

REVIEW

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New three-dimensional positioning algorithm through integrating TDOA and Newton's method

Junsuo Qu^{1*†}, Haonan Shi^{2†}, Ning Qiao², Chen Wu², Chang Su² and Abolfazl Razi³

Abstract

Passive time difference location is an important method for passive location. There are fuzzy positioning, no solution, and low positioning accuracy with the spherical coordinate conversion method in the four-station TDOA positioning algorithm. Focusing on these problems, we proposed a combination of TDOA and iterative Newton's method. The positioning method uses the result obtained by the four-station TDOA location algorithm as the initial value of the iterative Newton's method and solves the problem of no solution and fuzzy positioning caused by the four-station TDOA location algorithm by using the spherical coordinates conversion method. By simulating the target at a height of 5 km and traveling at a constant speed for 40 km, the positioning accuracy of the root mean square error is less than 45 m, which can achieve the same positioning accuracy of TDOA based on the least square algorithm. As the baseline length increases, the positioning accuracy is better than the least square algorithm.

Keywords: TDOA, Newton's method, Fuzzy positioning, Insoluble position

1 Introduction

Moving target positioning plays a very important role in military and civil applications. The research about related technology is considered as a hot topic in many fields. Time difference of arrival (TDOA) is a method of positioning by time difference, since the distance of the signal source can be determined by measuring the time it takes for the signal to arrive at the monitoring station [1]. The accurate location of the source can be determined by finding its distance from three or more monitoring stations [2]. It features high accuracy, strong anti-interference capability, and fast positioning. Thus, it is widely used in passive localization [3]. TDOA is the location of the radiation source by processing the measurement data collected by three or more stations. Three-dimensional positioning requires four stations to generate three pairs of hyperboloids, the surface intersection lines and the intersection

points to determine the location of the radiation source. However, it may not result in a unique solution. Fuzzy regions may be obtained due to uncertainty of regions [4], or the intersection may be null due to measurement noise and error [5].

Fuzzy positioning affects the positioning accuracy [6]. The traditional methods proposed for eliminating fuzzy positioning and addressing problems with no solutions can be divided into two main categories. One is to eliminate fuzzy positioning by adding auxiliary measurement devices. The second is solving problems with no solutions by assuming a fixed target location. The studies in [7] and [8] proposed the use of high-precision measuring instruments by combining two algorithms based on least squares and iterative Newton's method. The study in [9] proposed that the number of the base stations participating in the measurement calculation are the master stations in turn. This method was raised in earlier literature and has been further developed. Another method is to make information or parameters more effective without adding auxiliary information. The spherical coordinate's system

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conversion belongs to the second category. Using the conversion from Cartesian coordinates to spherical coordinates, we can obtain a function of the distance difference between the target and the main station as well as that of the main station to the other three stations. By substituting this function into the equation used for coordinate conversion, we can evaluate the coordinates of the target. The hybrid method combining TDOA and spherical coordinate's conversion performs better in terms of positioning accuracy than using spherical coordinate's conversion only. The angles between the auxiliary stations are used when solving the distance difference function. When the distance is long, a tiny angle difference can affect positioning accuracy. The simulation in [10] demonstrates the positioning accuracy based on the spherical coordinate conversion method when the target is far from the base stations. However, it does not include simulating the accuracy when positioning low-altitude targets and does not consider the effect of each auxiliary station's angle. Furthermore, it does not combine the parametric approach with the spherical coordinate conversion.

In view of the shortcomings of these methods, we propose a joint algorithm, which is based on a four-station TDOA positioning system and uses spherical coordinate transformation to eliminate positioning ambiguity and non-solution phenomena. The positioning result is then used as the initial value of the Newton iteration, and finally, a hybrid algorithm of iterative operations is performed. The feasibility and reliability of the method are proved by simulation and data analysis.

2 The analysis of fuzzy positioning and no solution

A passive TDOA location system processes the data from radiation source collected by measurement stations and estimates the time difference of arrival. In three-dimensional space, the time difference between two stations determines a hyperboloid with a pair of observatories as their focal points. The target needs at least three pairs of independent hyperboloid whose intersection defines the position, as such at least four base stations are required for positioning. For instance, the methods in [11] and [12, 13] used five and four base stations, respectively.

