dramatically when the k value is increased from 1 to 4. When the k value is increased from 4 to 8, the average error is between 0.476 m and 0.507 m without significant changes in the system positioning error or great improvement in system performance. It can be seen that the k value has a certain influence on the positioning performance of the LANDMARC system. To maximize the positioning accuracy of the system, selecting an appropriate k value is especially important.

5.4 Improvement of the LANDMARC Algorithm

To achieve ideal positioning accuracy and eliminate the impact of the k value on system performance, this paper proposes an improved LANDMARC algorithm based on adaptive virtual reference tag selection. In the positioning system designed for tunnel applications, reference tags cannot be densely arranged due to the limitations of tunnels. Therefore, Newton's interpolation method[7] is used to insert virtual tags[8] between fixed reference tags for better system positioning accuracy. The paper proposes an improved LANDRARC algorithm based on adaptive virtual reference tag selection (AVLS-LANDMARC). The adaptive k-nearest neighbor (AdaNN) algorithm determines the optimal k value by locating key tags, which can effectively reduce system positioning errors. The virtual reference elimination (VIRE) algorithm introduces the concept of virtual reference tags through linear interpolation and uses a matching map mechanism, which will somewhat improve the positioning accuracy of the system. As there is no linear relationship between the RSSI value and the distance between a reader and a tag, inserting virtual tags through linear interpolation will inevitably lead to a certain error. Given this, the AVLS-LANDMARC algorithm inserts virtual tags through nonlinear interpolation to achieve the ideal accuracy. The main process of Newton's interpolation method is as follows: Assume that there are n+1 points in total and the discrete series is $(x_i, f_i), i = 0,1,..., n$, $N(x)$ is an interpolating polynomial and satisfies $N(x_i) = f_i, i = 0,1,..., n$, the general formula of $N(x)$ can be obtained as:

$$N(x) = a_0 + a_1(x - x_0) + a_2(x - x_0)(x - x_1) + ... + a_n(x - x_0)(x - x_1)...(x - x_{n-1}) \quad (1)$$

By substituting the discrete series into Equation (1), we get:

$$N(x_0) = f_0 = a_0 \quad (2)$$

$$N(x_1) = f_1 = a_0 + a_1(x_1 - x_0) \quad (3)$$

$$\mathrm{N}(x_2) = f_2 = a_0 + a_1(x_2 - x_0) + a_2(x_2 - x_0)(x_2 - x_1) \quad (4)$$

The coefficients a_0, a_1, a_2 can be obtained as:

$$a_0 = f_0 \quad (5)$$

$$a_1 = \frac{f_1 - f_0}{x_1 - x_0} \quad (6)$$

$$a_2 = \frac{\dfrac{f_2 - f_0}{x_2 - x_0} - \dfrac{f_1 - f_0}{x_1 - x_0}}{x_2 - x_1} \quad (7)$$

According to the above equations, the expression of $a_i(i = 0,1,..., n)$ can be deduced as:

$$a_i = f[x_0, x_1, ..., x_i] \tag{8}$$

$$f[x_0, x_1, ..., x_n] = \frac{f[x_1, x_2, ..., x_n] - f[x_0, x_1, ..., x_{n-1}]}{x_n - x_{n-1}} \tag{9}$$

which is denoted as the n-th difference quotient. Then Newton's interpolation equation can be rewritten as:

$$N(x) = f_0 + f[x_0, x_1](x - x_0) + ... + f[x_0, x_1, ..., x_{n-1}](x - x_0)(x - x_1)...(x - x_{N-1}) \\ + f[x_0, x_1, ..., x_n](x - x_0)(x - x_1)...(x - x_N) \tag{10}$$

The advantage of Newton's interpolation method lies in its strong expandability as the system has a small workload when more discrete points are added for interpolating. Therefore, the AVLS-LANDMARC algorithm uses Newton's interpolation method to obtain the RSSI value of a virtual tag, which can achieve better results. The core idea of the improved algorithm proposed in this paper is as follows: A certain number of virtual reference tags are inserted between actual reference tags through Newton's interpolation method, which are all regarded as reference tags. Then the AdaNN algorithm is used to find the optimal value of k and finally determine the coordinates of the tags to be measured. Fig. 18 shows the flow of the AVLS-LANDMARC algorithm.

A total of 1,000 coordinates to be measured are randomly generated within the scope of reference tags, and 6 readers are set up. The LANDMARC (with the k value set to 4), AdaNN, VIRE, and AVLS-LANDMARC algorithms are used to perform simulation through MATLAB. The cumulative distribution of errors is then graphed in Fig. 19.

According to the above experimental results, when the cumulative probability is 0.5, system positioning errors in ascending order are 0.294 m (AVLS-LANDMARC algorithm), 0.387 m (VIRE algorithm), 0.438 m (AdaNN algorithm), and 0.513 m (LANDMARC algorithm). When the cumulative probability is 0.9, the AVLS-LANDMARC algorithm still produces the smallest positioning error, followed by the VIRE algorithm. The AdaNN and LANDMARC algorithms have similar positioning errors and low positioning accuracy

