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Research Article

Angle Estimation Using Local Searching for Bistatic MIMO Radar with Unknown MCM

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Multiple input and multiple output (MIMO) radar systems have advantages over traditional phased-array radar in resolution, parameter identifiability, and target detection. However, the estimation performance of the direction of arrivals (DOAs) and the direction of departures (DODs) will be significantly degraded for a colocated MIMO radar system with unknown mutual coupling matrix (MCM). Although auxiliary sensors (AS) can be set to solve this problem, the computational cost of two-dimensional multiple signal classification (2D-MUSIC) is still large. In this paper, a new angle estimation method is proposed to reduce the computational complexity. First, a local-search range is defined for each initial angle estimation obtained by the MUSIC with AS method. Second, the new estimation of DOAs and DODs of the targets is estimated via the joint estimation theory of angle and mutual coupling coefficient in the local search area. Simulation results validate that the proposed method can obtain the same precision and have the advantage over the global searching in computational complexity.

1. Introduction

A MIMO radar system transmits orthogonal waveforms via its antennas, which can supply more independent transmit/receive channels than that of traditional phased-array radar. There are two types of MIMO radar systems: one is statistical MIMO radar [1, 2] and the other is colocated MIMO radar [3]. The former is composed of widely separated antennas, which can achieve the spatial diversity gain and overcome the scintillation effect of targets. The antenna configuration of the latter is the same as that of phased array radar and can form virtual arrays, which result in performance improvement of target detection and parameter identification. In our work, we focus on a bistatic radar system based on the latter type of MIMO radar system.

The bistatic MIMO radar system combines the advantages of MIMO radar and bistatic radar system, which has been researched extensively. How to improve the estimation performance of direction-of-arrivals (DOAs) and direction of departures (DODs) is one of the hot research issues in existing studies. A great number of estimation methods have been proposed, such as maximum likelihood (ML) [4–7], subspace-based [8–12], and sparse signal representation (SSR) [13–15]. Compared to ML and SSR, multiple signal classification (MUSIC) and estimation of signal parameters via rotational invariance technique (ESPRIT) are two typical methods which can achieve high estimation performance with low computational complexity than that of ML and SSR [16]. These methods will work well under ideal conditions. In a real scenario, however, there is a mutual coupling effect between the elements of array, which has a great influence on the performance of angle estimation methods [17–20], and there is no exception for co-located MIMO radar using arrays [21–23].

There are many methods for solving the problem of mutual coupling effect, such as self-calibration method [24], sparse array method [25], and auxiliary sensors(AS) method [17, 21, 26, 27]. Among these methods, the AS method is proved to be the most effective and feasible method [17, 21, 26, 27]. In this method, the first and the last sensors of the transmit and receive array are set as auxiliary sensors. After that, the effects of unknown MCM can be eliminated, and then the MUSIC method can be directly applied to estimate the DOAs and DODs of targets. Unfortunately, AS method results in the loss of array aperture, which is caused by the reduction of the number of available array elements [17, 28, 29]. More importantly, there is high computational complexity since two-dimensional global searching to be performed by MUSIC in the process of the angle estimation [30–32].

In this paper, a local searching algorithm for the estimation of DOAs and DODs for the colocated MIMO radar in the presence of mutual coupling is proposed. The method has three phases. First, initial DOAs and DODs are estimated via AS method without knowing the mutual coupling coefficients. Second, a local search range is defined for each pair of DOAs and DODs obtained in the first phase. Finally, new angle estimates are obtained based on the theory of joint angle and mutual coupling coefficient estimation. We make a lot of analysis on the key factors, such as search range and search step length, which are closely related to the computational complexity and estimation accuracy of our algorithm. Simulation results validate that the proposed algorithm can achieve good performance in terms of lower complexity and high estimation accuracy.

This paper is organized as follows. Section 2 introduces the signal model of colocated MIMO system. Section 3 presents the process of the local search method for angle estimation and theoretically analyzes the computational complexity of that. Simulation results are given in Section 4 to demonstrate the performance of the proposed method. And Section 5 is the conclusion.

