An Implementation and Optimization Method of RTLS Based on UWB for Underground Mine

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***Abstract*—To obtain the specific location information of personnel in the underground mine, this paper describes a Real-Time Locating System (RTLS) based on Ultra-Wideband (UWB) technology. The system consists of wearable active tags, main and sub anchors, a server, and a client. Firstly, Alternative Double-Sided Two-Way Ranging (ADS-TWR), combined with digital filtering and linear fitting is used to pre-process the noise and bias of the ranging results, obtaining the anchor-tag distance with an error less than 10cm. In order to resolve the problem of position jump caused by random factors in the mine, the position of the moving target is initially estimated by Extended Kalman Filtering (EKF), and then the result is optimized secondarily by applying Mean Filtering (MF). Experimental results show that the accuracy of the system reaches 0.06m in the line-of-sight environment. The positioning accuracy is effectively improved and shows strong anti-noise interference performance.**

***Index Terms*—UWB, underground-mine RTLS, DS-TWR, Extended Kalman Filtering, Mean Filtering**

I. Introduction

The current mining method of mineral deposits is mainly underground mining, safety accidents such as mine collapse occur frequently. Therefore, it is extremely necessary to develop Real-Time Locating Systems (RTLS) to locate personnel in time. RF-based positioning solutions utilizing Bluetooth, Wi-Fi, ZigBee, RFID, and Ultra-Wideband (UWB) technology are common and commercially available [1]. UWB technology provides an excellent means for wireless positioning due to its high-resolution capability in the time domain. Its ability to resolve multipath components makes it possible to obtain accurate location estimates without the need for complex estimation algorithms [2]. This paper mainly describes the implementation and optimization method of underground mine positioning system based on UWB technology.

II. System Design

A. System Implementation

The underground mine locating system consists of wearable active tags, main and sub anchors, a server, and a client as shown in Fig. 1. Since the power supply is always available for anchors underground, the anchors are used as the Initiator which needs to frequently request in Two-Way Ranging progress. The Responder would be wearable tags, and can always work in low-power mode outside the positioning area. That is, a passive Anchor-Tag positioning system. Sub anchors will report the calculated distances to a single main anchor that exists in their area at a regular interval. The main anchor then performs the data filtering and tag locating algorithms, and uploads coordinates of tags and other information from tags to the server via ethernet cable. The RTLS on the server is used to view data and issue commands at any time through the client.

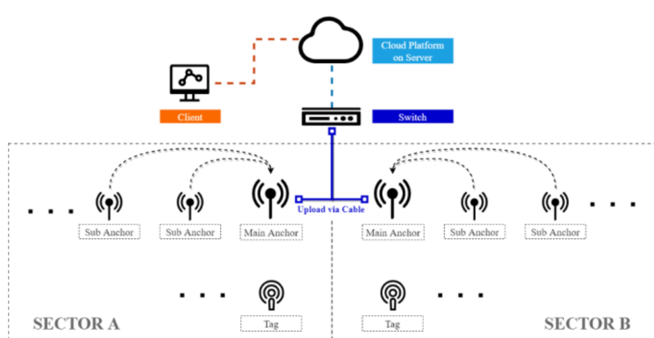

Fig. 1. System implementation.

B. Two-Way Ranging Implementation

1) Symmetric Double-Sided Two-Way Ranging

The message exchange of the Double-Sided Two-Way Ranging (DS-TWR) procedure is depicted in Fig. 2, the following equations represent ideal timing references.

$$R_a = 2T_f + D_b \tag{1}$$

$$R_b = 2T_f + D_a \tag{2}$$

In Symmetric Double-Sided Two-Way Ranging (SDS-TWR), by adding (1) and (2), we obtain

$$T_f = \frac{1}{4}(R_a - D_b + R_b - D_a) \tag{3}$$

Considering clock drifts of two devices, the actual value of $\hat{R}, \hat{D}$, and $\widehat{T_f}$ will be modeled as follows

$$\hat{R} = (1+e)R \tag{4}$$

$$\hat{D} = (1+e)D \tag{5}$$

$$\widehat{T_f} = \frac{1}{4}\left(\widehat{R_a} - \widehat{D_b} + \widehat{R_b} - \widehat{D_a}\right) \tag{6}$$

So that the error between the real and estimate value of T_f may be written as

$$\widehat{T_f} - T_f = \frac{1}{2}T_f(e_a + e_b) + \frac{1}{4}(e_a - e_b)(D_b - D_a) \tag{7}$$

It can be seen that in SDS-TWR, if D_a and D_b are approximately the same, the error between the real and estimated value of T_f can be reduced to a desirable level. However, on one hand, the clock drift can hardly be the same between two devices, on the other hand, the delay time D is determined by the device that takes a longer time to process packets, which may be unnecessary for another device. In that case, the whole procedure may take longer time than necessary. Furthermore, the packet collisions have easily occurred in an uncoordinated network, the whole procedure has to start all over again then. The efficiency will be greatly reduced with the increase of devices.