The TDOA positioning system consists of four base stations, we assume that the coordinate of the primary station is (x_0, y_0, z_0) , and the coordinates of each secondary station is $(x_i, y_i, z_i)_{i=1,2,3}$. As for four-station time difference positioning, assume that the spatial coordinate of the target is (x, y, z) , and the distance between the target and the primary station is r_0 , the distance between the target and each secondary station is $r_i (i = 1, 2, 3)$, and Δr_i is the distance from the target to the primary station and the secondary stations, c is the light propagation rate, and

$\Delta t_i (i = 1, 2, 3)$ is the time difference from the target to the primary station and the secondary stations. It follows that

$$\begin{cases} r_0 = \sqrt{(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2} \\ r_i = \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2} \\ \Delta r_i = r_i - r_0 = c \cdot \Delta t_i \end{cases} \quad (1)$$

The above equations can be rewritten as [8]

$$(x_0 - x_i)x + (y_0 - y_i)y + (z_0 - z_i)z = k_i + r_0 \cdot \Delta r_i \quad (2)$$

where

$$k_i = \frac{1}{2} [\Delta r_i^2 + (x_0^2 + y_0^2 + z_0^2) - (x_i^2 + y_i^2 + z_i^2)] \quad (3)$$

Equation (2) can be re-written in matrix form as follows:

$$AX = F \quad (4)$$

where

$$A = \begin{bmatrix} x_0 - x_1 & y_0 - y_1 & z_0 - z_1 \\ x_0 - x_2 & y_0 - y_2 & z_0 - z_2 \\ x_0 - x_3 & y_0 - y_3 & z_0 - z_3 \end{bmatrix} \quad (5)$$

$$X = [x, y, z]^T \quad (6)$$

$$F = \begin{bmatrix} k_1 + r_0 \cdot \Delta r_1 \\ k_2 + r_0 \cdot \Delta r_2 \\ k_3 + r_0 \cdot \Delta r_3 \end{bmatrix} \quad (7)$$

This TDOA-based localization system has three equations, but four unknowns x, y, z, r_0 . Suppose that r_0 is one known, when $rank(A) = 3$, the estimated value of the target position will be

$$\hat{X} = A^{-1} \cdot F \quad (8)$$

Set

$$A^{-1} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} = [a_{ij}]_{3 \times 3} \quad (9)$$

and the estimated position of the target would be

$$\begin{cases} \hat{x} = m_1 + n_1 \cdot r_0 \\ \hat{y} = m_2 + n_2 \cdot r_0 \\ \hat{z} = m_3 + n_3 \cdot r_0 \end{cases} \quad (10)$$

where

$$\begin{cases} m_i = \sum_{j=1}^3 a_{ij} \cdot k_j \\ n_i = \sum_{j=1}^3 a_{ij} \cdot \Delta r_j \end{cases} \quad (11)$$

Substitute (10) into (2), a quadratic equation where r_0 represents an unknown can be obtained using

$$a \cdot r_0^2 + 2b \cdot r_0 + c = 0 \quad (12)$$

where

$$\begin{cases} a = n_1^2 + n_2^2 + n_3^2 - 1 \\ b = (m_1 - x_0)n_1 + (m_2 - y_0)n_2 + (m_3 - z_0)n_3 \\ c = (m_1 - x_0)^2 + (m_2 - y_0)^2 + (m_3 - z_0)^2 \end{cases} \quad (13)$$

The three-dimensional coordinates of the target can be obtained by solving (12). When $\Delta = b^2 - ac = 0$, Eq. (12) has a unique solution. When $\Delta = b^2 - ac > 0$ or $\Delta = b^2 - ac < 0$, Eq. (12) yields respectively a fuzzy position or no solution. To eliminate fuzzy positioning, other measurement information or prior information from the radiation sources is needed. Typically, no method solves the equations by assuming that the target height is known [14]. In this paper, both cases of fuzzy positioning and no solution are addressed by using the spherical coordinate conversion.

