An Improved Triangle Centroid Localization Algorithm Based on PIT Criterion

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Research

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Abstract

Considering that the traditional triangle centroid localization algorithm based on RSSI is susceptible to surrounding environment, this paper improves the algorithm from two aspects of positioning accuracy and response speed also proposes an improved triangle centroid localization algorithm based on PIT criterion. Combined with actual positioning situation, the algorithm treats the calculated coordinates of the intersection points as the new beacon nodes. Thus, the area of triangle in the intersection region is reduced. Repeat positioning process until the predicted position of node is outside the triangle according to the PIT criterion. Compared with traditional triangle centroid localization algorithm, it showed from the simulation results that the improved triangle centroid localization algorithm can increase the localization accuracy up to 5 times based on the guaranteed response time when communication distance is 15~30m, and this algorithm has higher localization accuracy and faster response speed than centroid iterative estimation algorithm in larger communication range. In additions, the experimental platform is built to verify that the proposed algorithm can effectively reduce the positioning error.

Keywords: RSSI-based; Triangle centroid localization algorithm; Overlap area; Response time; centroid iterative estimation

1 Introduction

With the concept of smart dust being proposed, the research on wireless sensor networks has entered a new hot spot[1]. For example, the application field has gradually expanded from the defense and military aspects to modern environmental monitoring, medical rescue, forest fire prevention and other fields. The wireless sensor network includes many nodes. Through manual propagation, the nodes can independently form an organization network within a certain range, and the surrounding information is perceived and monitored. Before collecting the surrounding information, it is essential to locate the node itself, because the positioning without the corresponding nodes will become meaningless[2]. The positioning methods for sensor nodes are roughly divided into two categories: range-based positioning algorithms and range-free positioning algorithms [3]. The range-based positioning algorithm mainly includes the following four algorithms: the time of arrival (TOA) algorithm[4], the time difference of arrival(TDOA) algorithm [5], the angle of arrival(AOA) algorithm[6] and the received signal strength indication (RSSI) algorithm[7]. Range-free positioning algorithms mainly include centroid algorithm[8], distance vector-hop (DV-Hop) algorithm[9], amorphous algorithm[10] and approximate point-in-triangulation test (APIT) algorithm[11].

Since the range-free positioning algorithm does not need to accurately calculate the relative distance or relative angle compared with the range-based positioning algorithm, the hardware requirement and the communication cost are reduced, which can be more suitable to practical applications. This paper considers two aspects of positioning accuracy and response speed, the improved triangle centroid localization algorithm based on RSSI is studied. Since the wireless signal is easily affected by noise, multipath effect, diffraction, temperature and other factors in the surrounding environment, the data error obtained is large when using RSSI. In order to ameliorate the error caused by the positioning process, the methods adopted at home and abroad to reduce the error are mainly from two aspects. The first aspect is to optimize the transmission loss model of the wireless signal and establish a more realistic model; the second aspect is to optimize its positioning algorithm to reduce the errors. At present, the research mainly focuses on improving the positioning algorithm.

Aiming at the shortcomings of the traditional RSSI positioning algorithm, the domestic and foreign literature have studied this algorithm, such as adding the existence probability function[12], measuring error observer[13] or data mapping[14], and using WIFI signal instead of the original anti-interference ability weak signal[15], etc.

Through the above series of methods, the positioning accuracy of the improved RSSI positioning algorithm has been greatly improved. In addition, the RSSI positioning algorithm can be combined with other algorithms to reduce positioning errors, such as iterative calculation[16], weighted centroid algorithms[17][18]. These papers talked above only gives a qualitative analysis of accuracy but lacks response time considerations. However, it is also necessary to consider the response speed apart from the accuracy in practical applications.

From the perspective of improving accuracy and response time, this paper studies the improved triangle centroid localization algorithm based on RSSI. The algorithm treats the calculated intersection coordinates as a new beacon nodes and gradually reduces the triangle area in the intersecting region. The area is reduced by the best triangle inner point test method until the node is outside the triangle. Compared with the traditional triangle centroid localization algorithm, the algorithm has a higher positioning accuracy based on the guaranteed response time, and the positioning accuracy is also improved compared with the centroid iterative estimation positioning algorithm.

(1) We introduce the PIT judgment criterion instead of the simple centroid calculation based on the original triangle centroid localization algorithm. Compared with other complicated judgment criterion, this judgment criterion is simple and effective, and can reduce the positioning error.

(2) We deeply analyze the traditional triangle centroid localization algorithm, which improves the accuracy of positioning by reducing the triangle area and combining PIT judgment criteria, and the algorithm can be applied to field that require precision positioning.

(3) We use the ESP07 module to build the hardware experimental platform to test the proposed algorithm. The test results show that the positioning error of the proposed positioning algorithm is smaller than the error of the other two positioning algorithms, and the positioning error is only 1.42cm.

The reminders of the paper are organized as follows: Section 2 describes the implementation principle of RSSI algorithm and communication model. Section 3 describes the triangular centroid localization algorithm. Section 4 describes the improved triangular centroid localization algorithm. Section 5 evaluates the performance of the improved triangle centroid localization algorithm compared with the existing positioning algorithm. Finally, the conclusion and future directions are drawn in Section 6.

2 Communication Model and Implementation Principle

Based on RSSI measurements, empirical and theoretical models of signal propagation are generally used. The empirical model is based on the establishment of an offline database to compare the received signal strength with real-time positioning to obtain the corresponding coordinates. Since the collected data may not match the corresponding location in the database, the database requires sufficient data to reduce errors. The theoretical models commonly include the following: the free space propagation model, the two-ray ground model and the shadowing model. Free space propagation model is susceptible to obstructions and the fading rate is too fast. Two-Ray ground model is more complex and not suitable for signal transmission over shorter distances. Compared with the above two models, shadowing model has fewer restricted conditions and is easy to implement. So, the shadowing model is used in this experiment, which can be expressed as the following formula.

$$P_L(d) = P_L(d_0) - 10n\log(\frac{d}{d_0}) + X_\sigma \tag{1}$$

where $P_L(d)$ represents received signal strength; $P_L(d_0)$ represents the signal strength when the transmitting end and the receiving end are separated by 1 meter, its value range is generally 45~49; n represents environmental attenuation factor; d represents the calculated distance between the transmitting end and the receiving end; X_σ represents zero mean Gaussian random variable. The loss RSSI can be converted to the distance by the above path loss formula (1).

3 Traditional Triangular Centroid Localization Algorithm

Based on the communication model, it is considered that there is a great difference between the calculated received signal strength and actual situation. The coordinates of unknown node D can be accurately obtained by calculating the distance d_a^*、d_b^*、d_c^* from the beacon node A、B、C to the unknown nodes D in an ideal case which can also be used as the the radius of the circle A、B、C , and the obtained three circles have only one intersection point.

The ideal situation is shown in Fig.1(a), the RSSI-based triangle centroid localization algorithm can be represented as follows. Set the coordinates of the known beacon nodes A、B、C are (x_a, y_a) (x_b, y_b) (x_c, y_c), and the coordinates of the unknown node D are (x_d, y_d) . According to the distance calculation formula, the following equations can be obtained in equation (2).