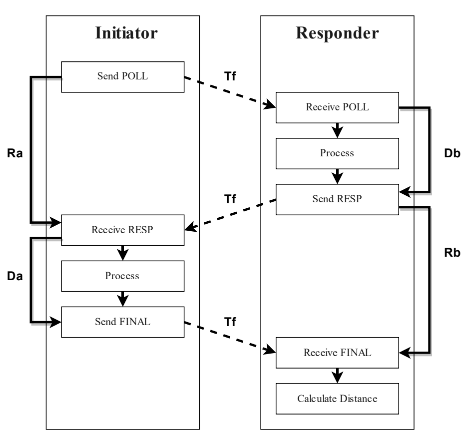

Fig. 2. DS-TWR procedure.

2) Alternative Double-Sided Two-Way Ranging

According to the method given by [3], rather than adding, multiplying (1) and (2), by expanding and rearranging, we have

$$\begin{aligned} T_f &= \frac{R_a R_b - D_a D_b}{2(R_a + D_a)} = \frac{R_a R_b - D_a D_b}{2(R_b + D_b)} \\ &= \frac{R_a R_b - D_a D_b}{R_a + D_a + R_b + D_b} \end{aligned} \tag{8}$$

$$\widehat{T_f} - T_f = e_a T_f = e_b T_f \tag{9}$$

It is clear that in ADS-TWR, the error is only related to the clock drift e_a, e_b and T_f. So, the delays of the devices do not need to be the same, the DS-TWR process can be shortened. Unlike the SDS-TWR, the error of ADS-TWR is only related to the clock drift of a single device, which means the results are in the same time domain, providing the possibility to make the unified correction to the results.

C. Location Algorithm Based on Extended Kalman Filter

This system preliminarily estimates the position coordinates of the moving targets by the Extended Kalman Filter. The Extended Kalman Filter is a non-linear filter based on time sequence, which can infer the true state of the system at the next moment based on the system state and predicted value at the previous moment. The state and measurement equations for position estimation are assumed to be as follows [4]:

$$X_k = f(X_{k-1}, W_{k-1}) \tag{10}$$

$$Z_k = \hbar(X_{k-1}, V_{k-1}) \tag{11}$$

where, $X_k = \begin{bmatrix} x_0, v_x \\ y_0, v_y \end{bmatrix}$ is a state vector of the target, (x_0, y_0) represents the initial position of the moving target, and (v_x, v_y) represents the horizontal and vertical components of the target velocity in the Cartesian coordinate system. Z_k represents the measurement matrix, $f(X_{k-1}, W_{k-1})$ and $\hbar(X_{k-1}, V_{k-1})$ represent the nonlinear equations of the system. W_k and V_k are the state error and observation error vectors composed of the covariance matrix Q and R. The values of the matrix Q and R are closely related to the experimental environment and affect the performance of the localization algorithm such as sensitivity.

We linearize (10) and (11), discard the higher-order terms, and compute the first-order Taylor expansion. On the basis of solving the linear problem by Kalman Filter [5], the Extended Kalman Filter is derived to estimate the target position equation as follows.

The prediction part of the EKF algorithm contains predictions of the state and the error covariance matrix:

$$\widehat{X_k}^{-} = A_k\widehat{X_{k-1}} \tag{12}$$

$$\mathrm{P_k}^{-} = \mathrm{A_k P_{k-1} A_k}^{\mathrm{T}} + \mathrm{W_k Q W_k}^{\mathrm{T}} \tag{13}$$

The correction part of the EKF algorithm contains updates of the Kalman gain, filter equations and error covariance.

$$K_K = P_k{}^{-}H^T(HP_kH^T + VRV^T)^{-1} \tag{14}$$

$$\widehat{X_k} = \widehat{X_k}^{-} + K_k\left(Z_k - h(\widehat{X_k}^{-},0)\right) \tag{15}$$

$$P_k = (I - K_kH)P_k{}^{-} \tag{16}$$

In (13), the matrix A represents the partial derivative matrix of the nonlinear equation f at the prediction point X_k. The matrix H represents the partial derivative matrix of the nonlinear equation h at the prediction point X_k, i.e., the Jacobi matrix.

