A KFL-TDOA UWB Positioning Method Based on Hybrid Location Algorithm

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Abstract. For the improvement of accuracy and efficiency of indoor positioning in complex environment, this paper proposed a new positioning method, which combined Ultra-Wide Band (UWB) based on time difference of arrival (TDOA) with linearized Kalman filters (KFL-TDOA), in order to obtain more accurate and stable positioning results. On this basis, two classic location algorithms, Chan and Taylor series expansion algorithm, were integrated to get lower Root Mean Square Error (RMSE) and better anti-interference performance under non-sight-of-light (NLOS) and multipath effect, compared with using them separately. The proposed method considered interference both in ranging phase and positioning phase caused by complex indoor environment. Simulation case studies were conducted to demonstrate how the proposed method was implemented and the simulation results showed that compared with traditional TDOA based positioning method, the proposed method has improvement in positioning accuracy and stability both in ideal environment and interference environment if the parameters were set reasonable.

Keywords: UWB indoor positioning · Kalman filtering · TDOA · Chan algorithm · Taylor series expansion algorithm

1 Introduction

Global Positioning System (GPS) is the most widely used positioning method in outdoor positioning, however, due to the blocking of buildings, especially multiple walls, satellite signals cannot piece through indoors, which leads to the development of indoor positioning [1]. In recent years, there is a wide range of needs for indoor positioning in various areas, including security, smart cities, medical, factories and so on. Currently, popular indoor positioning technology includes WiFi, Bluetooth, UWB and so on [2]. Among them, UWB positioning has its advantage of high accuracy and anti-interference because of its strong signal penetration and wide bandwidth, however under an environment with serious interference, the performance of positioning will still be greatly affected [3].

Compared with outdoor environment, the indoor environment is more complex. Obstacles and walls will reflect or even block the transmission of the positioning signal results in NLOS and multipath effect, which will reduce the accuracy of position results. At present, TDOA is the most extensive technology in wireless location system,

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on the basis of base station clock synchronization, the main error comes from the weaken of signal [4]. Traditional TDOA based location algorithm such as Chan algorithm and Taylor expansion algorithm and so on, only when the measurement error obeys zero mean Gaussian distribution can these algorithms have high precisions [5]. [6, 7] propose a hybrid location algorithm based on Chan and Taylor series expansion, however, in a real indoor environment, NLOS errors and multipath effects are often unavoidable, the simulation conditions is too ideal to reflect real systems.

Aiming at proposing a high-precision positioning algorithm that is practical to the actual environment, and improving the stability to external disturbances, this paper comes up with a TDOA based UWB indoor positioning method combined with Kalman filtering, using a hybrid location of Chan and Taylor expansion algorithm. The method considers noises in both the measurement phase and the positioning phase with its advantages of high stability and accuracy. To verify the algorithm, we build a UWB positioning system of 4 anchors with a target doing linear motion. Since measurement error exists during the process of mobile station (MS) and base station (BS) ranging, Kalman filtering is used to filter out mutation measurement data and fluctuation noise. To have a stable performance, we combine the Chan algorithm with Taylor series expansion algorithm. The simulation results shows that compared with traditional positioning method, the RMSE lows and the positioning performance in strong interference improves significantly.

The rest of paper is organized as follows: Sect. 2 gives a basic description of TDOA based UWB Positioning Theory. The KFL-TDOA positioning method is given in Sect. 3. Section 4 elaborates the hybrid positioning algorithm. Field evaluation on both positioning accuracy and precision are presented in Sect. 5 in the form of MATLAB simulation results. The paper is briefly summarized in Sect. 6.