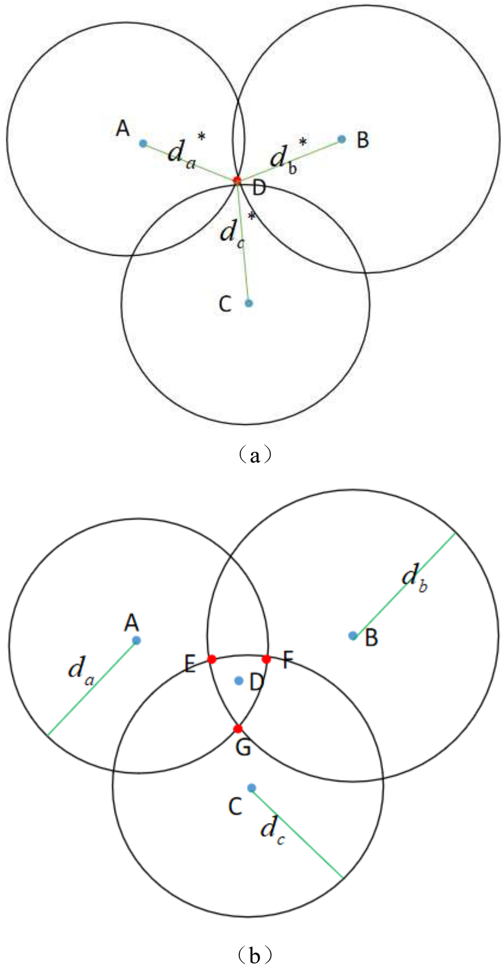


Fig. 1 Ideal model (a) and actual model (b). Thess figures depict how to calculate the distance between the beacon node and the unknown node under ideal model and actual model.

$$\begin{cases} \sqrt{(x_a - x_d)^2 + (y_a - y_d)^2} = d_a^* \\ \sqrt{(x_b - x_d)^2 + (y_b - y_d)^2} = d_b^* \\ \sqrt{(x_c - x_d)^2 + (y_c - y_d)^2} = d_c^* \end{cases} \tag{2}$$

According to equation (2), the equation (3) can be simplified as follow.

$$\begin{bmatrix} x_d \\ y_d \end{bmatrix} = \begin{bmatrix} 2(x_a - x_c) & 2(y_a - y_c) \\ 2(x_b - x_c) & 2(y_b - y_c) \end{bmatrix} \begin{bmatrix} x_a^2 - x_c^2 + y_a^2 - y_c^2 + d_c^{*2} - d_a^{*2} \\ x_b^2 - x_c^2 + y_b^2 - y_c^2 + d_c^{*2} - d_b^{*2} \end{bmatrix} \tag{3}$$

The coordinates of the unknown node D can be calculated by the equation (3).

The actual situation is shown in Fig.1(b), the RSSI is susceptible to multi-path attenuation and non-line of sight, resulting in the theoretical distance d from the converted beacon node to the unknown node is larger than the actual distance d^* [19], so that there are three intersections E、F、G of three circles, which constitute the triangle in overlapping area ΔEFG. The centroid of the triangle acts as the coordinates of the unknown node D. Set that the coordinates of intersection point E are (x_e, y_e), the following in-equations can be obtained with the coordinates of the known beacon node A、B、C.

$$\begin{cases} \sqrt{(x_a - x_e)^2 + (y_a - y_e)^2} \le d_a \\ \sqrt{(x_b - x_e)^2 + (y_b - y_e)^2} = d_b \\ \sqrt{(x_c - x_e)^2 + (y_c - y_e)^2} = d_c \end{cases} \tag{4}$$

According to the inequations (4), the coordinates of intersection point E (x_e, y_e) can be calculated. Similarly, the coordinates of other two intersection points F、G can be obtained, and according to the centroid formula, the coordinates of the unknown node D can be represented by $(\frac{x_e + x_f + x_g}{3}, \frac{y_e + y_f + y_g}{3})$.

4. Methodology

4.1 The Establishment of New Beacon Node

According to above traditional RSSI-based triangle centroid localization algorithm, the improved triangle

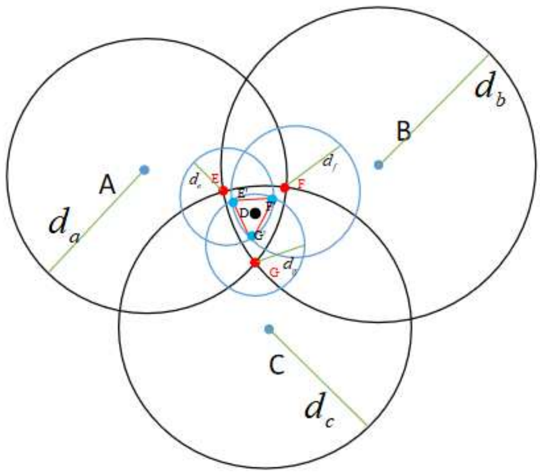


Fig. 2 Improved triangle centroid localization algorithm model. This figure shows how to calculate the coordinate of the unknown node under the improved triangle centroid localization algorithm

centroid localization algorithm is proposed in the paper. As can be seen from Fig.1(b), E、F、G is the intersection coordinate of three circles obtained by taking the beacon node A、B、C as the center and d_a、d_b、d_c as the radius. As shown in Fig.2, the intersection coordinate E、F、G (expressed with red dots) is taken as a new beacon node whose radius is the distance between the intersection coordinate E、F、G and the unknown node D (calculated by the path loss formula(1)), therefore, the intersection coordinates E'、F'、G' (expressed with blue dots) can be retrieved again as follow formula (5).

$$\begin{cases} \sqrt{(x_e - x_{e1})^2 + (y_e - y_{e1})^2} \le d_e \\ \sqrt{(x_f - x_{e1})^2 + (y_f - y_{e1})^2} = d_f \\ \sqrt{(x_g - x_{e1})^2 + (y_g - y_{e1})^2} = d_g \end{cases} \tag{5}$$

Set the coordinates of the intersection point E' is (x_{e1}, y_{e1}) which can be calculated by formula (5). Similarly, the coordinates of the intersection points F'、G' can also be obtained. According to above repeated calculation method, the coordinates of three intersection points $E^{(n)}$、$F^{(n)}$、$G^{(n)}$ generated by the n th iteration can be obtained.

4.2 Centroid Calculation Iteration Criterion

From the improved triangle centroid localization algorithm, it can be known that the size of the intersecting region triangle decreases as new beacon nodes are established. The basis for establishing a new beacon node is that unknown node D needs to be inside the triangle. In order to solve this problem, most of the current centroid algorithm termination criteria is to set the threshold until the condition is met and using this criterion will result in less accurate optimization. In this paper, based on the complexity and positioning error of the algorithm, the PIT criterion in the APIT algorithm can be used as the iterative exit criterion[11]. Compared with other criteria, the one is simple, and the positioning accuracy is relatively high, and the test error rate is low. In addition, the movement of unknown nodes in the PIT criteria can be simulated by exchanging information with neighbor nodes. Therefore, when a new triangle is generated, the judgment is based on the fact that a new beacon node is no longer established when the unknown node D is not within the triangle.

As shown in Fig. 3, it is assumed that there is the beacon node A、B、C and unknown node D. When the unknown node D does not have any neighbor nodes close to or away from the beacon nodes A、B、C, according to the PIT method, it can be found that the unknown node D exists inside the triangle. On the other hand, if there is a neighbor node that is close to or away from the beacon node A、B、C, it is judged that the unknown node is outside the triangle. In addition, due to the irregular placement of neighbor nodes, it may lead to judgment errors. The probability of occurrence of this situation is very low which is verified through experiments, and it is ignored in this experiment.