2. Signal Model

Consider a bistatic MIMO radar system with a transmitter and a receiver. Both the transmitter and the receiver are uniform linear arrays (ULA), which are equipped with M transmitting antennas and N receiving antennas, respectively. The distance between adjacent antennas is half a wavelength. It is assumed that there are Q targets in far-field, the DOD and DOA of the q th target relative to the transmitter and the receiver are φ_q and θ_q, respectively. In a MIMO radar system, the transmitter transmits M orthogonal waveforms $\mathbf{S}_m(t), m = 1, 2, \cdots, M$, which satisfies the condition of $\int_{T_p} \mathbf{S}(t)\mathbf{S}^H(t) = \mathbf{I}_M$. Here, T_P is the duration of the pulse, and $\mathbf{I}$ is the identity matrix. Thus, the received data at time t in the kth snapshot can be written as

$$\mathbf{x}_k(t) = \sum_{q=1}^{Q} \beta_{qk}\mathbf{a}(\theta_q)\mathbf{b}^T(\varphi_q)\mathbf{S}(t) + \mathbf{n}_k(t), \quad (1)$$

where $\mathbf{x}_k(t) \in \mathbb{C}^{N\times 1}$ is the received data vector, β_{qk} is the channel parameter representing reflection coefficient and Doppler frequency, $\mathbf{a}(\theta_q) = [1, e^{j\pi \sin \theta_q}, \cdots, e^{j\pi(M-1) \sin \theta_q}]^T$ and $\mathbf{b}(\theta_q) = [1, e^{j\pi \sin \varphi_q}, \cdots, e^{j\pi(N-1) \sin \varphi_q}]^T$ are receive steering vector and transmitting steering vector, respectively, $\mathbf{S}(t) = [s_1(t), s_2(t), \cdots, s_M(t)]^T$ is the signal vector, and $\mathbf{n}_k(t)$ is considered as the unknown uniform noise.

After matched filtering by M matched filters, a matrix form of the output data is given by

$$\mathbf{X}_k = \mathbf{A}(\theta)\mathbf{\Sigma}_k\mathbf{B}^T(\varphi) + \mathbf{N}_k, \quad (2)$$

where $\mathbf{X}_k \in \mathbb{C}^{M\times N}$ is the output data, $\mathbf{A}(\theta) = [\mathbf{a}(\theta_1), \mathbf{a}(\theta_2), \cdots, \mathbf{a}(\theta_Q)]$ and $\mathbf{B}(\theta) = [\mathbf{b}(\varphi_1), \mathbf{b}(\varphi_2), \cdots, \mathbf{b}(\varphi_Q)]$ are the transmit steering matrix and the receiving steering matrix, respectively, $\mathbf{\Sigma}_k = \mathrm{diag}\{\beta_{1k}, \beta_{1k}, \cdots, \beta_{Qk}\}$ is the channel parameters matrix, and $\mathbf{N}_k \in \mathbb{C}^{M\times N}$ is the noise.

However, the mutual coupling effect exits objectively in the arrays, which is not reflected in formula (2). In general, they can be described as mutual coupling matrix (MCM), also called band-symmetric Toeplitz matrix. So, in the case of mutual coupling, the actual data that the receiver outputs should be expressed as

$$\mathbf{X}_k = [\mathbf{C}_r\mathbf{A}(\theta)]\mathbf{\Sigma}_k[\mathbf{C}_t\mathbf{B}(\varphi)]^T + \mathbf{N}_k, \quad (3)$$

where $\mathbf{C}_t = \mathrm{toeplitz}([1, c_1, 0, \cdots, 0]) \in \mathbb{C}^{M\times M}$ and $\mathbf{C}_r = \mathrm{toeplitz}([1, c_2, 0, \cdots, 0]) \in \mathbb{C}^{N\times N}$ represent the MCM of transmit arrays and receive arrays, respectively.