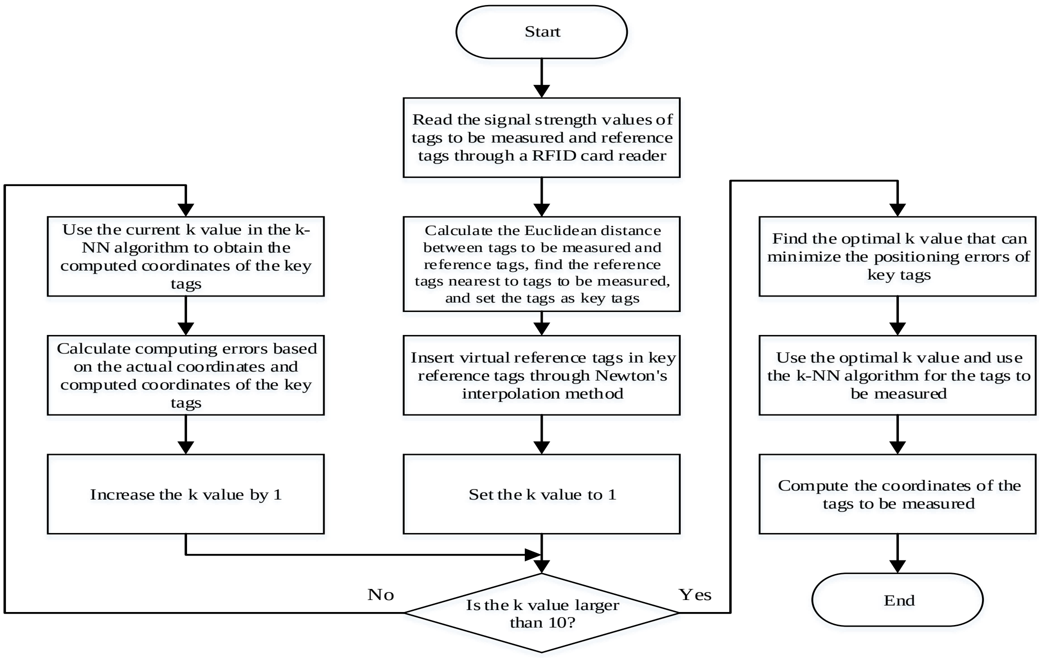

Fig. 18. Flowchart of the AVLS-LANDMARC algorithm

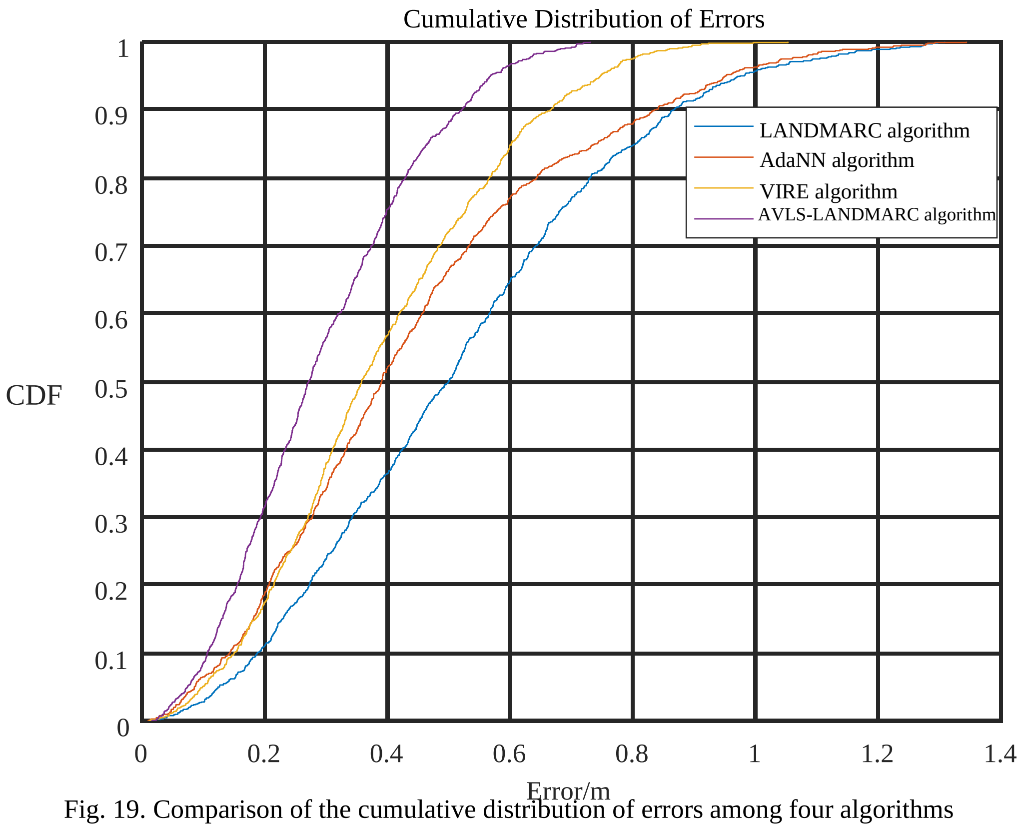

Fig. 19. Comparison of the cumulative distribution of errors among four algorithms

6. Conclusions

Many Chinese construction companies still need to improve their management capabilities, especially their ability to manage tunnel personnel and materials. Doubtlessly, the capability of managing tunnel personnel and materials will directly affect the safety of tunnel personnel and the distribution of materials in these companies. This paper designs the scheme for implementing a tunnel personnel and materials management system (including a positioning subsystem) based on RFID technology. This paper proposes AVLS-LANDMRC algorithm, which combines the advantages of adann algorithm and Vire algorithm on the basis of LANDMRC algorithm. Experiments show that AVLS-LANDMRC algorithm can provide higher accuracy and smaller error.In this scheme, we build a data transmission network with LoRa technology, and establish a data processing and display platform powered by web technology. All this will help manage tunnel personnel and supervises materials throughout their lifecycles.

Given my limited academic abilities and limited depth of research, there is still room for improvement in this design, especially in the following two aspects:

(1) The positioning algorithm improved in this paper is for two-dimensional positioning. To provide more accurate positioning services, the research will focus on three-dimensional positioning.

(2) The mine materials management system designed in this paper consists of a materials management platform and a personnel management platform. More functions can be developed in the future.

Acknowledgements

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