2 TDOA Based UWB Positioning Principle

The TDOA principle determined the target coordinates by computing the difference in propagation time of a signal from a MS to a BS. Each time propagation difference corresponding to a distance difference, so that a hyperbolic equation with the focus of two corresponding BSs can be obtained. In order to get the position of the MS, at least two sets of TDOA differences should be measured, which means at least three BSs are needed. The intersection of the two hyperbolars is the estimated position of the target [8]. [9] presents that the position accuracy increases as the number of BSs increases. Let (x, y) be the unknown MS position, and (X_i, Y_i) be the position of different BSs. The distance between MS and BSi R_i is given by:

$$R_i = \sqrt{(X_i - x)^2 + (Y_i - y)^2} \tag{1}$$

The distance difference refer to BS1 is given by:

$$R_{i,1} = c\tau_{i,1} = R_i - R_1 \tag{2}$$

where c is the speed of light, $\tau_{i,1}$ is the TDOA value.

A variety of positioning algorithms are based on the study of the speciality of TDOA hyperbolic equations. Figure 1 shows the basic principles of TDOA.

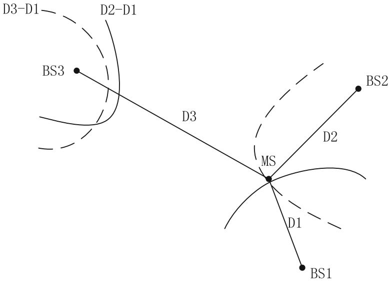

Fig. 1. TDOA positioning schematic

Current mainstream positioning methods based on TDOA principle, such as Chan algorithm, Taylor series expansion algorithm can have high precision only under low interference environment. In practical systems, noise and measurement errors is unavoidable, on the aim of targeting an algorithm which performs well in harsh environment, this paper use Kalman filter to reduce measurement error caused by noise.

3 KFL-TDOA Positioning Method

The real indoor environment is normally complex and full of noise and interference, which will cause the loss of positioning precision. Kalman filtering is used in this paper to restore the state of the real system from measurement noise, making this positioning method practical.

It is assumption that UWB indoor positioning's motion mode is linear. We set the state vectors as follows:

$$X_K = (x_k, y_k, v_k)^T \tag{3}$$

The fundamental equations of Kalman filtering include state equation and observation equation. The following state transition equations can be established:

$$\begin{bmatrix} x_k \\ y_k \\ v_k \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1 \\ 1 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_{k-1} \\ y_{k-1} \\ v_{k-1} \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} w_{x/k-1} \\ w_{y/k-1} \end{bmatrix} \tag{4}$$

where $w_{x/k-1}$ and $w_{y/k-1}$ are the process noise in x and y directions respectively, the standard form of Kalman filter prediction equation is given as follows:

$$X_{k+1/k} = A_{k+1}X_{k/k} + W_{k+1} \tag{5}$$

$$P_{k+1/k} = A_{k+1}P_{k/k}A_{k+1}^{T} + Q_w \tag{6}$$

where $X_{k+1/k}$ is the predicted state estimate; $P_{k+1/k}$ is the predicted estimate covariance; Q_w is the covariance matrix of process noise, in this paper, we take $Q_w = \begin{bmatrix} 10 & 0 & 0 \\ 0 & 10 & 0 \\ 0 & 0 & 20 \end{bmatrix}$; $A_{k+1} = \begin{bmatrix} 1 & 0 & 1 \\ 1 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$ is the state transition model which means in the ideal state, the motion form is a uniform linear motion in the direction of 45°; $W_{k+1} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} w_{x/k-1} \\ w_{y/k-1} \end{bmatrix}$ is the process noise.

The formulas in the update phase of KFL-TDOA UWB method is:

$$K_{k+1} = P_{k+1/k}H_{k+1}^{T}(H_{k+1}P_{k+1}H_{k+1}^{T} + R_k) \tag{7}$$

$$X_{k+1/k+1} = X_{k+1/k} + K_{k+1}(Z_{k+1} - H_{k+1}X_{k+1/k}) \tag{8}$$

$$P_{k+1/k+1} = (I - K_{k+1}H_{k+1})P_{k+1/k} \tag{9}$$

where K is the Kalman gain; $X_{k+1/k+1}$ is updated state estimate; $P_{k+1/k+1}$ is updated estimate covariance; R_k is covariance matrix observation noise; $H = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}$ is the observation model.