5 Results and discussion

5.1 Theoretical Analysis of Positioning Error

In the experiment, the positioning error is defined as Localization_error. If the coordinates of the unknown node are (x_{est}, y_{est}), and true coordinates are (x_{true}, y_{true}), the distance is represented as follow.

$$\text{Localization\_}error = \sqrt{(x_{est} - x_{true})^2 + (y_{est} - y_{true})^2} \tag{6}$$

Since all nodes in the simulation are randomly distributed, when other factors such as the communication radius are the same, the following two situations can usually be considered: there is no positioning error in the beacon node and a slight error in the beacon node itself.

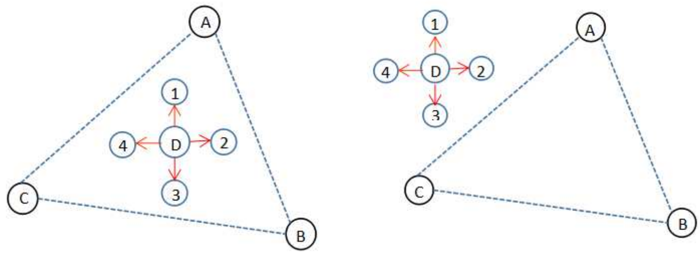
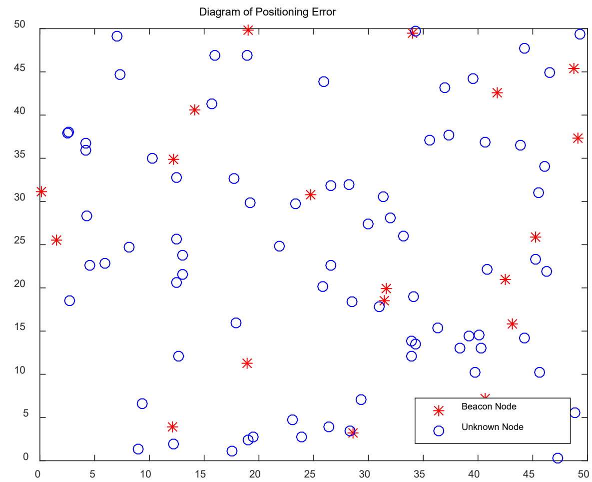
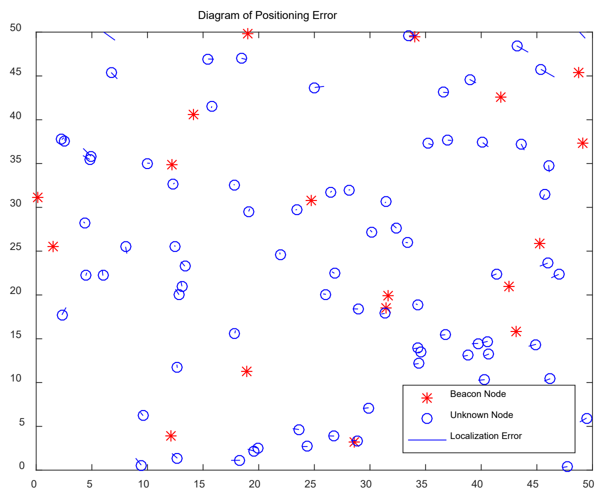


Fig. 3 The schematic diagram of the PIT. This figure shows how to judge whether the node is inside the triangle

Fig.4(a) shows the case where an unknown node is located when there is no error in the beacon node. Fig.4(b) shows the location of an unknown node when the error of the given beacon node itself is 2 m. In addition, as the error increases, the positioning error is more obvious. This error is generally only reflected when the node is deployed in a mountainous area or where the signal is poor. The positioning error of the beacon node itself is not considered in this experiment.



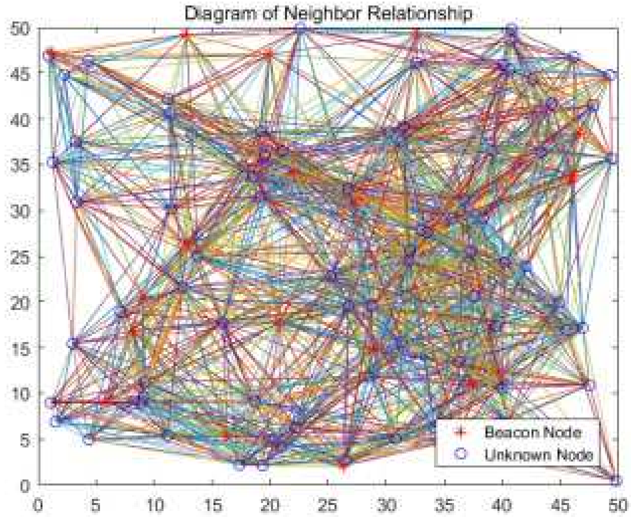
（a）



（b）

Fig. 4 No Error in the Beacon Node (a) and 2m Error in the Beacon Node (b). These figures describe the situation when there are errors and no errors in the beacon node.

Considering that the communication radius of the beacon node is 20m, Fig. 5(a) shows that the unknown nodes which have been located are regarded as the beacon node of other unknown nodes. Fig. 5(b) shows beacon nodes are used for positioning when they exist around the unknown node. If there is no beacon node, the already located unknown node is used for assisting positioning. As the unknown nodes calculated may have errors, the existing beacon nodes around can be used as much as possible to reduce the errors. So in this experiment, the neighbor beacon node is used when the unknown node has a neighbor beacon node. Otherwise, the located unknown node is used to assist the positioning.



（a）

（b）

Fig. 5. Use unknown nodes positioning when neighbor nodes exist (a) and don’t use unknown nodes positioning when neighbor nodes exist (b). The figures depict how to find the neighbor nodes.

5.2 Algorithm Steps

1) The nodes are randomly distributed in a certain area. After receiving the information(ID of beacon nodes), the unknown node averages the RSSI of the same beacon node;

2) After the unknown node collects the information, the beacon nodes are filtered according to the strength of their RSSI, and the three beacon nodes with the largest RSSI value are selected as the calculation basis;

3) For the set of beacon nodes, the coordinates of three intersection points are calculated in turn;

4) The PIT algorithm is used to determine whether the unknown node is within the triangle of the intersecting region. If the unknown node is within the triangle, the three

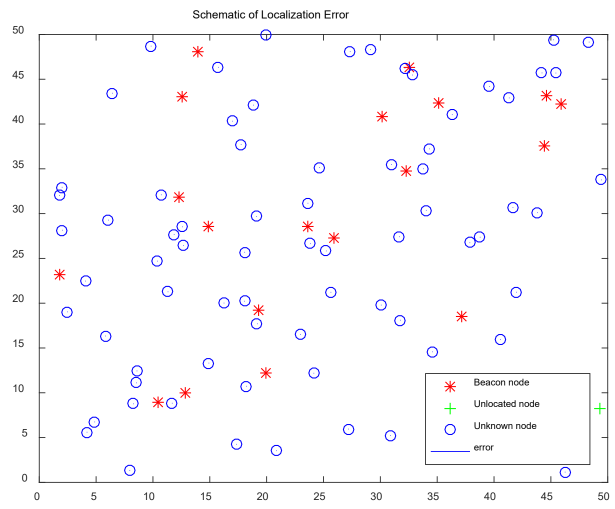


Fig.6 The Improved Triangle Centroid Localization Algorithm. This figure shows the distribution of all nodes

intersection coordinates are taken as the new beacon nodes. The area of the triangle is reduced, and then it is judged whether the unknown node is within the region of the smaller triangle. The calculation is stopped until the unknown node is not within the triangle of the intersecting region;

5) When the unknown node repeatedly judges that the triangles are not in the intersecting region, the coordinates of the three intersection points are calculated, and the coordinates of the unknown node are obtained by the centroid algorithm.

