MULTITARGET DETECTION AND LOCALIZATION METHOD FOR BISTATIC MIMO RADAR

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Abstract

In this paper, we present a scheme of detection and localization of multiple targets in the same range cell using two transmitters bistatic MIMO radar. The signal model is constructed by means of the rotational factor produced by transmitter. Based on the signal model, canonical correlation test (CCT) method is extended directly to determine the number of targets. Furthermore, a close form solution for localization the multiple targets is presented via ESPRIT. The direction of arrivals (DOAs) and direction of departures (DODs) of the targets can be solved and paired automatically. Simulation results demonstrate the effectiveness of the methods.

1 Introduction

Multiple-input multiple-output (MIMO) radar is attracting the attentions of both academic and the industrial world, for its potential advantages [1-9]. Many MIMO radar schemes have been proposed to exploiting the spatial diversity [1-3] (statistical MIMO radar), which requires large inter-element distances to ensure that a target is observed from different aspect. So the performance of target detection can be improved by non-coherent processing. Unlike statistical MIMO radar, co-located MIMO radar schemes [4-7], which have small inter-element space, were proposed to achieve the coherent processing gain. In [5], it is shown that MIMO radar allows one to obtain virtual aperture which is larger than real aperture and results in narrower beamwidth and lower sidelobes. Parameter identifiability is discussed in [7]; it proved that the maximum number of targets that can be unambiguously identified by the radar is increasing greatly. The high resolution capability of sparse aperture MIMO radar with coherence processing had been analyzed in [8]. In [9], adaptive techniques are applied to MIMO radar for estimating the radar cross section (RCS) of targets. However, the adaptive techniques in [9] need angle searching in the whole interesting sections. In [10], the scheme of target localization using bistatic MIMO radar was presented and the performance of localization had been analyzed. However, to obtain the location of the targets, two-dimension angle searching was necessitated.

In this paper, we present multitarget detection and localization method following the bistatic MIMO radar scheme in [10]. Based the signal model constructed by means of rotational factor produced by multi-transmitter, we first use the source number detection method to detection the number of targets. Then an ESPRIT based close-form solution for bistatic MIMO radar was developed to estimate the direction of arrivals (DOAs) and direction of departures (DODs) of the targets in the same range cell. The performances of detection and estimate are evaluated by probability of error of detection and root mean square error (RMSE).

2 Bistatic MIMO Radar Signal Model

The array structure of bistatic MIMO radar used in this paper is illustrated in Fig. 1 [10]. A 2-transmit/ N-receive (2T/ N R) antenna configuration is considered. For clarity and mathematical tractability, we use a simple model that ignores Doppler effects and clutters, and the range of the target is assumed much larger than the aperture of transmit array and receive array. Considering the RCS which is constant during a pulse period and varying independently pulse to pulse, our target model is a classical Swerling case II. is the inter-element space at the transmitter and  is the inter-element space at the receiver. Assume that the target is at angles ( , ), where is the angle of the target with respect to the transmit array (i.e. DOD) and is the angle with respect to the receive array (i.e DOA). denotes the carrier wavelength. , = [s(1), · · · , s(L)] , i = 1, 2 denotes the coded pulse of the th transmitter, where L represents the number of code in one pulse period. In the case of target at location ( , ), the received signal vector of the th pulse period is given by

\[ \mathbf{r}_q(n) = \mathbf{A}(?) \text{diag}(\mathbf{a}_q) \mathbf{B}(?) \mathbf{s}(n) + \mathbf{w}_q(n) \]  

where \((\cdot)^T\) denotes vector/matrix transpose. 
\[ \mathbf{r}_q(n) = [r_q^n, r_{q+1}^n, \cdots, r_{q+L}^n]^T \] and \( \mathbf{s}(n) = [s(n), s(n+1), \cdots, s(n+L)]^T \) with \( n = 1 \cdots L \). \( \mathbf{a}_q = [\alpha_{q,1}, \cdots, \alpha_{q,L}]^T \), where \( \alpha_{q,1}, \cdots, \alpha_{q,L} \) are the RCS of the targets in the th pulse period. \text{diag}(\mathbf{v})\) denotes a diagonal matrix constructed by the vector \( \mathbf{v} \). \( \mathbf{A}(?) = [\mathbf{a}(?)_1, \mathbf{a}(?)_2, \cdots, \mathbf{a}(?)_N] \) is the receive steering matrix.

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and \( \theta_{n}, \cdots, \theta_{r} \) are the DOAs of the targets. \( \mathbf{B}(\Theta) = [\mathbf{b}(\theta_{1}), \mathbf{b}(\theta_{2}), \cdots, \mathbf{b}(\theta_{r})] \) is the transmit steering matrix, and \( \Theta = \theta_{1} \cdots \theta_{r} \) are the DODs of the targets. 