The KFL-TDOA UWB positioning method executes the formulas in every loop, simulation results shows that under harsh environment the output data is stable and smooth, effectively reduces the impact of measurement errors and noise.

4 Hybrid Positioning Algorithm

Currently, two classical positioning algorithms based on TDOA equations are being widely used, one is Chan algorithm, the other is Taylor series expansion algorithm. These two algorithms have different characteristics, Chan algorithm has low complexity, only need two iterations can it derive the target position and the result does not depend on the selection of the initial value [10]. Taylor series expansion algorithm has a higher positioning accuracy, but depends on the selection of the initial value. In previous literature, the two algorithms are integrated on the aim of obtaining respective advantages. Use Chan algorithm to obtain initial coordinates, then use Taylor series expansion algorithm to iterates the final positioning results.

The Chan algorithm has two iterations, by linearizing the TDOA equations, past work has proved that take R_1 as unknown, the equation can be transformed into linear equations on x, y and $R = \sqrt{x^2 + y^2}$. When the number of BSs is larger than 4, the first estimated position is given as:

$$Z_a \approx (G_a^T Q^{-1} G_a)^{-1} G_a^T Q^{-1} h \tag{10}$$

where

$$G_a = -\begin{bmatrix} x_{2,1} & y_{2,1} & R_{2,1} \\ x_{3,1} & y_{3,1} & R_{3,1} \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ x_{m,1} & y_{m,1} & R_{m,1} \end{bmatrix}; \; h = \frac{1}{2}\begin{bmatrix} R_{2,1}^2 - x_2^2 - y_2^2 + x_1^2 + y_1^2 \\ R_{3,1}^2 - x_3^2 - y_3^2 + x_1^2 + y_1^2 \\ \cdot \\ \cdot \\ \cdot \\ R_{m,1}^2 - x_m^2 - y_m^2 + x_1^2 + y_1^2 \end{bmatrix}$$

Q is the covariance matrix of TDOA, (x_i, y_i) is the i-th BS's coordinates, $(x_{i,1}, y_{i,1})$ is the difference of the i-th BS and the first BS, $R_{i,1}$ is MS to the distance difference between the i-th and the first BS. The second estimated position is given as:

$$Z_a' = (G_a'^T \varphi'^{-1} G_a')^{-1} G_a'^T \varphi'^{-1} h' \tag{11}$$

where $G_a' = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 1 & 1 \end{bmatrix}$; $\varphi' = 4B' \mathrm{cov}(z_a) B'$; $B' = diag\{x^0 - X_1, y^0 - Y_1, R_1^0\}$; $\mathrm{cov}(z_a) = E[\Delta z_a \Delta z_a^T] = (G_a^{0T} \varphi^{-1} G_a^0)^{-1}$, the final result is given as follows:

$$Z_P = \sqrt{Z_a'} + \begin{bmatrix} X_1 \\ Y_1 \end{bmatrix} \tag{12}$$

Take Z_P as the initial value of Taylor series expansion algorithm.

The Taylor sequence expansion is a recursive algorithm that requires an initial estimated position, and the estimated position is improved by solving the local least squares (LS) solution of the TDOA measurement error in each recursion. For a set of TDOA measurements, the algorithm first performs Taylor expansion on the selected MS initial position (x0, y0), ignoring the second order component, which translates to:

$$M = G\Delta + \varepsilon \tag{13}$$

$$G = \begin{bmatrix} (X_1 - x)/R_1 - (X_2 - x)/R_2 & (Y_1 - y)/R_1 - (Y_2 - y)/R_2 \\ (X_1 - x)/R_1 - (X_3 - x)/R_3 & (Y_1 - y)/R_1 - (Y_3 - y)/R_3 \\ \cdot & \cdot \\ \cdot & \cdot \\ \cdot & \cdot \\ (X_1 - x)/R_1 - (X_m - x)/R_m & (Y_1 - y)/R_1 - (Y_m - y)/R_m \end{bmatrix}$$

