Mainlobe interference cancellation based on PCA + ECA in passive bistatic radar

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Abstract: The mainlobe interference is a noticeable issue in the passive bistatic radar. As the direction of arrival (DOA) of the interference is close to the DOA of the target echo, the interference hardly be cancelled by the adaptive spatial filtering. After clutter cancellation, the authors assume the mainlobe interference is the principal component of the array element signal. This study proposes the method based on the principal component analysis (PCA) and the extensive cancellation algorithm (ECA) to cancel the mainlobe interference in the echoes. The PCA is applied to extract the interference component from the array element signals, and the ECA is applied to cancel the interference with the extracted interference component as the reference. Finally, the simulation result proves the feasibility of the method proposed by this paper.

1 Introduction

The passive bistatic radar (PBR) system, which does not transmit the electromagnetic wave, depends on the existing transmitters as illuminators for opportunity to detect the potential targets. The range of the available illuminator signals includes the civilian and the commercial signals, such as frequency modulate (FM) signal [1, 2], global system for mobile communication (GSM) signal, global positioning system (GPS) signal, digital audio broadcast (DAB) signal, digital video broadcast-terrestrial (DVB-T) signal [3] and so on. Due to the silent receiving and the bistatic structure, many research institutions pay great attention to the PBR system.

The PBR system takes the structure of two channels to receive and process the signals, the reference channel and the surveillance channel. The reference channel receives the direct-path signal as the reference signal. The surveillance channel exploits the array antenna towards the area where surveillance is needed to receive the echoes. The echoes include the direct-path signal, the multipath signals, the target echoes, the interference and the channel noise. The interference mainly consists of the direct-path signal, the multipath signals and the deliberate directional interference. The direct-path signal and the multipath signals can be easily cancelled by the extensive cancellation algorithm (ECA) with the reference signal [4, 5]. Since the deliberate directional interference, including the sidelobe interference and mainlobe interference, would degrade the target detection performance of PBR system seriously, cancellation method is proposed in the following manuscript to suppress the directional interference.

Aiming at the sidelobe interference, the general cancellation method is adaptive spatial filtering. However, the mainlobe interference, whose direction of arrival (DOA) is close to that of the target echoes, is very difficult to be cancelled by the adaptive spatial filtering, as the adaptive spatial filter cannot provide a satisfied narrow ‘groove’ at the direction of interference. The mainlobe interference with the high power can be treated as the principal component of the echo. So the principal component analysis (PCA) algorithm can be exploited to extract the mainlobe interference [6, 7]. The complete signal processing structure of the proposed method is showed in Fig. 1.

2 Problem formulation

The PBR exploits the structure of two channels to receive and process the reference signal and the echoes. The PBR detects the targets by the coherent processing of two channels.

The reference channel signal is given by

\[ s_{\text{ref}}(t) = s_d(t) + n_{\text{ref}}(t). \]  \hspace{1cm} (1)

where \( s_d(t) \) is the direct-path signal, and \( n_{\text{ref}}(t) \) is the reference channel noise.

The surveillance channel signal after the clutter cancellation is given by

\[ s_{\text{sur}}(t) = \sum_{n=1}^{N} s_{\text{echo}}(t) + \sum_{k=1}^{K} s_{\text{jam}}(t) + n_{\text{sur}}(t). \]  \hspace{1cm} (2)

where \( s_{\text{echo}}(t) \) is the \( n \)th target echo, \( s_{\text{jam}}(t) \) is the \( k \)th interference, and \( n_{\text{sur}}(t) \) is the surveillance channel noise.

The output of matched filtering is given by...

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Fig. 1 Structure of signal processing
\[ s_d(t) = s_x(t) \otimes s_u(t) = \int_{-\infty}^{+\infty} s_x(u)s_u(t-u)du = \sum_{j=1}^{N} \int_{-\infty}^{+\infty} s_x(u)s_{echo}(t-u)du + \sum_{k=1}^{K} \int_{-\infty}^{+\infty} s_x(u)s_{jam}(t-u)du + \tilde{n}(t) \]

where \( \otimes \) is the convolution operation, \( s_x(t) \) and \( s_u(t) \) are the target signals and the interference signals after the matched filtering, and \( \tilde{n}(t) \) is the noise. \( \tilde{n}(t) \) is given by

\[ \tilde{n}(t) = \int_{-\infty}^{+\infty} s_x(u)n_{echo}(t-u)du + \int_{-\infty}^{+\infty} n_u(t)s_{echo}(t-u)du \].

