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An Algorithm for UWB Signals Tracking Based on Extended $H_\infty$ Filter

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Abstract

In this paper, we present a positioning and tracking method for UWB signals. By the low complexity array processing, the time of arrival (TOA) and direction of arrival (DOA) is estimated. A robust algorithm based on the extended $H_\infty$ filter is presented to accurately estimate the target’s real-time location and velocity. This method is effective to the no-Gaussian or biased system model and the unknown or not fully known observation errors statistical properties.

Keywords: UWB; TOA; DOA; extended $H_\infty$ filter; tracking

1. Introduction

Ultra-wideband (UWB) signals promise interesting perspectives for location estimation and object identification in short range environments. The use of location and tracking information is an excellent tool to improve productivity and to optimize the resources management in a wide range of sectors [1], [2]: industrial, medical, home-automation or military. For example, tracking the stocks in a warehouse, locating medical equipment and personnel in a hospital, monitoring the assembly line in a factory or developing intelligent audio guides that select narration according to the position of the visitor in a museum. What’s more, UWB technologies promise to overcome power consumption and accuracy limitations of both GPS and WLAN, and are more suitable for indoor location-based applications. The conventional methods for wireless positioning are based on the estimation of TOA, TDOA (time difference of arrival) or DOA, once multiple timing or angles of arrival are measured at a convenient number of base stations. In [3], a high resolution and low complexity subspace method has been applied to the delay estimation for DS-UWB system. In [5], a low complexity frequency domain TOA estimation
method has been proposed for the UWB signals. A joint estimation method of TOA and DOA for a single UWB source is performed on low complexity frequency domain approach in [4], on which this paper deals with the positioning estimation parameters based.

An additional potentiality of the tracking problem that has not been explored enough is the mobility of the moving targets, especially for the complexity surroundings. The use of a kalman tracker helps in reducing the variability of the positioning by optimally averaging in time. In [6], the use of extended kalman filter to track the position and velocity of a moving terminal in nonlinear system. In [8], a robust algorithm based on the $H_\infty$ filter is presented to estimate the ball’s location and velocity in a linear system. However, under the circumstances of the system model and observation error are often non-Gaussian and/or biased, and the statistical properties of the errors are often unknown or not fully known, both algorithms are not able to deal with.

In this paper, the problem of joint estimation of TOA and DOA is introduced for a single UWB source. The UWB pulse position modulation signal is considered, and a frequency domain MUSIC algorithm is introduced. This algorithm can estimate the TOA and DOA of the moving target accurately. Considering the uncertainties of the target system and the measurement noise statistics, a robust algorithm based on the extended $H_\infty$ filter is presented to accurately estimate the target’s real-time location and velocity. The effectiveness of this positioning and tracking strategy was also evaluated by the computer simulation. The outline of this paper is as follows: Section II introduces the UWB signals model. Section III introduces the TOA and DOA joint estimation scheme. Section IV, a robust tracking algorithm is presented. Finally, computer simulation results and conclusions are discussed in Section V and VI, respectively.

2. System model

We considered an IR-UWB system where transmission of an information symbol is typically implemented by the repetition of $N_f$ pulses of very short duration. The transmitted signal is expressed as,

$$s(t) = \sum_{k=-\infty}^{\infty} \sum_{j=0}^{N-1} p(t-T^k_j)$$

(1)

where $T^k_j = (kN_f + j)T_f + c_j T_c + b_k^T \delta_T$. Pulse Position Modulation (PPM) is assumed with $\{b_k\}$ being the information symbols taking values $\{0, 1\}$ with equal probability. $p(t)$ refers to the single pulse waveform, typically a Gaussian monocycle or its derivatives, and $T_p$ is the repetition pulse period. $T_p << T_f$ is the frame period. $N_f$ is the number of frames per symbol, $T_c$ is the chip period, $T_\delta$ is the PPM modulation time shift and $\{c_j\}$ is the time hopping sequence.

A typical model for the multipath fading channel is given by,

$$h(t) = \sum_{l=0}^{L-1} h_l \delta(t-T_l)$$

(2)

where $h_l$, $T_l$ denote the fading coefficient and the time delay by the $l$-th path respectively.

Let UWB source $s(t)$ impinge upon an $M$ element antenna array. The signal received by the $m$-th antenna at time $t$ is

$$x_m(t) = s(t) * h(t) + v_m(t)$$

(3)

$$= \sum_{l=0}^{L-1} h_l s(t - T_l, \bar{\theta}_l) + v_m(t)$$

(4)
where \( v_m(t) \) denotes the \( m-th \) antenna additive Gaussian noise, \( s(t) \) represents the UWB transmitted signal, and \( \xi_{m}(T, \theta) \) refers to the transmitted signal propagation delay associated to the \( m-th \) antenna and the \( l-th \) arrival path. For a ULA the propagation delay associated to the \( m-th \) antenna and the \( l-th \) arrival path for the transmitted signal is given by

\[
\xi_{m,l}(T, \theta) = T + m \frac{d}{c} \sin(\theta), \quad 0 \leq m \leq M - 1
\]  

(5)

With \( d \) being the distance between antenna elements in the array, \( c \) the speed of light and \( \theta_l \) the direction of arrival of the transmitted signal via the \( l-th \) arriving path.