5.3 Software Simulation

This experiment uses MATLAB simulation software to optimize the improved triangle centroid localization algorithm. During the simulation process, the distance estimates to each beacon ($P_L(d)$) was derived from the regular model. The simulation parameters are listed in Table 1.The simulation results are shown in Fig.6. Due to the random distribution of all nodes, there may be no neighbor beacon nodes around a few unknown nodes. Therefore, a small number of unknown nodes cannot be located through the beacon node or assisted by the unknown node that has been located.

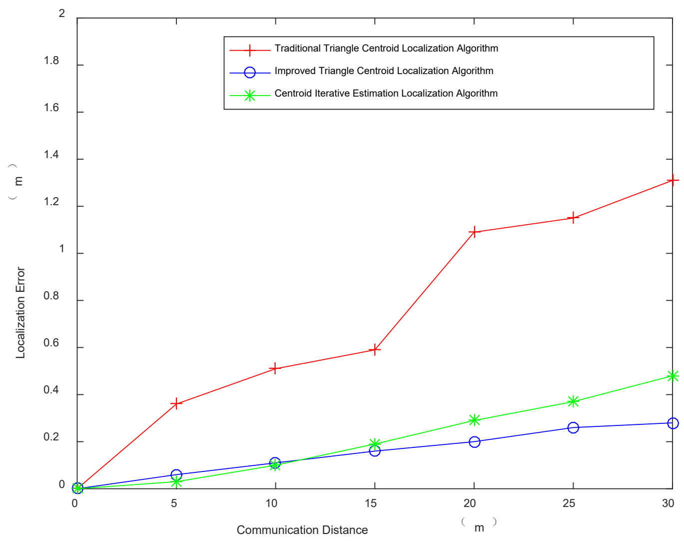
TABLE 1
SIMULATION PARAMETERS

Parameter	Parameter's value
Deployment area	50m×50m
Communication distance	0m-30m
Number of nodes	100
Unknown nodes	80
Beacon nodes	20
PL(d0) , d0 = 1	45db
η	4

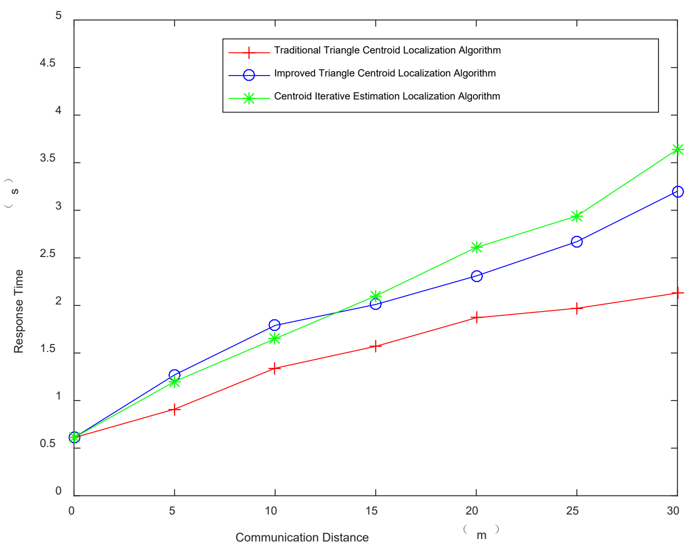
From the aspects of positioning error and response speed, the traditional triangle centroid localization algorithm, centroid iterative estimation localization algorithm[14] and improved triangle centroid localization algorithm are compared and analyzed in Fig.7.

As shown in Fig.7(a), with the increase of communication distance, the positioning errors of the three positioning algorithms are increasing continuously. However, compared with the traditional triangular centroid localization algorithm, the positioning error of the improved triangular centroid localization algorithm and centroid iterative estimation localization algorithm are significantly reduced. When the communication distance is 0~15m, the positioning accuracy of the centroid iterative estimation localization algorithm is slightly higher than the improved triangle centroid localization algorithm, and the accuracy of its improvement is basically unchanged. When the communication distance is 15~30m, the improved triangle centroid localization algorithm has higher positioning accuracy than the centroid iterative estimation localization algorithm, and the accuracy is increased by about 50%. It is indicated that the centroid iterative estimation localization algorithm will reduce the positioning accuracy when there are more beacon nodes, and the improved positioning algorithm maintains a relatively gentle error growth rate.

As shown in Fig.7(b), the response time differences between the conventional triangular centroid localization algorithm, the centroid iterative estimation localization algorithm and the improved triangular centroid localization algorithm are also considered. The response time of three algorithms increases with the increase of communication distance, and conventional triangular centroid localization



（a）



（b）

Fig. 7 The comparison of the Localization Error (a) and Response Time(b). The figure (a) describe the relationship between communication distance and localization error, the figure (b) the relationship between response time and communication distance.

algorithm has the fastest response speed, because this algorithm exists the few iterations. In addition, considering the response time of the centroid iterative estimation localization algorithm and the improved triangular centroid localization algorithm, since the number of beacon nodes is large, the centroid iterative estimation algorithm requires more time to select an appropriate beacon node. Therefore, the response time is much longer than improved triangle centroid localization algorithm in bigger communication range, and response time of improved triangle centroid localization algorithm roughly reduced by 17%. Based on Fig.7(a) and Fig.7(b), it can be known that the positioning accuracy of the improved triangular centroid localization algorithm is greatly improved on the basis of increasing the response time, and the algorithm has certain feasibility and practicability.

5.4 Hardware Simulation

The above simulation results of the positioning accuracy and response time are analyzed in detail. In addition, an experimental platform was built to verify the operability of the proposed algorithm in actual scenario. The Schematic diagram of the Test Area is shown in Fig.8. Due to the limit of experimental conditions, the measurement error of coordinates is verified in the experimental platform. The

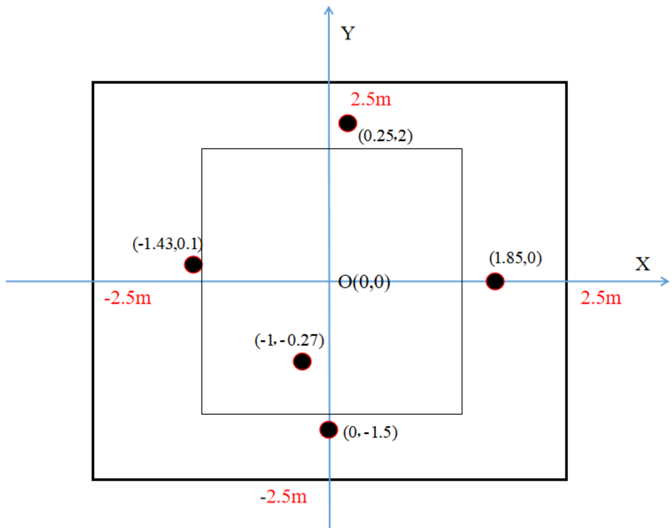


Fig. 8. The Schematic Diagram of the Test Scenario. This figure shows the test area and the location of the experimental nodes.

ESP07 modules are used to test five sets of data in three different algorithm respectively. The origin of measurement area is (0,0), and the results are shown in Table 2.