$$M = \begin{bmatrix} R_{2,1} - (R_2 - R_1) \\ R_{3,1} - (R_3 - R_1) \\ \cdot \\ \cdot \\ \cdot \\ R_{m,1} - (R_m - R_1) \end{bmatrix}; \Delta = \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix}; \varepsilon \text{ is the error of the algorithm.}$$

According to the weighted least squares algorithm, the covariance matrix Q of the TDOA measurement error is approximated by the approximation matrix of the error ε to obtain the estimate result, given as follows:

$$\Delta = (G^T Q^{-1} G)^{-1} G^T Q^{-1} M \tag{14}$$

In the next iteration, take $x = x_0 + \Delta x,\ y = y_0 + \Delta y$ the algorithm stops when $|\Delta x| + |\Delta y| < \sigma$, σ is a threshold value. The final (x, y) is the positioning result. Figure 2 shows the complete process of the positioning method proposed in this paper.

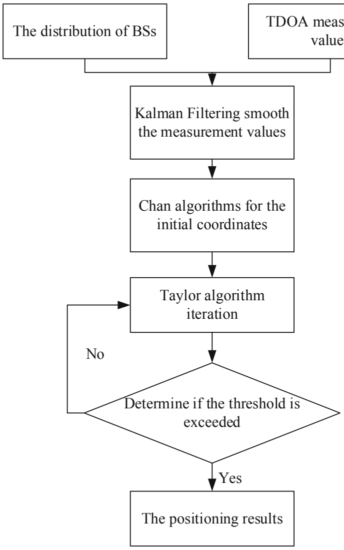

Fig. 2. The process of the KFL-TDOA positioning method with hybrid location algorithm

5 Simulation Verification

In this section, the MATLAB simulation results is given to verify the performance of the algorithms mentioned above. Considering that indoor positioning objects do approximate linear motion in most cases, we use a uniform linear motion along a 45-degree angle as a mathematical model. The simulation condition is followed: The coordinates of 4 anchors is set in advance, $BS1(0,0)$, $BS2(750,433)$, $BS3(750,-433)$,

$BS4(500, 500)$. Start coordinates is $(x_0 = 100, y_0 = 100)$, $v_x = v_y = 5$. Different levels of noises is considered in both the measurement phase and the positioning phase to better simulate the actual environment. The results are given as follows.

In Fig. 3, the number of sample points $N = 500$, the initial value of the state matrix $X_0 = \begin{bmatrix} 100 & 100 & 10 \end{bmatrix}^T$, system noise matrix $Q_w = \begin{bmatrix} 10 & 0 & 0 \\ 0 & 10 & 0 \\ 0 & 0 & 20 \end{bmatrix}$. The original data is interfered by noise, the figure shows that Kalman filtering can reduces measurement and system errors.

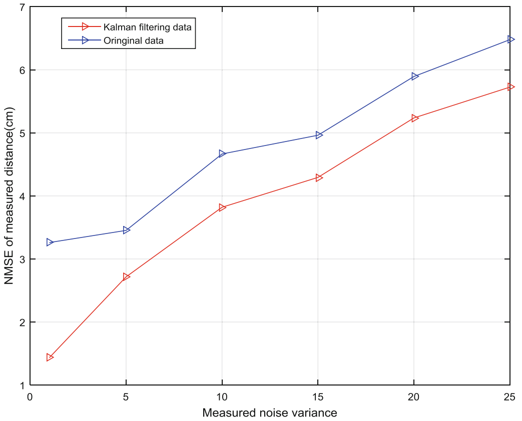

Fig. 3. The performance of Kalman filtering

In Fig. 4, the number of sample points $N = 100$, the rest of the parameters are set as Sect. 4. From the figure, it is obvious that the hybrid method's trajectory is smoother.