In order to process MIMO radar data, it is necessary to change the matrix $\mathbf{X}_k$ into a column vector $\mathbf{Y}_k$, which is given by

$$\mathbf{Y}_k = \mathrm{vec}(\mathbf{X}_k) = [\mathbf{C}_t \otimes \mathbf{C}_r][\mathbf{A}(\theta) \odot \mathbf{B}(\varphi)]\boldsymbol{\beta}_k + \mathbf{W}_k = \mathbf{C}\mathbf{K}(\theta, \varphi)\boldsymbol{\beta}_k + \mathbf{W}_k, \quad (4)$$

where $\mathrm{vec}(\cdot)$, $\mathbf{C} = \mathbf{C}_t \otimes \mathbf{C}_r$, and $\mathbf{A}(\theta) \odot \mathbf{B}(\varphi) = \mathbf{K}(\theta, \varphi)$ denote the vectorization operation, the equivalent of MCM, and the virtual steering matrix, respectively. The symbols $\otimes$ and $\odot$ stand for Kronecker product and Hadamard product, respectively. $\mathbf{K}(\theta, \varphi) = [\mathbf{k}(\theta_1, \varphi_1), \cdots, \mathbf{k}(\theta_Q, \varphi_Q)]$, in which the $\mathbf{k}(\theta_q, \varphi_q)$ satisfied with $\mathbf{k}(\theta_q, \varphi_q) = \mathbf{a}(\theta_q) \otimes \mathbf{b}(\varphi_q)$. $\boldsymbol{\beta}_k = \mathrm{vec}(\mathbf{\Sigma}_k)$, and $\mathbf{W}_k = \mathrm{vec}(\mathbf{N}_k)$.

The sampling covariance matrix of $\mathbf{Y}_k$ can be written as:

$$\mathbf{R}_Y = E\{\mathbf{Y}_k\mathbf{Y}_k^H\} = \mathbf{C}\mathbf{K}(\theta, \varphi)\boldsymbol{\beta}_k\boldsymbol{\beta}_k^H[\mathbf{C}\mathbf{K}(\theta, \varphi)]^H + \sigma^2\mathbf{I}_{MN}, \quad (5)$$

where σ^2 is the average noise power. If $\mathbf{C}$ is known, then the noise subspace and the signal subspace can be obtained by Eigenvalue decomposition of equation (5). Furthermore, the DOA can be estimated through subspace method. The truth of the matter that $\mathbf{C}$ is usually unknown, which will result in errors in angle estimation.

3. Proposed Method

3.1. Method. The proposed method consists of three phases as follows.

3.1.1. Phase 1. In the first phase, the sensors on either sides of the transmitter/receiver array are set to be auxiliary sensors, which are marked with grey color and shown in Figure 1. Then, we use the algorithm in reference [29] to obtain the initial angle estimations of all targets. It is noted that the

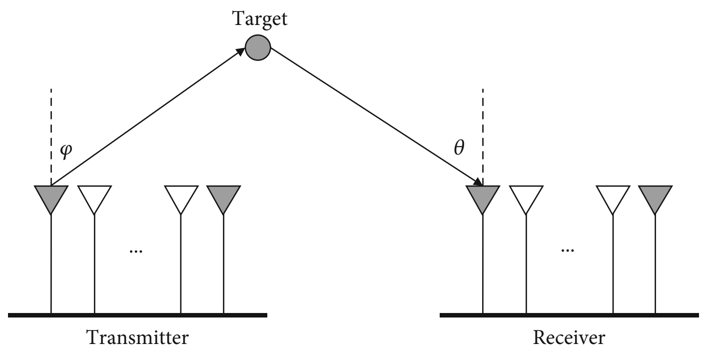

Figure 1: The single base MIMO radar array model with auxiliary sensors.

search step length can be allowed to be set longer in the process of spectral peak search. For example, the step length is 0.1 degree instead of 0.01 degree. Although the precision becomes worse with longer step length, the computational cost is significantly reduced in the same search area.