The EKF algorithm takes the state equation and the measurement equation as the object of study, obtains the error covariance matrix P_k, then updates the Kalman gain K_k, re-estimates the target position, and finally iterates the obtained estimates again [6]. Since the influence of random factors in the underground mine exhibits nonlinear system characteristics, the EKF algorithm can approximate the nonlinear characteristics of the system well, improve the positioning accuracy, and attenuate the noise interference.

III. Experimentation and Optimization

A. Experimental Environment

Simulation tests are carried out in a $14 \times 7 \times 6\, m^3$ laboratory, where the anchors are deployed in non-equal right triangles. The coordinates are corrected to two dimensions by algorithms. As shown in Fig. 3, we build the test platform which contains a test PC, a main anchor, two sub anchors, and an active positioning tag. The main anchor aggregates and uploads the experimental data.

B. Two-Way Ranging Optimization

A major factor affecting the ranging results is the signal strength, with the increasing of the distance, a bias that can be seen in Fig. 4 varies with the received signal level (RSL). For ADS-TWR, the error is only related to the single device clock

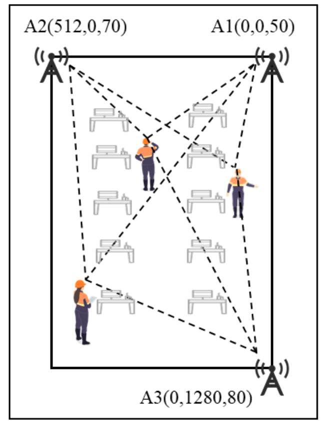

Fig. 3. Schematic diagram of the experimental scene.

drift, so the error is in the same time domain and can be corrected by fitting or simply adding an offset, bringing the positioning error within 10cm.

C. Optimization Based on Mean Filtering Algorithm

Fig. 5 (a)-(c) shows the distribution of localization target coordinates solved by three algorithms, the red line represents the real trajectory, the green represents the motion trajectory estimated by the algorithm, from left to right are Trilateration (TRI), Iterative Least Squares (ILS), and Extended Kalman Filter algorithm (EKF).

The comparison shows that the TRI localization result fluctuates more because this algorithm has no geometric solution in the region or the geometric solution is not unique. ILS suffers from a position jump problem because it is essentially a linear unbiased estimate and the mine environment exhibits nonlinear system characteristics, which are not applicable to this scenario. EKF makes the positioning trajectory smoother, but there are still some gaps with the actual trajectory.

In order to solve the problem of positioning coordinate jump, the estimated coordinates are optimized secondarily by using Mean Filtering (MF) to reduce the fluctuation of positioning results and improve the positioning accuracy [7]. Considering that the noise caused by random factors in the underground mine is similar to the particle noise in the image, the MF is used to optimize the target localization results obtained by EKF secondarily, which serves as a moving-average filter.

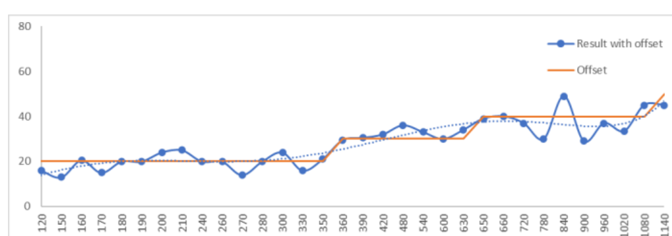

Fig. 4. Deviation analysis.

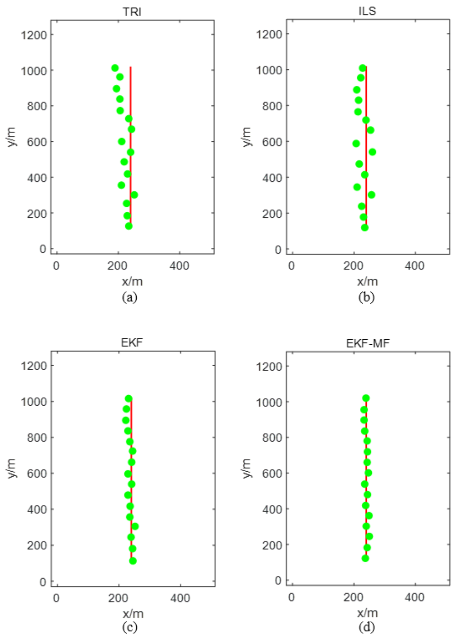

Fig. 5. Different algorithms for locating trajectories.

