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Multi-SVD based subspace estimation to improve angle estimation accuracy in bistatic MIMO radar

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ABSTRACT

A new multi-SVD based subspace estimation algorithm is proposed to improve the direction of departure (DOD) and direction of arrival (DOA) estimation accuracy for bistatic multiple-input multiple-output (MIMO) radar. First, the matched filter output is transformed to a 3-order tensor. Then the signal subspace is estimated by multi-SVD of the matrix unfoldings of this tensor or its covariance tensor. Since the multidimensional structure is utilized, the estimated signal subspace of our method has better accuracy than that of the traditional SVD/EVD method. Combined with the classical subspace based methods, such as MUSIC and ESPRIT, the proposed approach improves the angle estimation performance compared with the existing ones. Simulation results confirm the effectiveness of our method.

1. Introduction

Multiple-input multiple-output (MIMO) radar has gained increasing attention and becomes a hot research area for its potential advantages [1–3]. It utilizes multiple antennas to simultaneously transmit several orthogonal waveforms and receive reflected signals in similar ways. According to the configuration of transmit/receive arrays, two kinds of MIMO radars are formed. One is called statistical MIMO radar [1], which can resist the radar cross section (RCS) scintillation effect due to the widely spaced transmit antennas and receive antennas. The other one is named co-located MIMO radar [2], including monostatic and bistatic cases, whose elements in transmit and receive arrays are closely spaced. In co-located MIMO radar, one can obtain virtual aperture in the receiver which is larger than the real one through waveform diversity. This yields many advantages such as flexible spatial transmit beam pattern design and high resolution spatial spectral estimation [2,3].

Direction of arrival estimation is encountered in a variety of signal processing applications including radar [4] and communications [5,6]. In bistatic MIMO radar, direction of departure (DOD) and direction of arrival (DOA) estimation is a key issue, and several approaches have been studied [7–14]. A two-dimensional (2-D) capon based spectrum searching method is presented in [7]. 2-D MUSIC and reduced-dimension MUSIC (RD-MUSIC) are discussed in [8], and the latter has lower computational cost but a little performance loss than the former. The above schemes all need spectrum peak searching, which costs significantly. To lower computational cost, ESPRIT is applied [9–12]. In [9], DOD and DOA are estimated through two independent 1-D ESPRITs, but an additional pair matching operation is required. An automatically paired DOD–DOA estimation approach utilizing the inter-relationship between the two 1-D ESPRITs is proposed in [10]. Jin et al. [11] proposed an ESPRIT based method, but the number of transmit antennas is limited to two or three. By dividing the transmit array into two subarrays,

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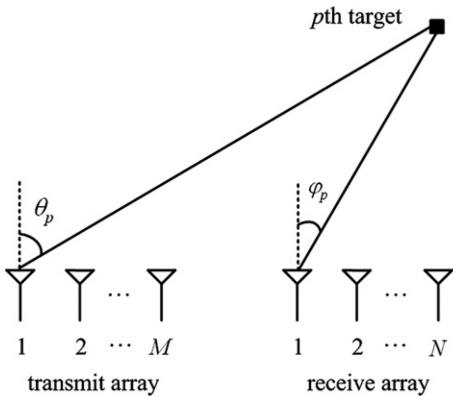

Fig. 1. Bistatic MIMO radar scenario.

another ESPRIT based method is presented in [12]. A polynomial root finding approach is proposed in [13]. The propagator method (PM) based method is given in [14] with lower computational cost but performance deterioration in low signal-to-noise-ratio (SNR) case than ESPRIT based methods. We can see that most of the existing methods are based on subspace estimation. They all require stacking the matched filter output into one structured matrix, and estimate the signal/noise subspace by SVD of this matrix or EVD of its covariance matrix. In fact, the matched filter output of a bistatic MIMO radar is multidimensional, and the traditional SVD/EVD based subspace estimate method does not make use of its inherent structure, which results in a significant performance loss in the parameter estimation.

In this paper, we proposed a new subspace estimation algorithm to improve the DOD and DOA estimation performance for bistatic MIMO radars. According to the multidimensional structure, multi-SVD [15,16] can be used. First, we formulate the matched filter output to a 3-order tensor, named measurement tensor. Then the signal subspace is estimated by multi-SVD of the matrix unfoldings of this measurement tensor or its covariance tensor. Simulation results validate that the proposed algorithm can yield more accurate estimation of the signal subspace than traditional methods, which results in better DOD–DOA performance when it is used to the subspace based parameter estimation methods, such as 2-D MUSIC and ESPRIT.

This paper is organized as follows. The signal model of the bistatic MIMO radar is described in Section 2. Section 3 presents the new multi-SVD based subspace estimation algorithm, and applies it to 2-D MUCISC and ESPRIT to estimate DOD–DOA. The computational complexity of the method is evaluated in Section 4. Section 5 gives some simulation results and compares the performance of the proposed method with the existing ones. Section 6 concludes the paper. The analytical performance evaluation of the proposed multi-SVD based subspace estimation algorithm is discussed in Appendix A.