3. Toa and doa joint estimation

Considering a N-DFT sample frequency vector, the Fourier transform of the received signal vector at the \( q-th \) antenna element can be expressed by [4],

\[
X_m(w_k) = \sum h_l S(w_k)e^{-j\xi_{m,l}(T, \theta)} + V_m(w_k)
\]  

(6)

where \( X_m \), \( S \) and \( V_m \) denote the Fourier transform of the received signal, transmitted signal and noise respectively.

Rearranging equation (6) into a matrix notation, the received signal is given by,

\[
X_m = \sum_{l=1}^{M-1} h_l S e_{\xi_{m,l}}
\]  

(7)

where the elements of the delay signature vector include the dependency with the angle of arrival in \( \xi_{m,l} \),

\[
e_{\xi_{m,l}} = [e^{-j\xi_{m,l}} \quad \ldots \quad e^{-j(N-1)\xi_{m,l}}]^T
\]

(8)

The estimation of the correlation matrix \( R \) from the frequency domain samples,

\[
R = \frac{1}{N_s} \sum_{s=1}^{N_s} Z(S)Z^H(S)
\]  

(9)

Where \( N_s \) is the number of snapshots, \( Z \) contains the DFT components of the received signal at the \( s-th \) snapshot, rearranged in a way that the columns of \( Z \) are associated to a single frame. That is, 

\[
Z(S)=[X_1(S) \quad X_2(S) \quad \ldots \quad X_M(S)]
\]

where \( X_j(S) = DFT\{ \sum_{m=0}^{M-1} h_m p(t - jT - T_{m,q}) + v_j(t) \} \), \( v_j(t) \) denotes the noise contribution.

\[
RE = EA
\]  

(10)

where \( \Lambda = diag(\lambda_0, \lambda_1, \ldots, \lambda_{N_s}) \), \( \lambda_0 \geq \lambda_1 \geq \ldots \geq \lambda_{N_s} \), \( E \) is the eigenvector, let \( E_n \) be the noise subspace whose columns are the eigenvectors corresponding to the smallest eigenvalue. The problem of interest is to estimate the TOA and DOA of UWB transmitted signal, i.e. \( \tau, \theta \), which can be achieved by the MUSIC pseudo-spectrum

\[
P(\theta, \tau) = \frac{\langle H(\theta, \tau) a(\theta, \tau) \rangle}{\langle H(\theta, \tau) E_n E_n^H(\theta, \tau) \rangle}
\]  

(11)

where \( \langle \cdot \rangle^H \) denotes Hermitian-transpose operation. The TOA and DOA of target user is indicated by the peak of (11).
4. Tracking algorithm

Kalman filters have been used in many moving target problems. They provide efficient and convenient minimum mean square error solutions for the state estimation problem, considering that both the process and the measurement noises of the target system are assumed as Gaussian with known statistical properties. However, in practical situations, the uncertainties and nonlinearities of the target system and the measurements normally do not satisfy the Gaussian assumption, and the noise statistics is usually not available. An extended \( H^e \) is presented, which is an combination of the linear \( H^e \) filter and the extended Kalman filter [7]. Considering \( B \) reference nodes. The measurement vector is formed

\[
z(k) = [z_{TOA} \quad z_{DOA}]^T
\]

where \( z_{TOA} = \{^\wedge T_0, \ldots, ^\wedge T_B \} \), the transition equation can be defined for continuous movement by

\[
s(k + 1) = As(k) + w(k)
\]

Where \( s(k) = [x(k)^T v_x(k)^T v_y(k)]^T \) is the state vector. \( A \) is the state matrix defined as

\[
A = \begin{bmatrix}
1 & 0 & \Delta & 0 \\
0 & 1 & 0 & \Delta \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

\[
w(k) = \begin{bmatrix}
w_x \\
w_y
\end{bmatrix}\text{ is the disturbance transition vector with covariance matrix } Q, \text{ where } w_x \text{ and } w_y \text{ are the speed noise vectors. Measurements of TOA and DOA are nonlinear in the position state variables:}
\]

\[
z(k) = f(s(k)) + v(k)
\]

Where \( z(k) = [z_{TOA} \quad z_{DOA}]^T, \ v(k) = [v_{TOA} \quad v_{DOA}]^T \). From the nonlinear measurement equation to the linear measurement equation

\[
\frac{df}{ds} \bigg|_{s(s(k), k-1)}
\]

where \( \hat{s}(k/k-1) \) is the state vector prediction, equal to the conditioned mean

\[
\hat{s}(k/k-1) = E[s(k \mid z(k-1))]
\]

The estimated output vector

\[
Y(k) = L(k)s(k)
\]

The output matrix \( L(k) \) is selected by the user according to the different applications. In our problem, we care about the moving target’s location and velocity, which just constitute the system state, so here
\( L(k) \) is specified as an identity matrix. Therefore, the filtering problem is thus to find an estimate \( \hat{Y}(k) \) of the measurement \( z(k) \). The filter has to minimize the following cost function [8],

\[
J = \frac{\sup_{u,v \in \mathbb{R}} \left\| x_{k}^2 + y_{k}^2 \right\|}{\gamma} < 1
\]

(21)

where \( Q_k, W_k, V_k \) are the weighting matrices for the estimation error, the process noise and the measurement noise. Moreover, \( Q_k \geq 0, W_k \geq 0, V_k \geq 0 \). The notation \( \left\| x_{k}^2 + y_{k}^2 \right\| \) is defined as \( \sup_{y \in \mathbb{R}} x_{k}^2 + y_{k}^2 \), sup denotes the supremum and \( \gamma \) is the noise attenuation level.