3.1.2. Phase 2. In order to compensate for the decrease of accuracy caused by the first phase, $\boldsymbol{Q}$ local search areas with the same size are defined for Q targets. And we let the initial estimation of qth target $\langle \breve{\theta}_q, \breve{\varphi}_q \rangle$ from phase 1 as the center of the qth local search area $\langle \breve{\theta}_q \pm \Delta\theta, \breve{\varphi}_q \pm \Delta\varphi \rangle$. The details are shown in Figure 2. In Figure 2, $\Delta\theta$ and $\Delta\varphi$ indicate the size of the local search area. And the red and blue dots represent one of the initial angle estimation value obtained in phase 1 and the angle estimations to be estimated, respectively. To simplify, we assumed that $\Delta\theta = \Delta\varphi$ in this paper.

3.1.3. Phase 3. In the third phase, we define $(S+1)$ points of the DOAs and the DODs to be searched in the qth local search area for the qth targets are $\langle \breve{\theta}_q - \Delta\theta, \cdots, \breve{\theta}_q - \theta_s, \breve{\theta}_q, \breve{\theta}_q - \theta_s, \cdots, \breve{\theta}_q + \Delta\theta \rangle$ and $\langle \breve{\varphi}_q - \Delta\varphi, \cdots, \breve{\varphi}_q - \varphi_s, \breve{\varphi}_q, \breve{\varphi}_q - \varphi_s, \cdots, \breve{\varphi}_q + \Delta\varphi \rangle$, respectively, where $\theta_s = (2\Delta\theta)/S$. Then, the total number of search points in the qth local search are $(S+1)^2$. Indeed, this phase will increase the cost of computation, but its computation is still much less than that of MUSIC with search step 0.01 degree. We will discuss it in detail later in the section of simulation. After completing the above procedure, the final angle estimation of all targets is based on the theory of joint estimation of angle and mutual coupling coefficient [17].

In equation (4), the mutual coupling matrix can be expressed as

$$\mathbf{C} = \mathbf{C}_t \otimes \mathbf{C}_r = \begin{bmatrix} \mathbf{C}_1 & \mathbf{C}_2 & 0 & \cdots & 0 \\ \mathbf{C}_2 & \mathbf{C}_1 & \mathbf{C}_2 & \cdots & 0 \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ 0 & \cdots & \mathbf{C}_2 & \mathbf{C}_1 & \mathbf{C}_2 \\ 0 & \cdots & 0 & \mathbf{C}_2 & \mathbf{C}_1 \end{bmatrix}, \tag{6}$$

where $\boldsymbol{C}_1$ and $\boldsymbol{C}_2$ are Toeplitz matrix, which are given by

$$\begin{cases} \mathbf{C}_1 = \mathbf{C}_r = \text{toeplitz}\{[1, c_2, 0, \cdots, 0]\} \in \mathbb{C}^{N\times N}, \\ \mathbf{C}_2 = c_1 \cdot \mathbf{C}_r = \text{toeplitz}\{[c_1, c_1 c_2, 0, \cdots, 0]\} \in \mathbb{C}^{N\times N}, \end{cases} \tag{7}$$

where c_1 and c_2 are the unknown mutual coupling coefficients of transmit arrays and receive arrays, respectively.

According to the literature [17], we have

$$\mathbf{C}_k \mathbf{a}(\theta, \rho) = \mathbf{T}_{\mathbf{N}}[\mathbf{a}(\theta)]\rho_k, k = 1, 2, \tag{8}$$

where $\rho_1 = [1, c_1]^T, \rho_2, = [c_1, c_1 c_2]^T$, $\mathbf{T}_{\mathbf{N}} = \mathbf{T}_{\mathbf{N}}^1 + \mathbf{T}_{\mathbf{N}}^2$ is a transformation matrix which can be given by

$$\begin{aligned} [\mathbf{T}_N^1]_{i,j} &= \begin{cases} \mathbf{a}(\theta)_{i+j-1} & i+j \le N+1, \\ 0 & \text{otherwise}, \end{cases} \\ [\mathbf{T}_N^2]_{i,j} &= \begin{cases} \mathbf{a}(\theta)_{i-j+1} & i \ge j \ge 2, \\ 0 & \text{otherwise}. \end{cases} \end{aligned} \tag{9}$$