Fig. 5(d) shows that the EKF with MF (EKF-MF) proposed in this paper makes the results even closer to the real trajectory. The principle of MF can be defined as:

$$\hat{X}(n) = \frac{1}{L}\sum_{i=n-l}^{i=n+l} X\,(i) \tag{17}$$

where $\hat{X}(n)$ denotes the target position after MF, $X(i)$ denotes the estimated target position after Extended Kalman Filtering, $X(n)$ denotes the filter centroid, and $L = 2l + 1$ is the size of the filter window.

As expressed in (18), the noise generated by random factors in the mine can cause the measurement error at that point in the form of pulses. These points will eventually produce spikes in the measurement result of the target motion trajectory. The purpose of using the MF is to eliminate this noise.

$$X(n) = X^{*}(n) + \delta_n \tag{18}$$

According to the principal analysis, the MF takes the error evenly by each point of the filtering window, which cannot eliminate the error completely, but can suppress the influence of random factors in the mine to a certain extent.

D. Error Analysis

Let the coordinate error e_i of the i-th measurement as [8]

$$e_i = \sqrt{{e_{xi}}^2 + {e_{yi}}^2} \tag{19}$$

Where e_{xi},e_{yi} denotes the error of the i-th measurement in the x and y directions. The max error E_{max} and the Root Mean Square Error E_{RMSE} indicates the positioning effect, which is

$$\mathrm{E_{RMSE}} = \sqrt{\frac{\sum_{i=1}^{n} {e_i}^2}{n}} \tag{20}$$

Fig. 6 gives the E_{max} and the E_{RMSE} of the tag positioning results in different algorithms. By using EKF-MF, the E_{max} reduces 82%, 70%, 40%, and the E_{RMSE} reduces 77.8%, 72.7%, 33.3%, respectively, compared with TRI, ILS, and EKF. Proving that the noise is suppressed and the positioning accuracy is effectively improved by adding offset to raw ranging results and using EKF-MF.

Fig. 7 gives the comparation of the performance between different algorithms. The greater the ranging error, the greater impact on the positioning accuracy. As the measurement noise increases, the performance of the EKF-MF algorithm still behaves stably. At a larger noise of 0.15m, the E_{RSME} reduces 84.2%, 82.4%, 45.5% by using EKF-MF, compared with TRI, ILS, and EKF.

The above data analysis shows that the optimization method proposed in this article not only improves the positioning accuracy but also advances in anti-noise performance.

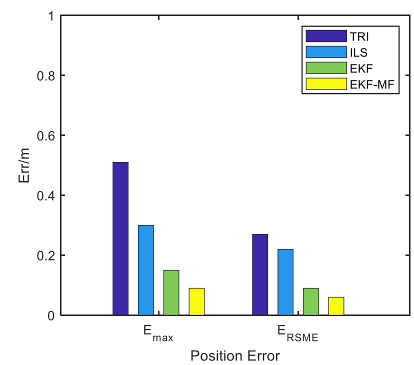

Fig. 6. The statistical error of location in different algorithms.

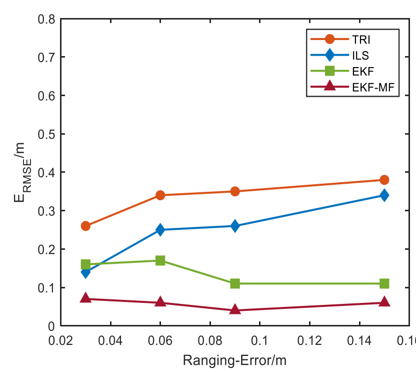

Fig. 7. E_{RMSE} of different algorithms under different ranging errors.

IV. Conclusion

To locate personnel in the underground mine, this paper designs an RTLS based on UWB. By wearing active tags, the anchors pre-deployed in the positioning area could locate personnel in real-time. With digital filtering and linear fitting, the bias related to RSL can be optimized. Based on the initial calculation of the tag result by EKF, the MF is used to reduce the influence of random factors in the mine to obtain a smoother result. The ability of system positioning accuracy and anti-interference is significantly enhanced.

The UWB signal strength does not uniformly attenuate in different directions. Hence the error is related to the anchor-tag angle. In future research, consider deploying more anchors using Ad-hoc network technology, combining multiple angle measurement results to decrease error, further improve system accuracy and performance. Moreover, with the extension and development of the mine, anchors can be continuously deployed without modifying the system through Ad-hoc network technology to expand the RTLS space.

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