3 Using spherical coordinate conversion to eliminate fuzziness and no solution

Figure 1 demonstrates conversion between the spherical and Cartesian coordinate systems. In Fig. 1, M is the aerial target; O is the main station; and $A, B,$ and C are the three auxiliary base stations. θ is the angle between station B and the x -axis, and α and β denote the pitch and azimuth angles, respectively. Assume that φ_1 and φ_2 are the angles between $A, B,$ and $C,$ respectively. The length between the main station O and $A, B,$ and C is denoted respectively by $L_1, L_2,$ and L_3 . In this figure, OM and $MB,$ respectively, r_0 and Δt_2 in Equi(X-Y). According to the spherical coordinate interpolation method for $\Delta MOB,$ we have

$$(r_0 - \Delta r_2)^2 = r_0^2 + L_2^2 - 2r_0L_2 \cos(\beta - \theta) \cos \alpha \quad (14)$$

After simplification, it converts to

$$r_0L_2 \cos(\beta - \theta) \cos \alpha - r_0\Delta r_2 = \frac{1}{2} (L_2^2 - \Delta r_2^2) \quad (15)$$

Similarly, applying the same equation to ΔMOA and $\Delta MOC,$ it follows that

$$\begin{cases} r_0L_3 \cos(\beta - \theta - \varphi_2) \cos \alpha - r_0\Delta r_3 = \frac{1}{2} (L_3^2 - \Delta r_3^2) \\ r_0L_2 \cos(\beta - \theta) \cos \alpha - r_0\Delta r_2 = \frac{1}{2} (L_2^2 - \Delta r_2^2) \\ r_0L_1 \cos(\beta - \theta - \varphi_1) \cos \alpha - r_0\Delta r_1 = \frac{1}{2} (L_1^2 - \Delta r_1^2) \end{cases} \quad (16)$$

If we set

$$L_1 = L_2 = L_3 = L, k_i = \frac{1}{2} (L_i^2 - \Delta r_i^2), i = 1, 2, 3 \quad (17)$$

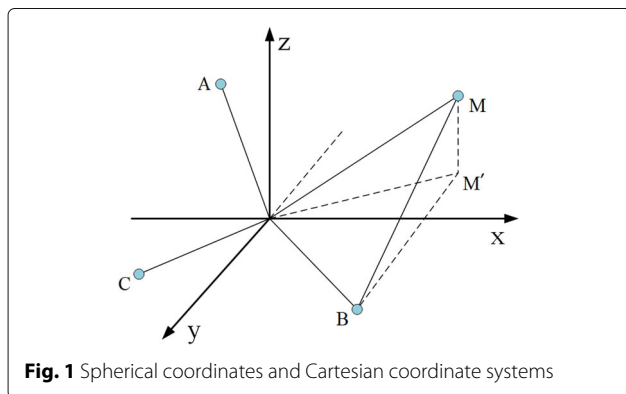


Fig. 1 Spherical coordinates and Cartesian coordinate systems

then we obtain

$$r_0 = \frac{k_2 \sin \varphi_2 - k_3 \sin \varphi_1 - k_1 \sin(\varphi_2 - \varphi_1)}{\Delta r_1 \sin(\varphi_2 - \varphi_1) - \Delta r_2 \sin \varphi_2 + \Delta r_3 \sin \varphi_1} \quad (18)$$

3.1 A Eliminating fuzzy positioning

Addressing the fuzzy positioning and no-solution cases for four-station TDOA positioning system has been a major concern. Fuzzy positioning is due to obtaining multiple values for underdetermined positioning equations when the rank of A is below 3, and the no-solution case is for over determined and inconsistent equations when the rank of A is above 3. Using spherical coordinate conversion, fuzzy positioning can be eliminated by integrating (18) and four-station TDOA location equations, as follows

$$\begin{cases} r_i = \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2} \\ \Delta r_i = r_i - r_0 = c \cdot \Delta t_i \\ r_0 = \frac{k_2 \sin \varphi_2 - k_3 \sin \varphi_1 - k_1 \sin(\varphi_2 - \varphi_1)}{\Delta r_1 \sin(\varphi_2 - \varphi_1) - \Delta r_2 \sin \varphi_2 + \Delta r_3 \sin \varphi_1} \end{cases} \quad (19)$$

By solving this equation set, fuzzy positioning can be eliminated and the target value can be obtained with no ambiguity.

3.2 B Eliminating the no-solution case

After knowing the value of r_0 , the distance between the target and the main base station, we can use conversion between the spherical and Cartesian coordinates to obtain

$$\begin{cases} x' = r_0 \cos \varphi \cos \alpha \\ y' = r_0 \sin \varphi \cos \alpha \end{cases} \quad (20)$$

and by the rotation of coordinates, we locate the target as

$$\begin{cases} x = x' \cos \theta - y' \sin \theta \\ y = x' \sin \theta + y' \cos \theta \end{cases} \quad (21)$$

It is easy to obtain the value of z by equation

$$z = \sqrt{r_0^2 - x^2 - y^2} \quad (22)$$

The no-solution case is due to the inconsistency of the equation set itself. It can be eliminated by substituting (4) into (20), (21), and (22) to obtain the estimated target value.