TABLE 2
EXPERIMENTAL RESULT IN TEST SCENARIO

Actual Coordinate (cm)	Triangle Centroid Algorithm(cm)	Centroid Iterative Estimation(cm)	Improved Triangle Centroid(cm)
(185,0)	(188,2)	(185,2)	(185,2)
(-143,10)	(-144,13)	(-140,10)	(-142,11)
(0,-150)	(4,149)	(2,-149)	(1,-151)
(25,200)	(26,204)	(24,202)	(25,198)
(-100,-27)	(-98,-30)	(-101,-25)	(-100,-26)
Average Error(cm)	3.86	2.12	1.42

The positioning errors were measured in experimental platform under the three algorithms which name the triangle centroid algorithm, the centroid iterative and the improved triangle centroid algorithm respectively. According to the test results in Table 2, it can be seen that the triangle centroid positioning algorithm has largest positioning error compared with the other algorithms, and the error reaches about 3.86cm. In addition, the tested data indicates that the proposed improved triangular centroid localization has the least positioning error, and the error only about 1.5cm. Due to the lack of experimental conditions and experimental equipment, only positioning error was measured in the experimental platform, and the response time of various algorithms was not measured in paper.

6 Conclusion and future work

This paper considers the two aspects of positioning accuracy and response speed, and the improved triangle centroid localization algorithm is proposed based on the traditional RSSI-based triangle centroid localization algorithm. The algorithm reduces the area of the overlap region by generating new beacon nodes, and applies the PIT in the APIT algorithm as the basis for the area reduction of the overlap region. The simulation results show that compared with the traditional triangular centroid localization algorithm, the algorithm improves the positioning accuracy by 6 times on the basis of double the response time. In addition, by analyzing the error of the beacon node itself and the judgment of the neighbor beacon node, the model is closer to the actual positioning situation.

Since the ESP07 module is used in the experimental test platform which its price is low, and the positioning function can be realized. The higher the hardware cost, the faster the calculation speed may be, and the difference in response time between algorithms may be negligible, but it still needs to be verified in kind. However, when the algorithm selects the new beacon nodes, it does not consider the error of the new beacon nodes. The next step is to consider how to reduce the error in this aspect. In addition, the time complexity and space complexity can also be used as the research object of the next topic. At the same time, in addition to the research of algorithm on a two-dimensional plane, it can be considered whether the algorithm also has an efficient positioning function in the three-dimensional space[20].

Abbreviations

RSSI: received signal strength indication;
TOA: time of arrival;
TDOA: time difference of arrival;
AOA: angle of arrival;
APIT: approximate point-in-triangulation;
PIT: point-in-triangulation

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Authors' contributions

ML proposed the main idea, performed the simulation, and analyzed the result. He is the main writer of this paper. FJ gave some important suggestions for the paper, CP have revised the paper. All authors read and approved the final manuscript.

Declarations

The raw data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

Competing interests

The authors declare that they have no competing interests.

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Figure title and legend section

Fig. 1 Ideal model (a) and actual model (b). Thess figures depict how to calculate the distance between the beacon node and the unknown node under ideal model and actual model.

Fig. 2 Improved triangle centroid localization algorithm model. This figure shows how to calculate the coordinate of the unknown node under the improved triangle centroid localization algorithm.

Fig. 3 The schematic diagram of the PIT. This figure shows how to judge whether the node is inside the triangle.

Fig. 4 No Error in the Beacon Node (a) and 2m Error in the Beacon Node (b). These figures describe the situation when there are errors and no errors in the beacon node.

Fig. 5. Use unknown nodes positioning when neighbor nodes exist (a) and don't use unknown nodes positioning when neighbor nodes exist (b). The figures depict how to find the neighbor nodes.

Fig.6 The Improved Triangle Centroid Localization Algorithm. This figure shows the distribution of all nodes.

Fig. 7 The comparison of the Localization Error (a) and Response Time(b). The figure (a) describe the relationship between communication distance and localization error, the figure (b) the relationship between response time and communication distance.

Fig. 8. The Schematic Diagram of the Test Scenario. This figure shows the test area and the location of the experimental nodes.

Figures

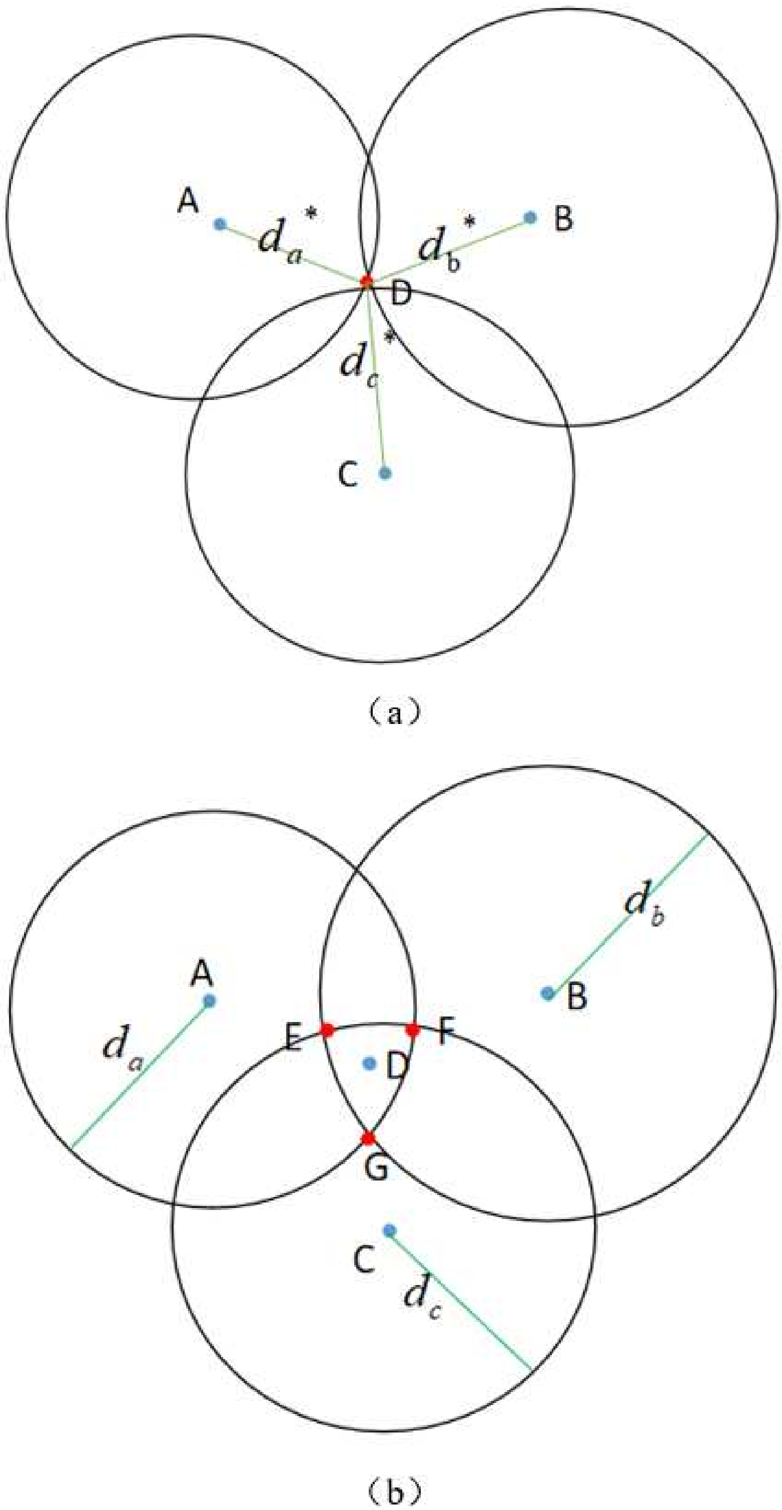


Figure 1

Ideal model (a) and actual model (b). Thess figures depict how to calculate the distance between the beacon node and the unknown node under ideal model and actual model.