A transformation matrix $\mathbf{T}_M = \mathbf{T}_M^1 + \mathbf{T}_M^2$ is similarly defined as

$$[\mathbf{T}_M^1]_{i,j} = \begin{cases} \mathbf{b}(\varphi)_{i+j-1} & i+j \le M+1, \\ 0 & \text{otherwise}, \end{cases} \tag{10}$$

$$[\mathbf{T}_M^2]_{i,j} = \begin{cases} \mathbf{b}(\varphi)_{i-j+1} & i \ge j \ge 2, \\ 0 & \text{otherwise}. \end{cases} \tag{11}$$

From equations (8)–(11), we have

$$\mathbf{Ck}(\varphi, \theta) = \mathbf{C}[\mathbf{b}(\varphi) \otimes \mathbf{a}(\theta)] = (\mathbf{T}_M \otimes \mathbf{T}_N) \begin{bmatrix} \rho_1 \\ \rho_2 \end{bmatrix} = \mathbf{T}(\varphi, \theta)\rho, \tag{12}$$

where $\rho = [1, c_1, c_1, c_1 c_2]^T$. The estimates of DOAs can be obtained by the following equation

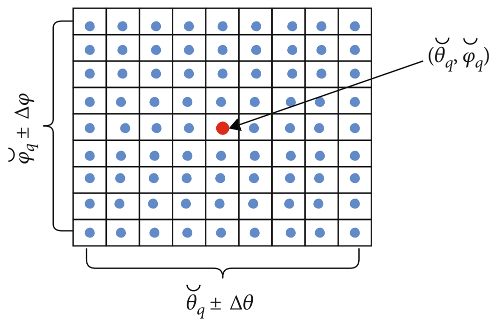

FIGURE 2: A local search area around the initial estimation of the qth target.

$$\left\| \mathbf{E}_n^H \mathbf{Ck}\left(\varphi_q, \theta_q\right) \right\|^2 = \left\| \mathbf{E}_n^H \mathbf{T}\left(\varphi_q, \theta_q\right) \rho \right\|^2 = 0, q = 1, 2, \cdots, Q. \tag{13}$$

The equivalent expression of the equation (13) is as follows

$$\rho^H \mathbf{T}^H \mathbf{E}_n \mathbf{E}_n^H \mathbf{T} \rho = 0. \tag{14}$$

In formula (14), the vector ρ is regarded as an eigenvector, which can be obtained via the eigen decomposition of $\mathbf{T}^H \mathbf{E}_n \mathbf{E}_n^H \mathbf{T}$. And the eigenvalue is zero when the estimates of the angle are equal to the true DOAs. However, the estimates always deviate from the real values. Therefore, an optimization function is constructed, which is given by

$$< \widehat{\varphi}, \widehat{\theta} > = \arg \min_{\varphi, \theta} (\lambda_{\min} [\mathbf{D}(\varphi, \theta)]), \tag{15}$$

where $\mathbf{D}(\varphi, \theta) = \mathbf{T}^H \mathbf{E}_n \mathbf{E}_n^H \mathbf{T}$, and the function of $\lambda_{\min}[\cdot]$ is to select the smallest one from the eigenvalues via ED of $\mathbf{D}(\varphi_n, \theta_n), i = 1, 2, \cdots, N^2 + 1$. In other words, for a local search range, where the angles with minimum eigenvalue are new estimates of DOAs. The eigenvector ρ is corresponding to the minimum eigenvalue, and the mutual coupling coefficients matrix ρ is corresponding to the minimum eigenvalue.

$$\rho = e_{\min} \left[\mathbf{D}\left(\breve{\theta}, \breve{\varphi}\right) \right]. \tag{16}$$

In order to better demonstrate our method, we summarize the realization process of the proposed algorithm in Algorithm 1.