From the above process, we know that if the time difference between the target to the master station and to the secondary stations is known, we can obtain the relation between time difference and r_0 and then calculate the three-dimensional coordinates of the target directly using the spherical coordinates conversion method [15]. To tackle different base station layouts, we only need to adjust different baseline lengths and angles between the base stations.

4 Spherical coordinate conversion and layout of stations

TDOA localization and the spherical coordinate’s conversion allow for adjusting the angles and baseline lengths between the base stations. However, the layout mode will also change correspondingly which impacts the positioning accuracy [16, 17].

Suppose that the time error of each base station is 10 ns, each baseline length is 50 km, and the site measurement error is 2 m, correlation coefficient of the time measurement error and the flattened measurement error is 0.3, and the positioning height is 10 km. In this positioning system, we set the main station as the original point. We can simulate the positioning accuracy in star and triangular layouts. Simulation results are shown in Fig. 2.

From Fig. 2, the positioning accuracy of the star layout outperforms that of the triangular layout by 30%. With the star layout, the closer the target and main station, the higher the location accuracy, hence the motion path will be circle alike. On the other hand, with triangular layout, if the positioning accuracy distribution is stronger, the target will be closer to the x -axis and the positioning accuracy will be higher. Therefore, when we use spherical coordinate system, the star layout can play a better role in positioning accuracy [18]. Although changing the angle between the base stations can enable us to locate the target, positioning accuracy will be far better when they are arranged in a star way.

5 Newton’s method

After solving the fuzzy positioning and the no-solution cases and analyzing how positioning accuracy is affected by different station layouts, we can consider the estimated value as the initial value and use the Newton’s iterative

algorithm to enhance the results. Newton’s method is an algorithm that uses gradient of a function similar to the gradient descent algorithm to iteratively solve optimization problems. It has been proven to converge faster than the gradient descent for many cases [19]. We start with an initial value and then start the iterative estimation until we get a solution satisfying certain estimation criteria. The closer the initial value to the true value, the better the convergence of this algorithm [20]. Therefore, it is significant to select an appropriate initial value to ensure an acceptable convergence rate. According to the conditions of Newton’s algorithm, the established mode of target positioning system is converted into

$$f_i(x, y, z) = \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2} - \sqrt{(x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2} - c\Delta t_i \tag{23}$$

and its Jacobian matrix is

$$f'(x, y, z) = \begin{bmatrix} \frac{\partial f_1}{\partial x} & \frac{\partial f_1}{\partial y} & \frac{\partial f_1}{\partial z} \\ \frac{\partial f_2}{\partial x} & \frac{\partial f_2}{\partial y} & \frac{\partial f_2}{\partial z} \\ \frac{\partial f_3}{\partial x} & \frac{\partial f_3}{\partial y} & \frac{\partial f_3}{\partial z} \end{bmatrix} = \begin{bmatrix} A_{11}A_{12}A_{13} \\ A_{21}A_{22}A_{23} \\ A_{31}A_{32}A_{33} \end{bmatrix} \tag{24}$$

When the Jacobian matrix is non-singular, the target position can be expressed as

$$\begin{bmatrix} x^{k+1} \\ y^{k+1} \\ z^{k+1} \end{bmatrix} = \begin{bmatrix} x^k \\ y^k \\ z^k \end{bmatrix} - f_i(x, y, z)^{-1} \begin{bmatrix} f_1(x^k, y^k, z^k) \\ f_2(x^k, y^k, z^k) \\ f_3(x^k, y^k, z^k) \end{bmatrix} \tag{25}$$