The received target echoes are reflected by the targets, but the interference is the direct signal from the interference source. The interference-to-noise ratio (INR) of interference is greater than the signal-to-noise ratio (SNR) of target echoes. The target echoes will be masked by the interference.

The audio signal of analogue TV is chosen as the simulation signal. Fig. 2 shows the sketch of the simulation components in the echoes. Fig. 3 shows the range–Doppler (R–D) map with the interference existing. As can be seen, the simulation targets are masked by the interference. (The discontinuous red circles indicate the location of simulation targets).

### 3 Method summary

The PCA is a classical algorithm of the statistics data analysis, the feature extraction and the data compression. The primary goal of the PCA is to cancel the correlation between the multiple groups of data and search a smaller subset to express the redundant data.

First, centre the ordinary data by subtracting the mean value

\[ x \leftarrow x - E(x), \]

\[ x = [x_1(t) \ x_2(t) \ \cdots \ x_n(t)]^T. \]

The PCA is a kind of linear transformation. The extracted principal component is given by

\[ y = W^Tx, \]

\[ y = [y_1(t) \ y_2(t) \ \cdots \ y_m(t)]^T, \quad m < n, \]

where \( y \) is the principal component, \( W \) is the weight matrix. The \( n \)-dimensional data \( x \) is compressed to the \( m \)-dimensional data \( y \). The PCA can be treated as the projection processing. The \( m \)-dimensional subspace is expanded by the \( m \) normalisation orthonormal base vectors of \( W \). The projection of \( x \) in this subspace is given by

\[ \hat{x} = W^TWx. \]

According to the mean square error (MSE) rule, the cost function is given by

\[ J_{MSE}(t) = \sum_{j=1}^{m} \beta^{j-1} \| x(j) - W^T(t)y(j) \|^2, \]

where \( \beta \) is the forgotten factor, and the value is \( 0 < \beta \leq 1 \). It is effective to take \( \beta < 1 \) for tracking the non-stationary change of the source data.

In (10), the weight matrix \( W(t) \) is fourth order. The vector \( W(t)x(j) \) can be replaced approximately by the vector \( y(j) = W(j-1)x(j) \). The modified cost function is given by

\[ J_{MSE}(t) = \sum_{j=1}^{m} \beta^{j-1} \| x(j) - W^T(t)y(j) \|^2, \]

where \( \beta \) is the forgotten factor, and the value is \( 0 < \beta \leq 1 \). It is effective to take \( \beta < 1 \) for tracking the non-stationary change of the source data.

This study exploits the projection approximate subspace tracking (PAST) to solve the weight matrix \( W(t) \). The PAST is described as follows:

\[ y(t) = W(t-1)x(t) \]

\[ h(t) = P(t-1)y(t) \]

\[ m(t) = h(t)/\beta + y^T(t)h(t) \]

\[ P(t) = \frac{1}{\beta} \text{Tri} [ P(t-1) - m(t)h(t)h^T(t) ] \]

\[ e(t) = x(t) - W^T(t-1)y(t) \]

\[ W(t) = W(t-1) + m(t)e(t) \]

where \( \text{Tri}[\] is to transpose the upper triangular part of the matrix and copy it to the lower triangular part in order to make the matrix \( P(t) \) symmetrical. The \( n \times n \) unite matrix is chosen as the initial value of the matrix \( W(t) \) and the matrix \( P(t) \).

The PAST algorithm needs no matrix inversion operation. The PAST algorithm owns the real low compute complex and the fast convergence rate.