3.2. Computational Complexity of Proposed Method. The value of step length is usually set as 0.01° in global searching. That means the number of search points is 18001 in the range of -90° ~90°. The computational cost of $\mathbf{T}^H \mathbf{E}_n \mathbf{E}_n^H \mathbf{T}$ is $O[8MN(MN - Q) + 16MN]$, and the complexity of eigen decomposition of $\mathbf{D}(\varphi, \theta) \in \mathbb{C}^{4\times4}$ is $O(64)$ for each point via joint estimation of angles and mutual coupling coefficients method. Therefore, the total computational cost of the global searching is $O\{18001 * 64 * [8MN(MN - Q) + 16MN]\}$.

Different from the global searching method, the main calculation process of the proposed method consists of two parts. The first part is to achieve the initial angle estimation via MUISC with the auxiliary element method. The computational cost of this part is $O[3601 * MN(MN - Q) + (MN - Q)]$ under the assumption that the search step length is 0.05°and the search range is -90° ~90°. The angle estimation method of the second part is the same as the first part but with local search, in which the computational cost is $O\{Q(S+1)^2 * 64 * [8MN(MN - Q) + 16MN]\}$. The complexity of the local search method is $O\{[3601 * MN(MN - Q) + (MN - Q)] + Q(S+1)^2 * 644[8MN(MN - Q) + 16MN]\}$.

Let $S = 10$ and set the variation range of the local search to be ±0.05°, then the local search method can achieve the same angle estimation accuracy as the global search method. For simplicity, let $Q = MN - 1$. To compare the computational complexity of the two methods, we define the computational cost ratio of the global search method to the local search method as γ. When $M = N = 12,10,8$, γ is equal to 1.0402, 1.5024, and 2.2367, respectively. It is indicated that the local search method has the advantage over the global search in lightweight applications.

4. Simulation Results and Discussions

In this section, we will demonstrate the performance of the proposed method via three simulations. Consider a L-type bistatic MIMO radar whose transmitter and receiver are ULAs with 8 array elements, which are separated by half wavelength. And $Q = 3$ known uncorrelated targets are located in the far-field with angles $(\theta_1 = 10°, \varphi_1 = 10°)$, $(\theta_1 = 30°, \varphi_1 = 30°)$, and $(\theta3 = 45°, \varphi_3 = 45°)$, respectively. The transmit signals are orthogonal discrete multifrequency signals [*], and additive noise is zero mean, i.i.d., white Gaussian processes with variance σ^2. We set the number of Monto Carlo trial (K) and snapshots (P) to be 500 and 100, respectively. The validity of angle estimation is measured by root mean square error (RMSE):

$$RMSE = \sqrt{\frac{1}{2KQ} \sum_{k=1}^{K} \sum_{q=1}^{Q} \left[\left(\theta\wedge_{k,q} - \theta_q\right)^2 + \left(\phi\wedge_{k,q} - \phi_q\right)^2 \right]}, \tag{17}$$

where $< \widehat{\theta}_{k,q}, \widehat{\varphi}_{k,q} >$ denotes the qth DOA and DOD in the kth trial, and $< \theta_q, \varphi_q >$ denotes the true DOA and DOD of the qth target.

4.1. Simulation Experiment 1: RMSE Simulation of Angle Estimation of the Proposed Method with Different Segments. Before doing this experiment, we had obtained the initial angle estimations $\{\widetilde{\theta}_q, \widetilde{\varphi}_q\}$ of Q known targets via auxiliary elements method, in which the search step length was set to be 0.1°. In this experiment, the local search range of each angle estimation is $< \widetilde{\theta}_q \pm 0.5°, \widetilde{\varphi}_q \pm 0.5° >$. $S_1 = 10$, $S_2 = 20$, and $S_3 = 40$ are different segments, and the corresponding

1: Use MUSIC with AS method, find the initial angle estimation $\langle \breve{\theta}_q, \breve{\varphi}_q \rangle$.