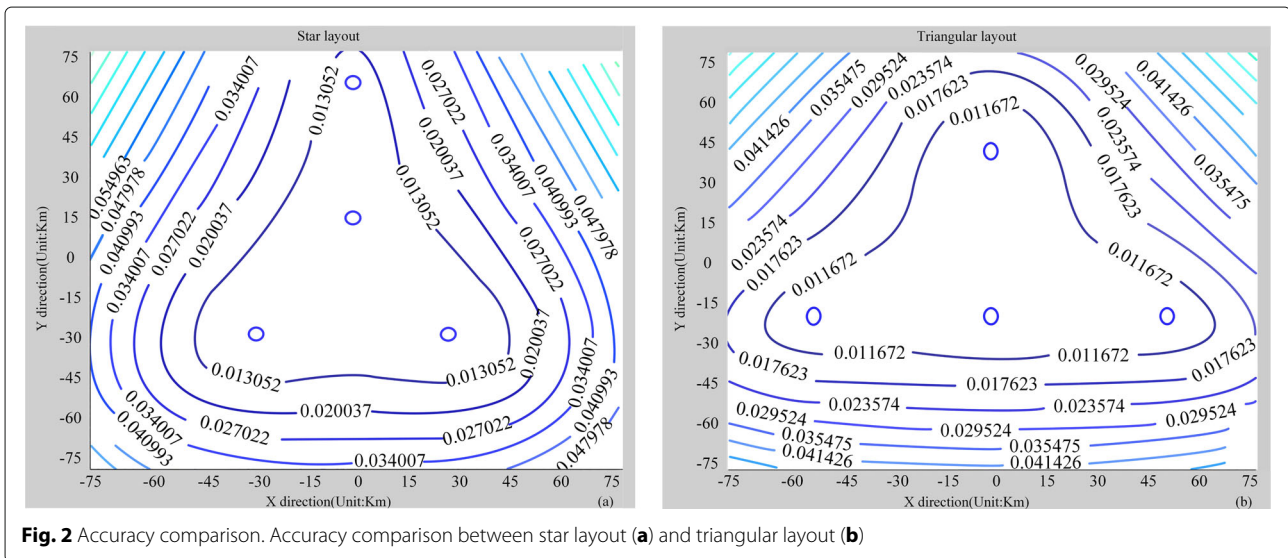
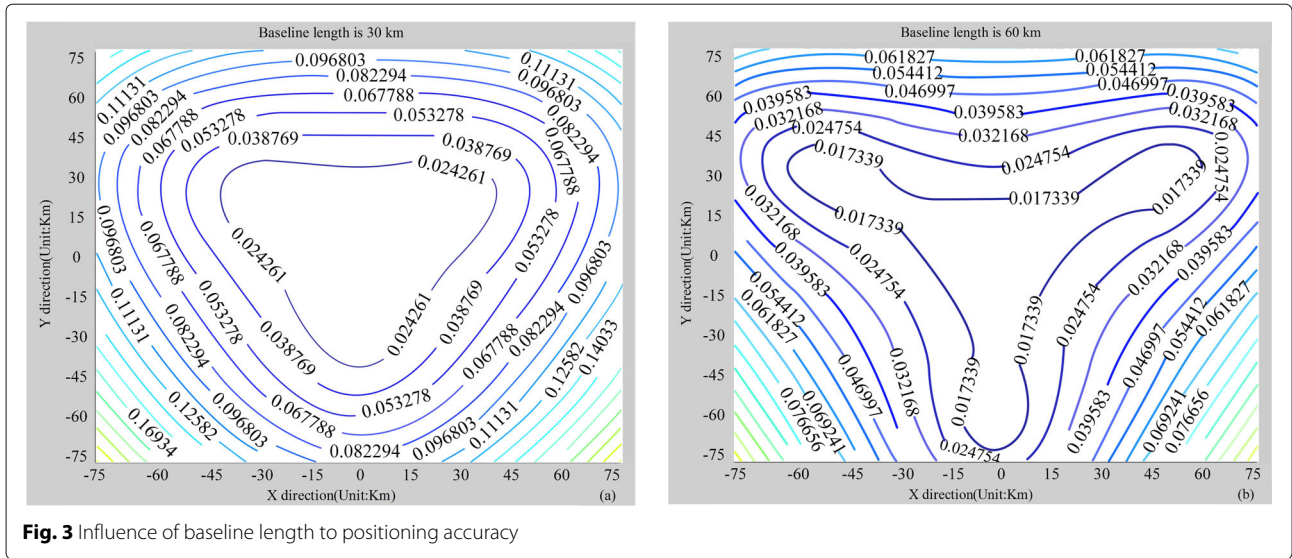


Fig. 2 Accuracy comparison. Accuracy comparison between star layout (a) and triangular layout (b)