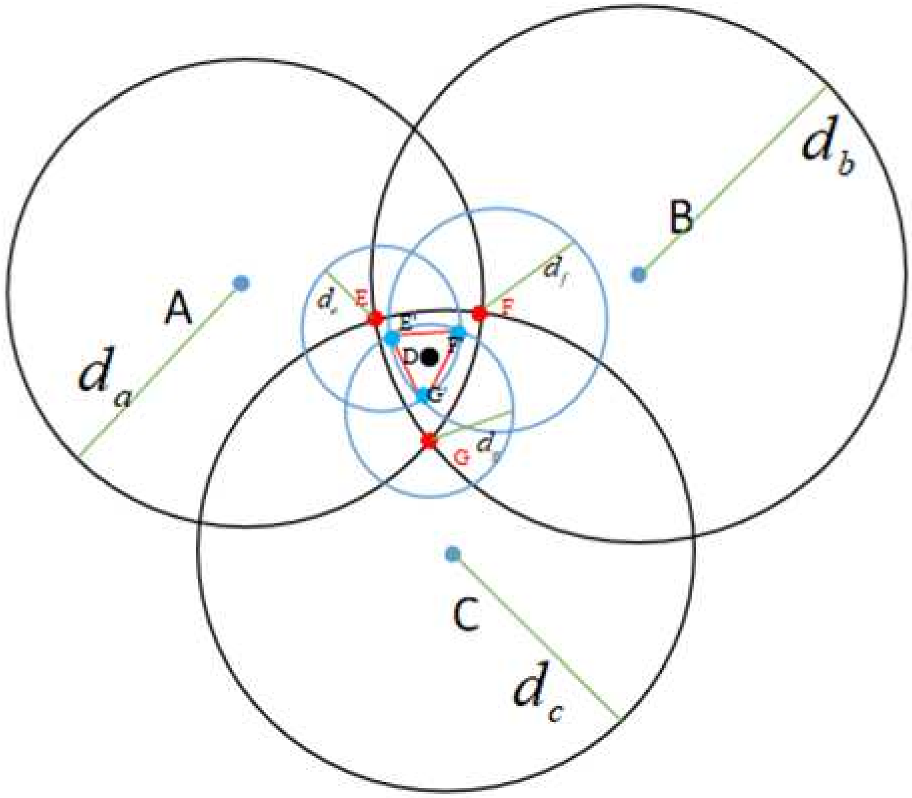


Figure 2

Improved triangle centroid localization algorithm model. This figure shows how to calculate the coordinate of the unknown node under the improved triangle centroid localization algorithm

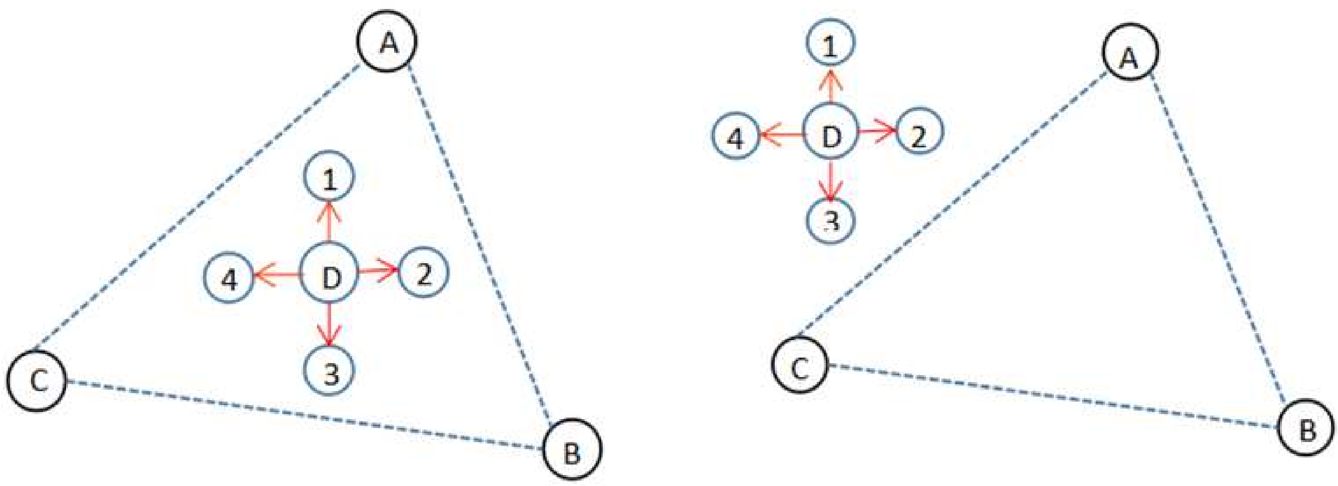
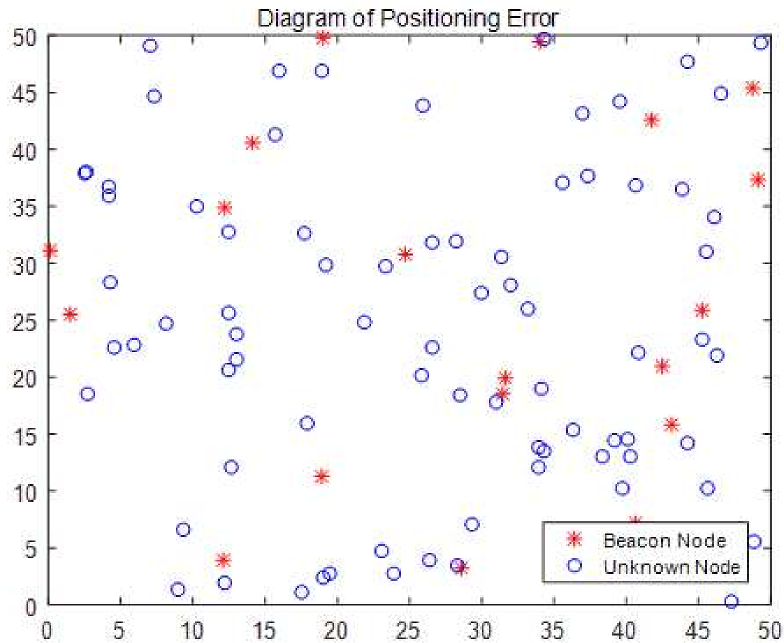
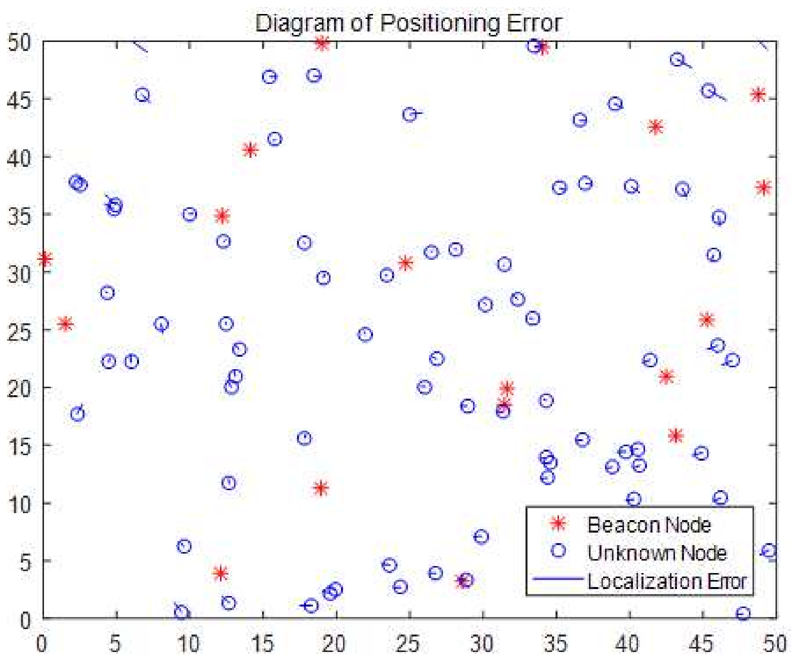