2: Define a local search range $\langle \breve{\theta}_q \pm \Delta\theta, \breve{\varphi}_q \pm \Delta\varphi \rangle$, divide $\breve{\theta}_q \pm \Delta\theta$ and $\breve{\varphi}_q \pm \Delta\varphi$ into $S+1$ segments, obtain $(S+1)^2$ angle points to be estimated.

3: Compute the mutual coupling matrix $\boldsymbol{C}$ and the transformation matrix $\boldsymbol{T}$ according to (6) and (8)–(12), respectively.

4: Using noise covariance matrix $\mathbf{E}_n$ and $\boldsymbol{T}$ obtained in step 3, compute $\mathbf{D}(\varphi, \theta)$ according to $\mathbf{D}(\varphi, \theta) = \mathbf{T}^H \mathbf{E}_n \mathbf{E}_n^H \mathbf{T}$ for each angle point.

5: Compute the eigen decomposition of $\mathbf{D}(\varphi, \theta)$.

6: The angle point corresponding to the minimal eigenvalue obtained from step 5, which is select as angle estimation of the qth target according to (15).

7: Obtain the mutual coupling coefficients according to (16).

Algorithm 1: The proposed method.

search step length is 0.1°, 0.05°, and 0.025°, respectively. The number of points to be estimated is 121, 441, and 1681, respectively.

Figure 3 shows the RMSEs of the proposed method with different segments in the case of the fixed search range. From Figure 3, we can see that the proposed method can achieve better performance with the increase in the number of search segments.

4.2. Simulation Experiment 2: RMSE Simulation of Angle Estimation of the Proposed Method with Different Search Range. For simplicity, the number of search segments is fixed at 10 in this experiment. That is to say, the number of search points is 121. By setting the search step length d to be 0.05° and 0.1°, we get the search range is ±0.25° and ±0.5°, respectively. Figure 4 shows the RMSEs of the proposed method with different search range in the case of fixed search segments. We have noted that large search step length provides better performance in the case of lower SNR. This is because there is a large deviation between true angle and initial angle estimation obtained under the conditions of low SNR. As a result, the probability of a small search range covering the true angle is less than that of a large search range. With the increase of SNR, the performance of small range search is improved significantly.

4.3. Simulation Experiment 3: Comparison of the Proposed Method, Standard MUSIC, and MUSIC with Auxiliary Sensors. Experiments 1 and 2 merely show that the proposed method itself is affected by the search range and search step length. To prove the good performance of the proposed method under the condition of unknown MCM, we make a comparison of it with traditional DOA estimation methods based on spectral peak search, such as standard MUSIC method and MUSIC with auxiliary sensors method. At first, we set the search length to be 0.1° for all methods tested. Then, for the proposed method, a local search is established with a range from −0.05° to +0.05°, and segments are equal to 11, which resulting in 121 grid points is necessary to be estimated. Figure 5 shows the estimation RMSEs of the three different methods. From Figure 5, we can see that standard MUSIC cannot estimate the angles under the condition of mutual coupling. The MUSIC with auxiliary sensors method can obtain the angle estimation, but its RMSE is larger than that of the proposed method. The same RMSE will be