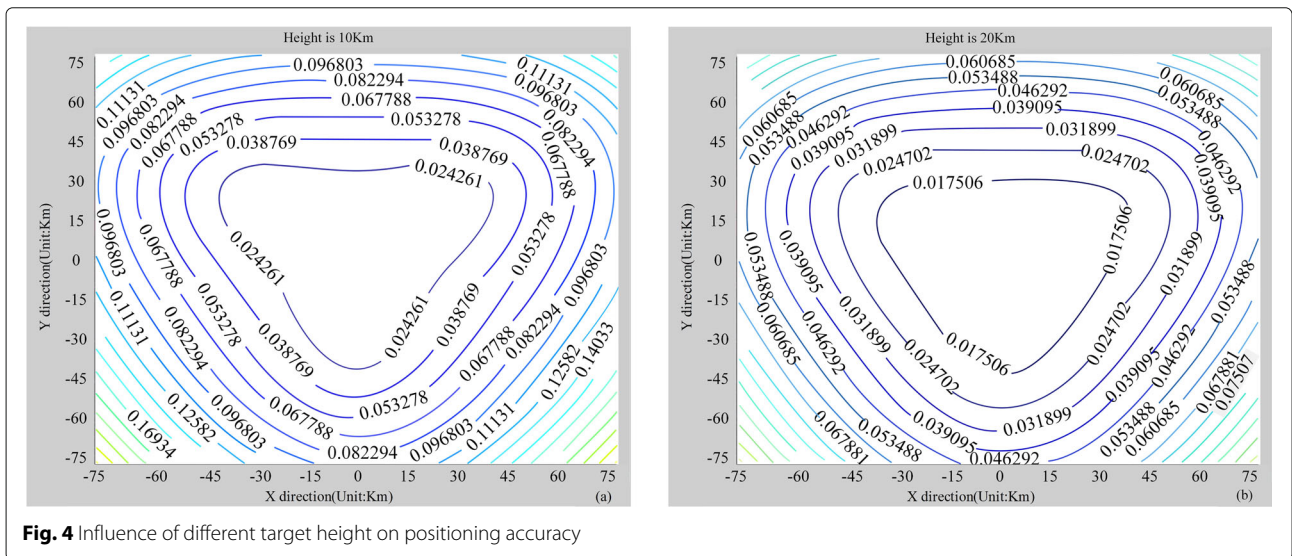


6 Numerical analysis of the proposed algorithm

When we use passive positioning system to locate a target in the air, the layout of its base stations has a considerable impact on the positioning accuracy [21]. As reported in the literature (e.g., [22]), when the target's flight direction or trend remains uncertain, the star-shaped layout will yield a more accurate position. Next, we simulate the factors that influence the positioning accuracy under star layout. We set the time error of base station is 10 ns and the site measurement error is 6 m, the correlation coefficient of the time error and the flattened measurement error is 0.1. Firstly, we verify the impact of the baseline length to positioning accuracy. We set the target height is 8 km and set the baseline lengths as 30 km and 60 km, respectively. Figure 3 shows that the smaller

baseline length, the lower positioning accuracy. However, in a real environment, the baseline length cannot be too long because of geographical environment and communication between base stations. Then, we verify the impact of targets at different heights on positioning accuracy. We set the baseline length as 30 km and set the target heights as 10 km and 20 km, respectively. Figure 4 shows that the lower height, the lower positioning accuracy. Under the star layout, the target height is set to 20 km, and the positioning accuracy curve is distributed with an ellipsoidal isoline with the main station as the center point.

Finally, we verify the influence of the height of the base station on the positioning accuracy. We set the distance between the base stations as 30 km and set the height of the base stations as 0.1 km and 0.3 km, respectively.