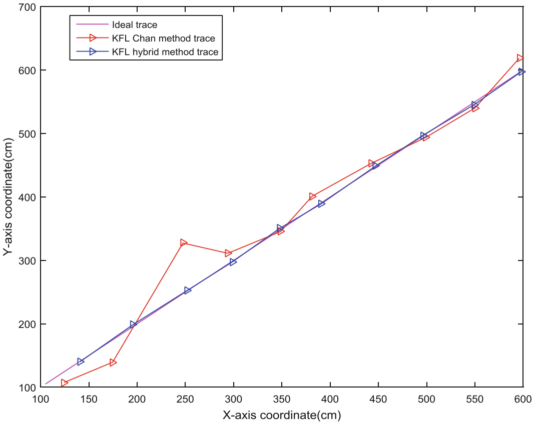

Fig. 4. The simulated paths of different methods

In Fig. 5, the number of sample points $N = 500$. Compared with traditional Chan algorithm, Chan algorithm with Kalman filtering, hybrid positioning algorithm without Kalman filtering, Fig. 5 shows that the method this paper proposed has lower NMSE value, and when noise interference in the environment is serious, it has stronger anti-interference ability than Chan algorithm.

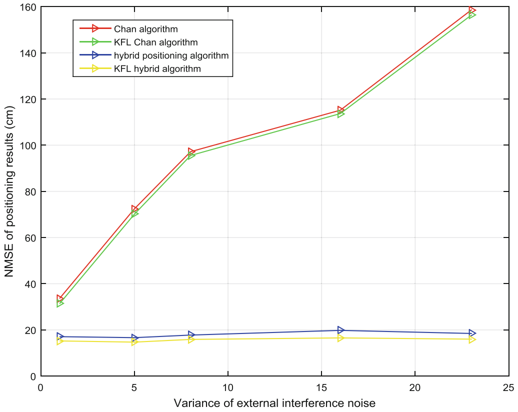

Fig. 5. The NMSE value of different positioning algorithms

Figure 6 shows that the convergence speed of the algorithm is not significantly slower due to the combinations of the algorithm, since Chan algorithm needs 2 iterations. Compared with Taylor series expansion which the initial value is chosen arbitrarily, the proposed algorithm has a better performance.

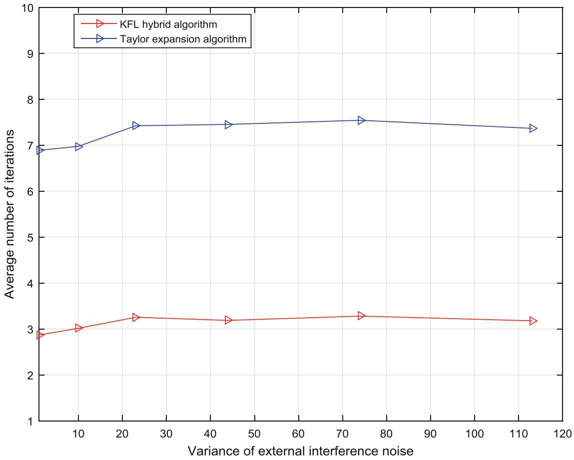

Fig. 6. Average iterations of different positioning algorithms

6 Conclusion

In view of the simulation conditions of the current positioning algorithms are too ideal, the results are often cannot reflect the actual system. A KFL-TDOA positioning method based on hybrid location algorithm is proposed in this paper. The proposed method adds noise interference to both measurement process and the positioning process. The method first use Kalman filtering in order to smooth the measurement error, then combine Chan algorithm with Taylor series expansion algorithm to obtain a precision positioning result. Simulation results are given to verify the performance of the algorithm in positioning accuracy, anti-interference and iteration speed.

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