The target position as \( r = (x, y) \), the \( b \)-th reference node as \( r_b = (x_b, y_b) \), Then the position relates to TOA and DOA measurements like

\[
C_{r_b}^{(b)} = \sqrt{(x - x_b)^2 + (y - y_b)^2} = \|r - r_b\|_2 = d_b
\]

(22)

\[
\sin \theta_b^{(b)} = \frac{(y - y_b)}{\sqrt{(x - x_b)^2 + (y - y_b)^2}} = \frac{(y - y_b)}{d_b}
\]

(23)

The linearization matrices \( G_{TOA} \in \mathbb{R}^{2n^2} \)

\[
G_{TOA}(k) = \begin{bmatrix}
\hat{x}(k-1) - x_b & \hat{y}(k-1) - y_b \\
\frac{d_1(k-1)}{d_1(k-1)} & \frac{d_1(k-1)}{d_1(k-1)} \\
\frac{d_2(k-1)}{d_2(k-1)} & \frac{d_2(k-1)}{d_2(k-1)} \\
\vdots & \vdots \\
\frac{d_n(k-1)}{d_n(k-1)} & \frac{d_n(k-1)}{d_n(k-1)}
\end{bmatrix}
\]

(24)

The measurement equation (15) is linearized as

\[
z(k) = G(k)s(K) + v(k)
\]

(26)

The mean square error of the estimate is the trace of the covariance matrix, which contains the accuracy parameter that will characterize the behavior of the tracker,

\[
P(k+1) = E \left\| \hat{s}(k+1) - \hat{s}(k+1) \right\|_2
\]

(27)

The state estimation \( \hat{s}(k+1) \) and the updating equations that forces \( J < 1/\gamma \) are given as follows:

\[
L(k) = (I - \gamma P(k) + G^T(k)V^{-1}G(k)P(k))^{-1}
\]

(28)

\[
K(k) = AP(k)L(k)G^T(k)W^{-1}
\]

(29)

\[
\hat{s}(k+1) = A\hat{s}(k) + K(k)(z(k) - G(k)\hat{s}(k))
\]

(30)

\[
P(k+1) = AP(k)L(k)A^T + W
\]

(31)
Where \( I \) is the identity matrix, \( K(k) \) is the \( H_\infty \) gain matrix. The initial state estimate \( \hat{s}(0) \) should be initialized to our best guess of \( s(0) \), and the initial value \( P(0) \) should be set to give acceptable filter performance. In general \( P(0) \) should be small if we are highly confident of our initial state estimate \( \hat{s}(0) \).

Although we need not to know the statistics of noises \( w_k \) and \( v_k \) in the \( H_\infty \) filter, we should tune the weight matrices \( kQ, kW, kV \) carefully, because these values determine the estimation error in the performance criterion (21). The weight matrices \( kQ, kW, kV \) can be chosen according to the experience about the noise. As the performance criterion, \( \gamma \) can not be very large, because otherwise some eigenvalues of the matrix \( P \) may have magnitudes more than one. These eigenvalues prevent a proper derivation of the \( H_\infty \) filter equations, so that the \( H_\infty \) filter problem has no solution.

5. Simulation results

Next we evaluate the position tracking algorithm using the estimated TOA and DOA for different scenarios. The tracking zone is \( 30m \times 30m \) with one access point provided with 4-element array, and the arrays are equipped in the noise statistics. Finally, the computer simulations show an effectiveness of the proposed tracking strategy.

![Figure 1. Tracking Results 1](image1)

![Figure 2. Tracking Results 2](image2)

![Figure 3. Position Estimation Error](image3)

position of (15,0). LOS is considered only. The target moves to follow a curve and a spiral path with arbitrary velocity. The measurement noise statistics is unknown. The position is measured 10 times per
second and the length of simulation is 50 seconds. The tracking results are shown in Fig.1 and Fig.2, which we can see the proposed extended H∞ filter eliminated the high frequency components of the measurement noise and estimated the moving target’s position values sufficiently. Fig.3 illustrates the estimated position errors in x and y directions corresponding to the Fig.1 simulation.

6. Conclusion

In this paper a frequency domain MUSIC the algorithm to jointly estimate the TOA and DOA for UWB antenna arrays is introduced. Then, a new approach for Kalman tracking based on the TOA and DOA measurements for moving target’s location has been proposed. This algorithm based on the extended H∞ filter is robust and can estimate the target’s real-time location and velocity accurately considering the uncertainties of the target system and the measurement

References