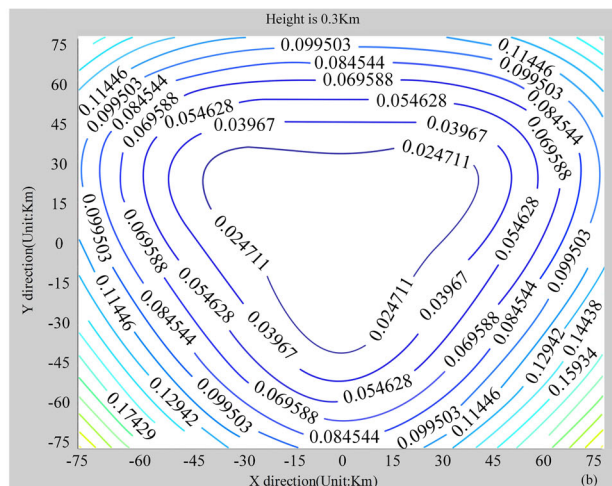
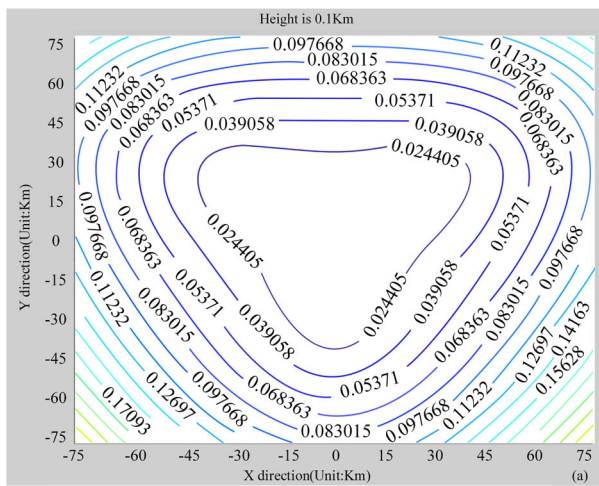


Fig. 5 Influence of the height of the base station on positioning accuracy

According to Fig. 5, when the height between stations decreases, the positioning accuracy will increase. Compared with Figs. 3 and 4, it shows that changing the baseline length and the height of the target has a greater impact on positioning accuracy than changing the height of the base station. According to the simulation, it can be observed that the farther the target is from the main station in the measurement range, the lower the positioning accuracy is. The positioning accuracy curve can be approximated as an equivalent circle centered on the master station after several simulation shows. So it meets the basic requirements of positioning accuracy. Therefore, the star layout is the best choice after taking all the abovementioned elements into consideration.

When simulating the target positioning system, we set the coordinates of main stations $O, A, B,$ and C as $(0,$

$0, 0), (26, 15, 0), (-26, 15, 0),$ and $(0, 30, 0),$ respectively. The unit is kilometer, the time measurement error is set to 10 ns, the angle between the base stations is $\varphi_1 = \varphi_2 = 120^\circ,$ and the baseline length is $L = L_1 = L_2 = L_3 = 30$ km. As shown in Fig. 6, the target keeps uniform rectilinear motion at altitude 5 km above the $x-y$ plane (MN is the motion path). We average over one hundred execution of the algorithms with different initialization and analyze the root mean square error of the target path to test the performance of the proposed hybrid algorithm. The analysis result is shown in Fig. 7. The minimum error is 5 m when the sampling sequence is between 40 and 70, which shows that the algorithm can effectively improve the three-dimensional positioning accuracy of the four-station TDOA positioning system. And the maximum positioning error is less