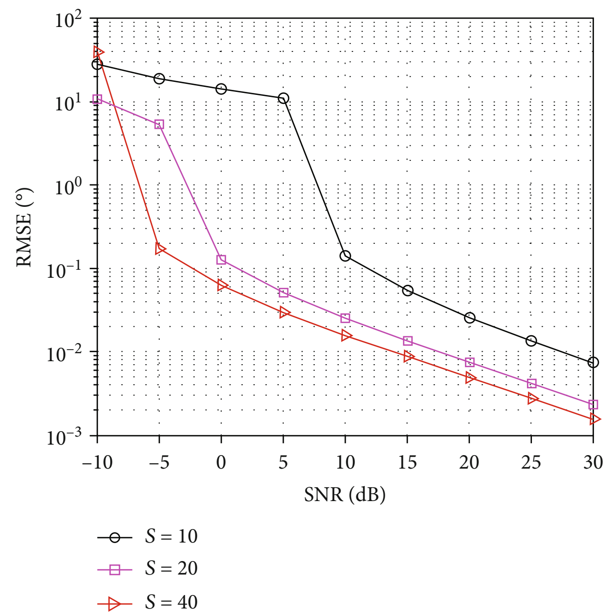

Figure 3: The RMSEs versus SNR for segments = 10, 20, and 40.

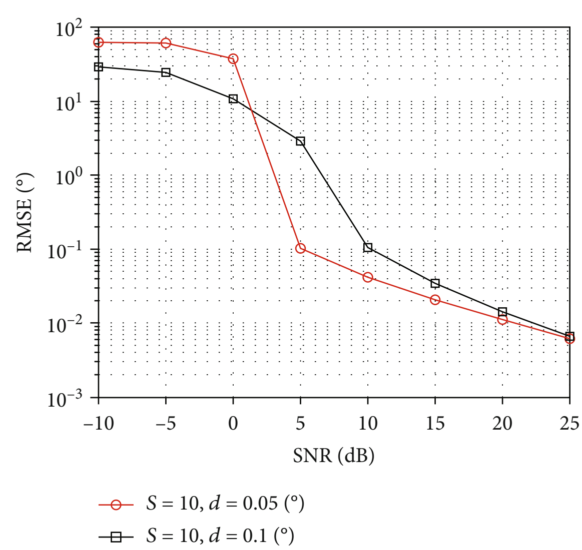

Figure 4: The RMSEs versus SNR for search step length =±0.25° and ±0.5°.

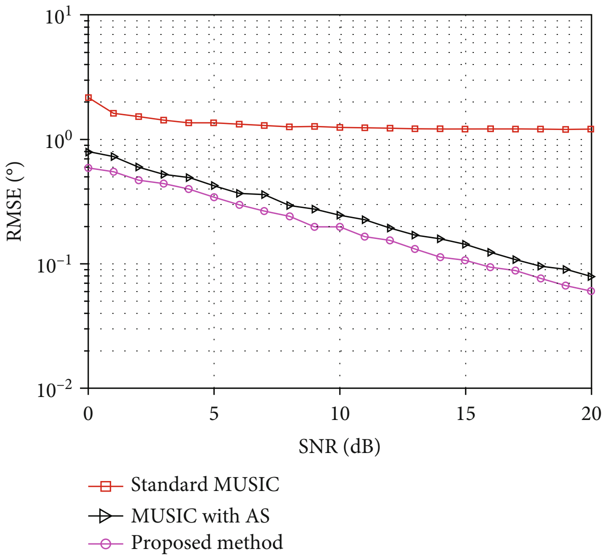

FIGURE 5: The RMSEs of angle estimation versus SNR in experiment 3.

obtained if the search step length is equal. But the MUSIC with auxiliary sensors has a higher computational complexity than that of our method, which is proved in Section 3.

5. Conclusion

In this paper, we have studied the problem of DOAs and DOD estimation of bistatic MIMO radar in the presence of unknown mutual coupling. The auxiliary sensor method is one of the effective methods to solve this problem. But it still has a high computational cost while the MUSIC algorithm is used for 2D global searching. To reduce the computational cost of that, a local search method has been proposed. The angle estimation performance of the proposed method has an advantage over that of MUSIC with auxiliary element method via global searching in computational complexity. The main reason is that it allows the auxiliary element method to obtain the initial value of the angle with a larger search step length. And the angular accuracy degradation, which caused by globe searching with large search length, can be compensated by local searching. In addition, the mutual coupling coefficients can be obtained based on the joint estimation theory. Our work shows that the proposed algorithm is more suitable for lightweight applications.

Data Availability

The data included in this paper are available without any restriction.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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