The ECA is a kind of time domain cancellation algorithm based on the subspace projection. The cost function is given by

\[ J = \parallel s_{sur} - s_{jam}v \parallel^2, \]

where \( v \) is the projection matrix. Compute the gradient of the cost function and make the gradient equal to 0:

\[ \frac{\partial \parallel s_{sur} - s_{jam}v \parallel^2}{\partial v} = 2s_{jam}(s_{sur} - s_{jam}v) = 0. \]

Simplifying (14), one can obtain

\[ s_{jam}^H s_{jam} = s_{jam}^H s_{sur}. \]
The expression of the projection matrix $v$ is given by
\[
v = s_{\text{jam}}H^{-1}s_{\text{jam}}s_{\text{sur}}.
\] (16)

The echo $s_{\text{sur}}$ cancelled interference is given by
\[
\hat{s}_{\text{sur}} = s_{\text{sur}} - s_{\text{jam}}(s_{\text{jam}}^H)^{-1}s_{\text{sur}}.
\] (17)

4 Simulation

The simulation is constructed to prove the feasibility of the method proposed by in this paper. The audio signal of analogue television is chosen as the available illuminator signal. The reference signal is the actual received audio signal of analogue television. Based on the actual reference signal, the target echoes are constructed. The interference signals are the audio signals from the other television programmes. The parameters of the simulation are given by Table 1.

Fig. 4 shows the simulation result of the matched filtering after the interference cancellation. Fig. 4a is the platform of R–D map. As can be seen from Fig. 4a, three target peaks are found. It is demonstrated that the masked targets can be detected distinctly without the impact of the interference.

The Doppler dimension of the R–D map is shown in Fig. 4b. Compared with Fig. 3, three peaks appear at the location of 20, −55 and 75 Doppler bin. The locations of the peaks correspond with the Doppler frequency of the targets. The range dimension of the R–D map is shown in Fig. 4c. As can be seen from Fig. 4c, three peaks appear at the location of 39, 79 and 109 range bin. The locations of the peaks correspond with the range bins of the targets. Fig. 4 shows after the interference is cancelled, the masked targets can be detected clearly.

The result of the matched filtering indicates that the PCA + ECA algorithm can extract the interference components from the array element signals and cancel the interference in the echoes with the extracted components as the reference. Without the impact of the interference, the target can be detected. The result proves the feasibility of the method proposed by this paper.

The other simulation is constructed to study the cancellation performance of the method proposed by this paper. The similarity is taken as the performance index of the interference cancellation. The function of the similarity is given by
\[
\gamma(J, s_{\text{echo}}) = \frac{\sum_{i=1}^{N} J(i)s_{\text{echo}}(i)}{\sqrt{\sum_{i=1}^{N} |s_{\text{echo}}(i)|^2} \sqrt{\sum_{i=1}^{N} |J(i)|^2}},
\] (18)

where, $J(i)$ is the interference, $s_{\text{echo}}(i)$ is the echo. Compute the similarity $\gamma_i$ between the interference and the echo after the interference cancellation. On the condition of different INRs, the similarities are shown by Fig. 5.
As can be seen from Fig. 5, with the INR increasing, the similarity $\gamma_1$ between the interference and the echo after the interference cancellation reduces gradually. When the INR reaches 26 dB, the similarity tends to be stable. When the INR is larger, the similarity $\gamma_1$ is smaller. The smaller similarity means that when the INR is larger, the interference component in the echo is less after the interference cancellation. The larger INR makes the extraction performance of PCA algorithm better, the interference can be cancelled by the ECA with the extracted principal component as the reference. The simulation result proves that the interference cancellation performance of the method proposed by this paper improves with the INR increasing.

Compute the similarity $\gamma_2$ between the interference and the echo before the interference cancellation, and compute the difference value $\Delta \gamma$ between $\gamma_2$ and $\gamma_1$. As can be seen from Fig. 6, the difference value $\Delta \gamma$ increases with the INR increasing. When the INR reaches 26 dB, the difference value $\Delta \gamma$ tends to be stable. The larger $\Delta \gamma$ means that the better performance of the interference cancellation. The conclusion drawn from Fig. 6 is the same as Fig. 5. The result shows when the INR is larger, the cancellation performance of the method proposed by this paper is better.

5 Conclusion
Aiming to the issue of the mainlobe interference in the PBR, the paper proposes a method based on the PCA+ECA to cancel the interference components in the echoes, in result that the target signals masked by the interference can be detected. The method proposed by this paper extracts the interference components form the array element signals with the PCA algorithm. Then, with the extracted components as the reference, the ECA is applied to cancel the interferences from the echoes. The simulation result proves the feasibility of the method proposed by this paper.

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7 References
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