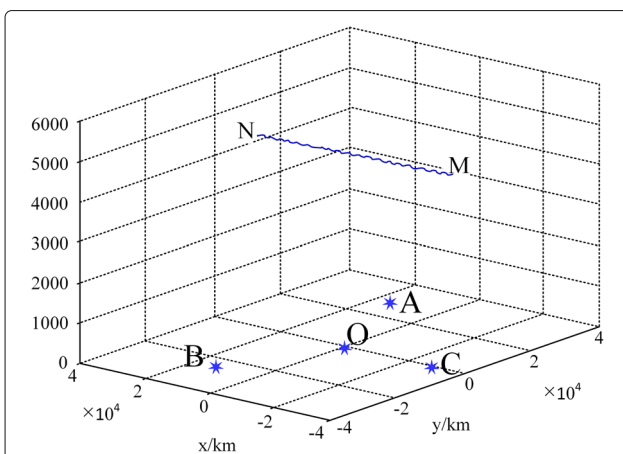


Fig. 6 Motion path of the target

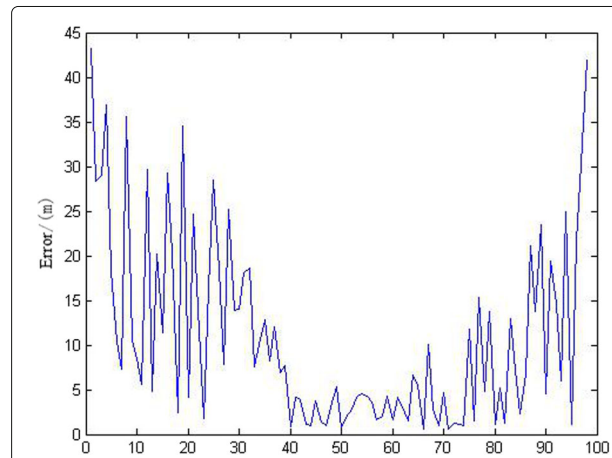


Fig. 7 Analysis of root mean square error simulation

Table 1 Accuracy comparison between the two location algorithms

Target's exact coordinates	The least square algorithm			Conversion algorithm based on spherical coordinates		
	X-axis error	Y-axis error	Z-axis error	X-axis error	Y-axis error	Z-axis error
[− 116, − 62, 8]	− 0.1857	− 0.1016	− 0.1424	− 0.1009	− 0.0470	0.0326
[50, 28, 8]	0.0137	0.0073	0.0799	0.0153	0.0110	0.0195
[200, 180, 30]	0.5151	0.4794	0.3249	0.3793	0.3567	0.0043
[100, 181, 10]	0.2055	0.4137	0.2259	0.1854	0.3341	− 0.1986
[− 150, 200, 5]	0.2663	− 0.3826	− 0.4472	− 0.1494	0.1948	0.4513
[100, 120, 100]	0.1280	0.1665	0.1706	0.0993	0.1232	0.0962
[160, 140, 50]	0.3118	0.2836	0.1989	0.2291	0.2117	0.0584
[50, 50, 100]	0.0097	0.0116	0.0438	0.0242	0.0254	0.0513
[30, 30, 1]	0.0051	0.0070	0.4102	0.0085	0.0103	0.0253
[50, 50, 10]	0.0192	0.0230	0.0555	0.0262	0.0298	0.0028
[60, 40, 3]	0.0273	0.0189	0.2414	0.0248	0.0201	0.0370

than 45 m, which is acceptable in most engineering applications.

To further evaluate the performance of this algorithm, we compare it against the least square method through simulation in different areas by measuring errors and accuracy. Results in Table 1 show that the proposed hybrid algorithm achieves the same location accuracy of TDOA algorithm based on the least squares method. (i) The least square algorithm can obtain the coordinates of the target by operating weighted least square method twice. It features high accuracy and low calculation complexity when the noise obeys the Gauss distribution. The least squares method requires at least five base stations and is subject to time difference measurement error. (ii) The z-axis location accuracy of the proposed hybrid algorithm is always higher than that of the least squares algorithm. (iii) When the distance between the target and the base stations becomes larger, the location accuracy of our algorithm will be better than that of the least square algorithm.

7 Conclusion

In this paper, we propose a joint algorithm that can achieve high-precision positioning of TDOA and fast convergence of Newton's method. After the algorithm is integrated with the spherical coordinate transformation method, it can improve the fuzzy positioning and the inconsistent positioning equations, so that it can be used for low-altitude target positioning. Compared with least square method and Newton's method, the positioning accuracy has been significantly improved, especially the z-axis, and the proposed method is better than the others. The results further indicating the algorithm can effectively improve the three-dimensional positioning accuracy of the four-station TDOA positioning system. The positioning results are more precise even if the long distance between the target and the base stations, and

the positioning accuracy achieved within 45 m, which provides a suitable solution for engineering applications. Different layouts of the base stations will affect the positioning accuracy, and the positioning effect reaches the best effect when the system is a star-shaped station. For more complex scenarios in the future, we can further analyze the influence factors of the positioning algorithm. The positioning accuracy is not only related to the spatial position of the target and each base station, but also affected by factors such as the location of the reconnaissance station, the geographical location of the positioning base station, and the time difference measurement error and base station position measurement error. With the involvement of a large number of IoT devices in the future, there will be higher requirements for the real-time and reliability of target positioning accuracy, which is also an important direction for future research.

Abbreviations

TDOA: Time difference of arrival

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Authors' contributions

QJS, SHN, QN, WC, and SC carried out all research steps including finding the problem, analyzing the related works, and finding, implementing, and simulating the proposed method as well as writing the manuscript. AR has contributed in analyzing the data and editing the paper. All authors read and approved the final manuscript.

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Availability of data and materials

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Competing interests

The authors declare that they have no competing interests.

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