The targets should be detected before the targets. The number of the targets was constructed to estimate DOAs and DODs of the targets. 

\[ \mathbf{a}(\Theta) = [\mathbf{a}_{1}(\theta_{1}), \cdots, \mathbf{a}_{r}(\theta_{r})] \] 
and \( \mathbf{b}(\Theta) = [\mathbf{b}_{1}(\theta_{1}), \cdots, \mathbf{b}_{r}(\theta_{r})] \). The noise vectors \( \mathbf{w}_{q}(n) \) is assumed to be independent, zero-mean complex Gaussian distribution with \( \mathbf{w}_{q} \sim N(0, \mathbf{R}_{N}) \).

3 Multitarget Detection and Estimate Method

In this section, two transmit antennas bistatic MIMO radar model was constructed to estimate DOAs and DODs of the targets. The number of the targets should be detected before localization the targets.

3.1 Targets Detection Method

In the case of two transmit antennas, when the signals of \( Q \) pulses period are transmitted, (3) can be expressed as follows:

\[ \mathbf{Y}_{1} = \mathbf{A}(\Theta) \mathbf{H} + \mathbf{N}_{1}, \]  
\[ \mathbf{Y}_{2} = \mathbf{A}(\Theta) \mathbf{D}_{2} \mathbf{H} + \mathbf{N}_{2}, \]  

where, \( \mathbf{Y}_{n} = [\mathbf{y}_{n1}, \cdots, \mathbf{y}_{nm}] \) and \( \mathbf{N}_{n} = [\mathbf{n}_{n1}, \cdots, \mathbf{n}_{nm}], m = 1, 2 \); \( \mathbf{H} = [\mathbf{a}_{1}, \cdots, \mathbf{a}_{q}] \).

The covariance matrix of the noises has the property as follows:

\[ \mathbf{E}[\mathbf{N}_{1} \mathbf{N}_{2}^{H}] = \mathbf{E}[\sum_{t=1}^{m} \mathbf{w}_{q}(n)\mathbf{s}_{n}(n)^{*}] \mathbf{E}[\sum_{t=1}^{m} \mathbf{w}_{q}(n)\mathbf{s}_{n}(n)^{*}]^{H} \]

\[ = \begin{bmatrix} \mathbf{R}_{s} & 0 \\ 0 & \mathbf{R}_{s} \end{bmatrix}, \]

where \( \mathbf{R}_{s} = \mathbf{R}_{N} / L \).

From (4), (5) and (6), we find that the signal model of the bistatic MIMO radar had been changed to satisfy the conditions of canonical correlation test (CCT) method [11]. Thus the CCT method can be applied to estimate the number of tags for bistatic MIMO radar.

The covariance matrix of receive data can be written as follows:

\[ \mathbf{R}_{11} = \mathbf{E}[\mathbf{Y}_{1}\mathbf{Y}_{1}^{H}] = \mathbf{A}(\Theta) \mathbf{R}_{N} \mathbf{A}(\Theta)^{H} + \mathbf{R}_{s}, \]
\[ \mathbf{R}_{21} = \mathbf{E}[\mathbf{Y}_{2}\mathbf{Y}_{1}^{H}] = \mathbf{A}(\Theta) \mathbf{D}_{2} \mathbf{R}_{N} \mathbf{A}(\Theta)^{H} + \mathbf{R}_{s}, \]
\[ \mathbf{R}_{22} = \mathbf{E}[\mathbf{Y}_{2}\mathbf{Y}_{2}^{H}] = \mathbf{A}(\Theta) \mathbf{D}_{2} \mathbf{D}_{2}^{H} \mathbf{R}_{N} \mathbf{A}(\Theta)^{H} + \mathbf{R}_{s} \]  

where \( \mathbf{R}_{N} = \mathbf{E}[\mathbf{H} \mathbf{H}^{H}] \).

As the formulas in [11], a matrix can be constructed and decomposed by singular value decomposition (SVD) as follows:

\[ \tilde{\mathbf{R}} = \mathbf{R}_{11}^{-1/2} \mathbf{R}_{12} \mathbf{R}_{12}^{-1/2} = \bar{\mathbf{U}} \mathbf{\Lambda} \bar{\mathbf{V}}^{H} \]

where \( \bar{\Lambda} = \text{diag}\{\sigma_{1}, \sigma_{2}, \cdots, \sigma_{N}\} \) denotes the diagonal matrix constructed by the singular value and satisfied the relationship \( \sigma_{1} \geq \sigma_{2} \geq \cdots \geq \sigma_{N} > 0 \). The number of targets estimate can be formular as a hypothesis testing problem

\[ c(k) = \left[ 2Q -(2N + 1) \right] \sum_{k=1}^{N} \ln(1 - \sigma_{k}^{2}) > T_{k} \]

where \( H_{k} \) denotes the hypothesis there are more than \( k \) targets present. The test is iterated for \( k = 0, \cdots, N - 1 \) until a primary hypothesis is accepted. Then the estimated number of targets is assigned the value \( k \).