Notations: we use the superscripts $(\cdot)^{\mathrm{T}}$,$(\cdot)^{\mathrm{H}}$, $(\cdot)^{*}$,$(\cdot)^{-1}$and$(\cdot)^{\dagger}$ for transposition, conjugate transposition, complex conjugate, matrix inversion and matrix Moore–Penrose pseudo-inverse, respectively. $\mathbf{I}_M$ is an $M\times M$ identity matrix.$\otimes$ and $\oplus$ symbolize the Kronecker product and Khatri–Rao product (column-wise Kronecker product), respectively. $||\cdot||_{\mathrm{F}}$ denotes matrix Frobenius norm. $\overline{\mathbf{A}}$ denotes the estimation of $\mathbf{A}$. diag $(\mathbf{a})$ forms a diagonal matrix that holds the entries of $\mathbf{a}$ on its diagonal. Angle (a) stands for the phase of a. vec $(\mathbf{A})$ builds a vector $\mathbf{a}$ by stacking the individual columns of the matrix $\mathbf{A}\in\mathbb{C}^{M\times N}$ one after each other, i.e., $(\mathbf{a})_{(n-1)M+m}=(\mathbf{A})_{m,n}$.

2. Signal model

Consider a narrowband bistatic MIMO radar with M-element transmit array and$N$-element receive array, both of which are half-wavelength spaced uniform linear arrays (ULA). Assume that there are P non-coherent targets located at some interested range cell in far-field. The p th target is located at (θ_p,φ_p), where θ_p is the angle of the p th target with respect to the transmit array, i.e., DOD, and φ_p is the angle with respect to the receive array, i.e., DOA. The bistatic MIMO radar scenario is shown in Fig. 1. The output of the nth receive antenna in the qth pulse is

$$\mathbf{x}_{n,q}=\sum_{p=1}^{P}\beta_{p,q}e^{j2\pi f_{dp}qT_{\mathrm{r}}}b_n(\varphi_p)\mathbf{a}^{\mathrm{T}}(\theta_p)\mathbf{S}+\mathbf{z}_{n,q} \tag{1}$$

where $\beta_{p,q}$ is the reflection coefficient of the pth target in the qth pulse, f_{dp} is the Doppler shift of the pth target, T_{r} is the pulse repetition interval, $\mathbf{a}(\theta_p)=[1,e^{j\pi\sin\theta_p},\cdots,e^{j\pi(M-1)\sin\theta_p}]^{\mathrm{T}}$ is the transmit steering vector, and $b_n(\varphi_p)$ is the nth element of the receive steering vector $\mathbf{b}(\varphi_p)=[1,e^{j\pi\sin\varphi_p},\cdots,e^{j\pi(N-1)\sin\varphi_p}]^{\mathrm{T}}$.$\mathbf{S}=[\mathbf{s}_1,\cdots,\mathbf{s}_M]^{\mathrm{T}}\in\mathbb{C}^{M\times L}$ is the matrix including M orthogonal narrowband transmit signals, L is the number of samples per pulse. $\mathbf{z}_{n,q}$ is the noise term for the qth pulse, $q=1,2,\cdots,Q$, and Q is the number of pulses during a coherent processing interval (CPI). The received signal of the qth pulse can be expressed as

$$\mathbf{X}_q=[\mathbf{x}_{1,q}^{\mathrm{T}},\cdots,\mathbf{x}_{N,q}^{\mathrm{T}}]^{\mathrm{T}}=\mathbf{B}\boldsymbol{\Lambda}_q\mathbf{A}^{\mathrm{T}}\mathbf{S}+\mathbf{Z}_q \tag{2}$$

where $\mathbf{A}=[\mathbf{a}(\theta_1),\cdots,\mathbf{a}(\theta_P)]$ and $\mathbf{B}=[\mathbf{b}(\varphi_1),\cdots,\mathbf{b}(\varphi_P)]$ are the transmit array manifold and receive array manifold, respectively. $\boldsymbol{\Lambda}_q$=diag $(\mathbf{c}_q)$ with $\mathbf{c}_q=[\beta_{1,q}e^{j2\pi f_{d1}qT_{\mathrm{r}}},\cdots,\beta_{P,q}e^{j2\pi f_{dP}qT_{\mathrm{r}}}]$ and $\mathbf{Z}_q=[\mathbf{z}_{1,q}^{\mathrm{T}},\cdots,\mathbf{z}_{N,q}^{\mathrm{T}}]^{\mathrm{T}}$. The matched filter output of the qth pulse is

$$\mathbf{Y}_q=\mathbf{B}\boldsymbol{\Lambda}_q\mathbf{A}^{\mathrm{T}}+\mathbf{E}_q \tag{3}$$

where $\mathbf{Y}_q$=$\mathbf{X}_q\mathbf{S}^{\mathrm{H}}$, $\mathbf{E}_q$=$\mathbf{Z}_q\mathbf{S}^{\mathrm{H}}$. Let $\mathbf{y}_q$=vec($\mathbf{Y}_q$) and stack $\mathbf{y}_q$ one after another, we have

$$\mathbf{Y}=[\mathbf{y}_1,\cdots,\mathbf{y}_Q]=(\mathbf{A}\oplus\mathbf{B})\mathbf{C}^{\mathrm{T}}+\mathbf{E} \tag{4}$$

where $\mathbf{C}^{\mathrm{T}}=[\mathbf{c}_1^{\mathrm{T}},\cdots,\mathbf{c}_Q^{\mathrm{T}}]$, $\mathbf{E}=[\mathbf{e}_1,\cdots,\mathbf{e}_Q]$, and $\mathbf{e}_q$=vec($\mathbf{E}_q$).

3. Improve DOD–DOA estimation using multi-SVD

In the subspace based DOD–DOA estimate methods, e.g., 2-D MUSIC [8] and ESPRIT [10], the signal/noise subspace can be determined by the following two ways. (1) Let the estimated signal subspace $\overline{\mathbf{U}_{\mathrm{s}}}$ be the left singular vectors of $\mathbf{Y}$ associated with the P significant singular values, and let the estimated noise subspace $\overline{\mathbf{U}}_{\mathrm{n}}$