Figure 3

The schematic diagram of the PIT. This figure shows how to judge whether the node is inside the triangle



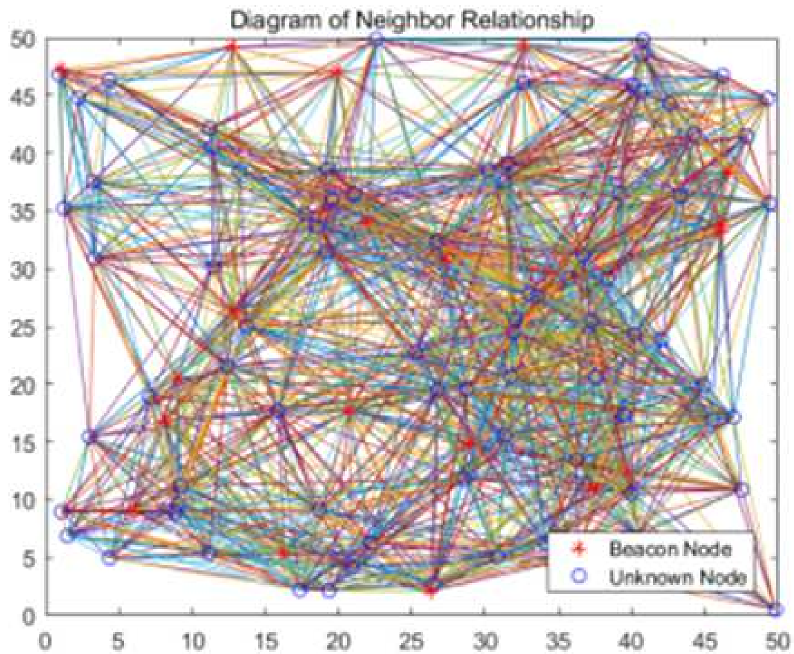
（a）



（b）

Figure 4

No Error in the Beacon Node (a) and 2m Error in the Beacon Node (b). These figures describe the situation when there are errors and no errors in the beacon node.



（a）

（b）

Figure 5

Use unknown nodes positioning when neighbor nodes exist (a) and don't use unknown nodes positioning when neighbor nodes exist (b). The figures depict how to find the neighbor nodes.

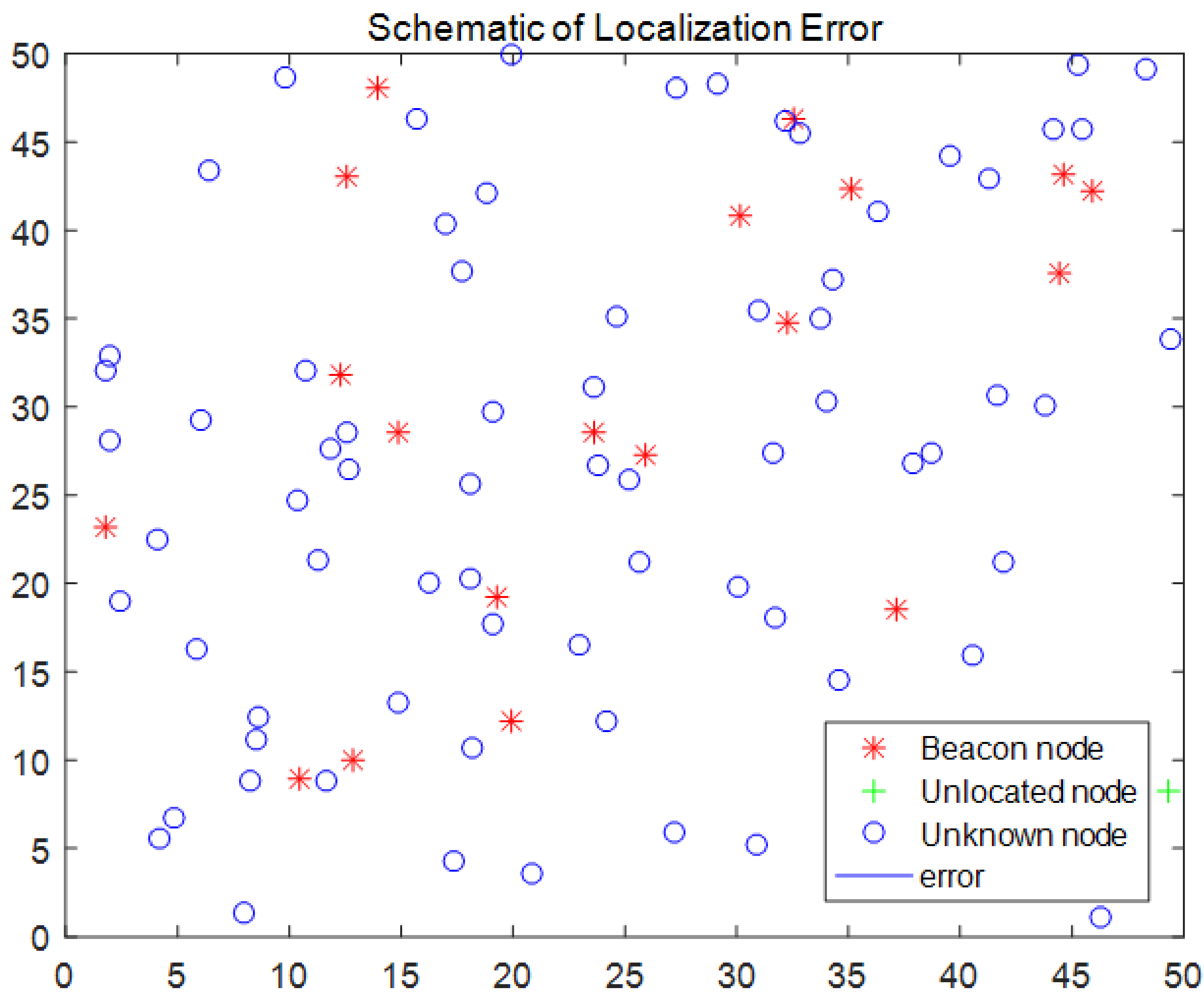


Figure 6

The Improved Triangle Centroid Localization Algorithm. This figure shows the distribution of all nodes