The threshold \( T_{k} \) can be obtained by the allowable probability of false alarm as follows:

\[ P_{f} = \int_{H_{k}}^{\infty} \frac{1}{2\pi^{m/2} \Gamma(m/2)} y^{m/2 - 1} e^{-y/2} dy, k = 1, 2, \cdots, N - 1 \]

where \( m = 2(N-k)^{2} \) is the degree of freedom of \( \chi^{2} \) distributions.

3.2 Close Form Solution for Targets Localization

To obtain the close form solution of DOA and DOD of targets, we first construct a matrix \( \mathbf{R} = \mathbf{R}_{21} \mathbf{R}_{21}^{H} \), where \( \mathbf{R}_{21}^{H} \) is the Penrose-Moore inverse (pseudo inverse) of \( \mathbf{R}_{11} \). Let \( \{\mathbf{u}_{1}, \cdots, \mathbf{u}_{m}\} \) and \( \{\mathbf{v}_{1}, \cdots, \mathbf{v}_{r}\} \) be the left and right singular vectors of \( \mathbf{R}_{11} \) respectively. We define the Penrose-Moore inverse of \( \mathbf{R}_{11} \) as

Fig.1 Bistatic MIMO radar scenario
\[ R_{II} = \sum_{i=1}^{p} \frac{1}{\sigma_i} v_i u_i^H \]  
\[ \text{RA} = A, D_2 \]  
\[ R = U \theta U^H \]

where \( \theta = \text{diag}(\sigma_1, \ldots, \sigma_p) \). From (14) and (15), estimates of the DOAs and DODs are given by \( U \) and \( \theta \), respectively.

As a result, the DODs of the targets are
\[ \theta_i = \arcsin\left( \frac{\lambda}{2\pi d_i} \right), \quad i = 1, \ldots, \tilde{P} \]

The DOAs can be estimated by all the elements of \( U \). \[ \theta_i = \frac{1}{N-1} \sum_{j=2}^{N} \arcsin\left( \frac{u_{i,j}}{u_{i,j-1}} \right) \frac{\lambda}{2\pi d_i}, \quad i = 1, \ldots, \tilde{P} \]

where \( u_{i,j}, j = 1, \ldots, N, i = 1, \ldots, \tilde{P} \) being the \( j \)th row and \( i \)th column element of \( U \). It should be mentioned that bistatic MIMO radar can locate as many targets as the number of receive antennas. The DOAs and DODs of the targets are paired automatically.

**4 Simulation Results**

In this section, we demonstrate via simulations the detection and localization performance of the proposed scheme in this paper. Two transmit antennas and eight receive antennas is considered. The array structure is the same as Fig.1, and with half- wavelength space between adjacent elements is used both for transmitter and receiver. Hadamard codes are selected as transmit signals. \( L = 32 \) is the number of codes in one pulse period. The variances of the RCS of the targets are 1. All the simulations are carried out in the presence of spatial color noise. The correlation coefficient of the color noise is 0.6.

In the bistatic MIMO radar, the targets which are in the same range cell should be distributed on the surface of a ellipse with the focuses at receivers and transmitters respectively. In the simulations, the angles are selected arbitrarily for simple. Assume seven targets in a range cell. The locations of the targets are given in Table I.

<table>
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<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
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<td>-50</td>
<td>-10</td>
<td>-40</td>
<td>60</td>
<td>30</td>
</tr>
<tr>
<td>DOA</td>
<td>-50</td>
<td>-40</td>
<td>-20</td>
<td>10</td>
<td>40</td>
<td>20</td>
<td>50</td>
</tr>
</tbody>
</table>

Table1: Locations of Seven Targets (degree)

In Fig. 1, we plot the the probability of error of the number targets detection using CCT method. The probability of false alarm is selected as \( P_f = 0.01 \) and \( P_f = 0.001 \) respectively to determine the thresholds of the detection. For each simulation, 20000 Monte Carlo trials are run. The influence of SNR and the number of pulses are investigated by the simulation. It is shown that the CCT method is robust to detect the number of the targets. The probability of error of the detection approximates the probability of false alarm in spite of the change of the SNR and the number of pulses. The CCT method can be used effectively in the bistatic MIMO radar system.

The ESPRIT based angle estimate results in Fig. 2 are obtained with 100 Monte Carlo trials when the SNR is 10dB. It can be observed that the systems can locate all the 7 targets near the exact targets location. The dependence of the RMSE of proposed estimation method on SNR and the number of pulses are plotted in Fig. 3. Since the performance of the estimation is related to the location of the target, we evaluate the estimation performance using the average RMSE of seven targets. It is shown that the performance of DOA is much better than the one of DOD above certain SNR using the proposed two transmitters MIMO radar scheme.
5 Conclusions

A two-transmitter bistatic MIMO radar scheme has proposed to detection and localization multiple targets in the same range cell. The model of the scheme had be constructed by means of the rotational factor produced by multi-transmitter. CCT method and ESPRIT method had been applied to detect the number of the targets and estimate the location of the targets based on the model. Computer simulations demonstrate the effective of the proposed scheme.

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References