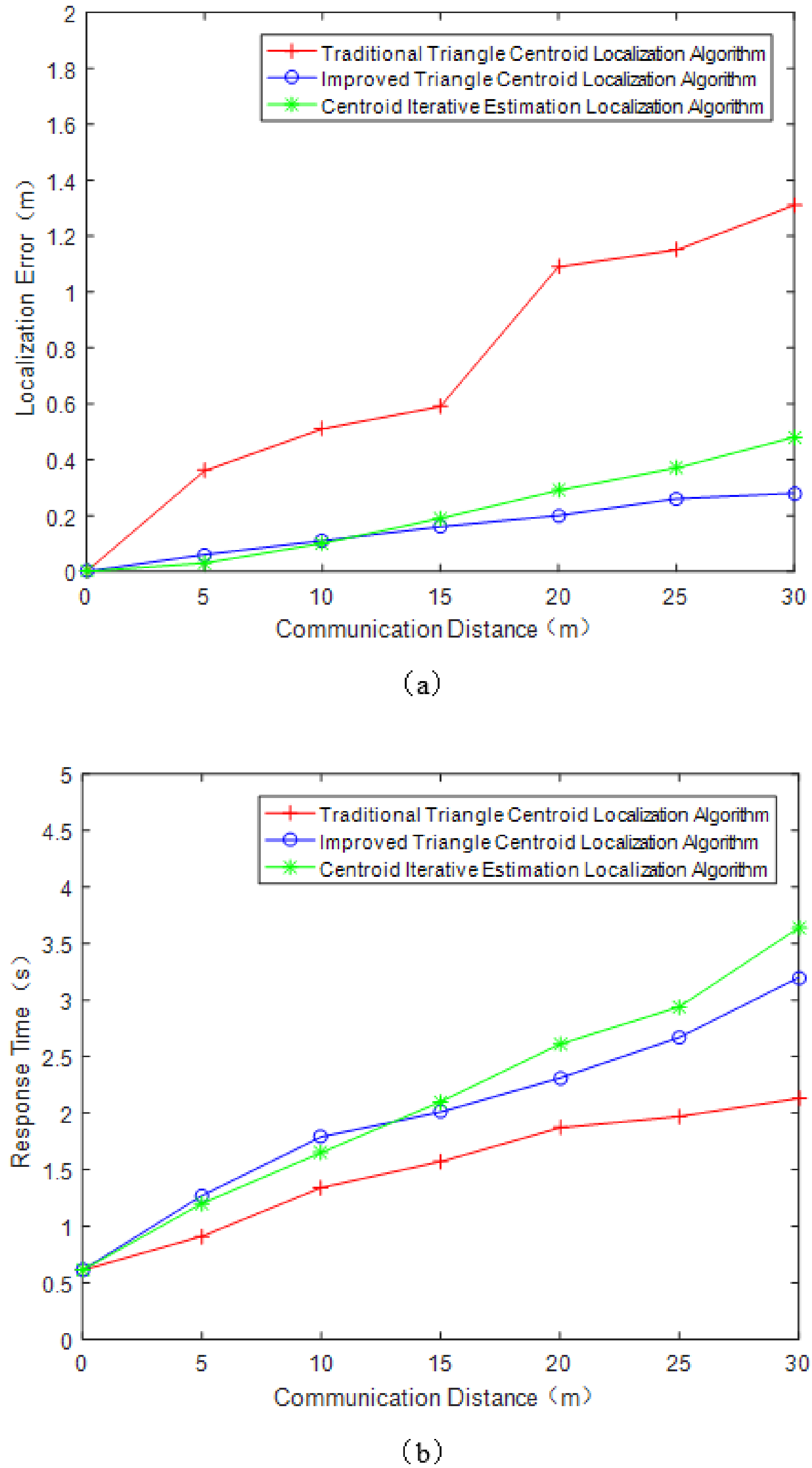


Figure 7

The comparison of the Localization Error (a) and Response Time(b). The figure (a) describe the relationship between communication distance and localization error, the figure (b) the relationship between response time and communication distance.

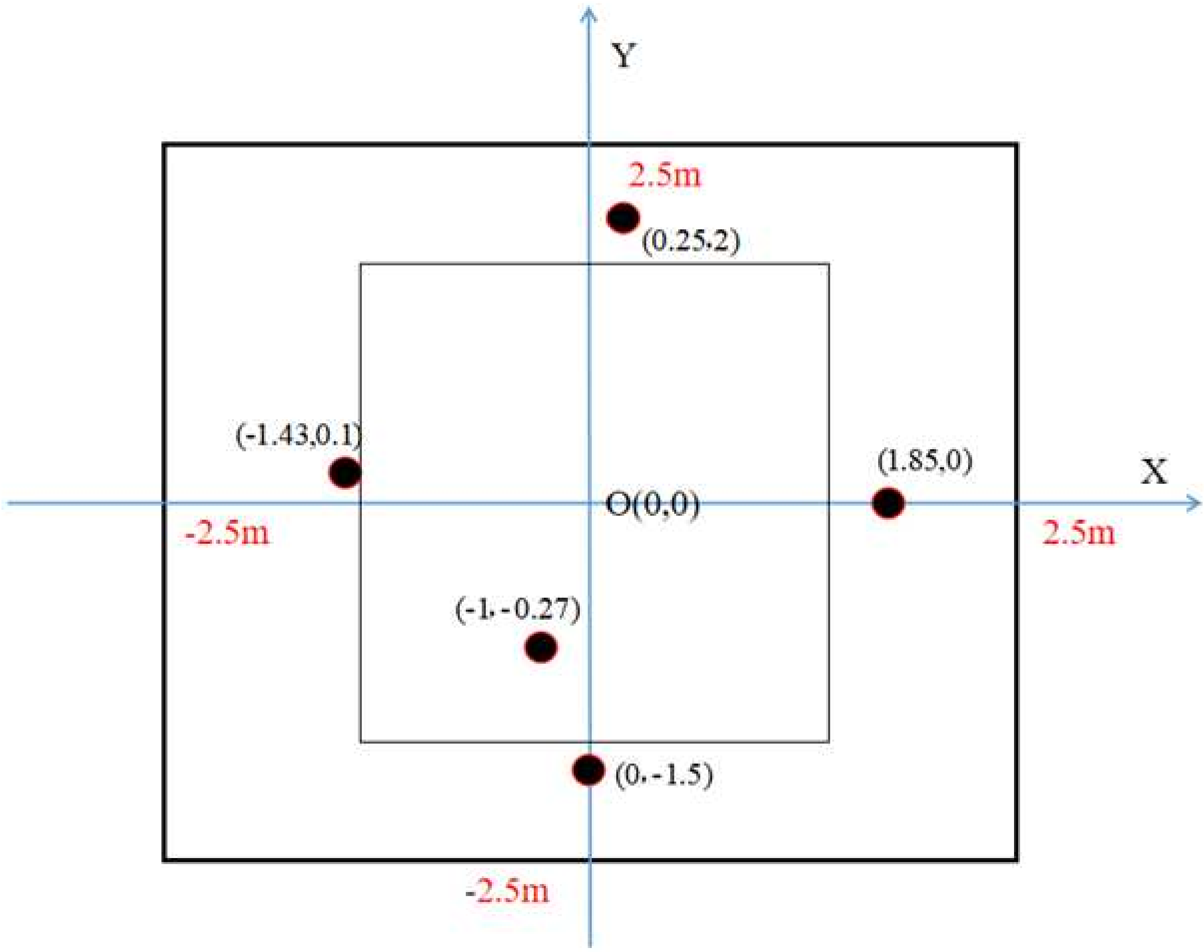


Figure 8

The Schematic Diagram of the Test Scenario. This figure shows the test area and the location of the experimental nodes.