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Matrix completion-based MIMO radar imaging with sparse planar array

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ABSTRACT

Multiple-input multiple-output (MIMO) radar with sparse planar arrays is expected to provide one snapshot imaging of complex motion targets at low hardware costs. In recent years, compressive sensing (CS) has been applied to MIMO radar imaging with limited antenna arrays. However, CS has to convert the matrix into a vector, which results in a large measurement matrix and a demanding amount of storage. Matrix completion (MC) is a new theory of recovering the entire data with partial observations. Compared with CS, MC is more suitable for matrix operations and avoids the basis mismatch problem. Due to the potential advantages, we introduce MC to MIMO radar imaging using a sparse planar array. Despite the success of MC in other fields, direct application in MIMO radar imaging leads to several problems, such as strict restrictions of the low-rank property and uniform random samples in MC. To solve these problems, a structured MC(StMC)-based method is proposed. With the method, MIMO radar imaging via a sparse planar array is converted to complete a low-rank structured matrix, which can be easily solved as a semi-definite program problem. Experimental results confirm the validity of the proposed method.

1. Introduction

The Inverse Synthetic Aperture Radar (ISAR) technique has been widely studied to extract the image information from aerospace targets [1–4]. However, the disadvantage of ISAR is the difficulty of complex motion compensation. A real aperture antenna array can avoid motion compensation by sampling the target information during a single snapshot illumination [5–8], however, hundreds of elements and meters in size are required in practice. By using a multiple-input multiple-output (MIMO) technique, MIMO radar [9] can obtain many additive virtual array elements, which significantly reduces the number of elements and size of the real aperture array. Therefore, MIMO radar imaging with one snapshot has attracted significant attention in the past years. In [10,11], a two-dimensional (2D) imaging method is studied using wideband MIMO radar with a linear array [10] or narrowband MIMO radar with two perpendicular linear arrays [11]. Further research on three-dimensional (3D) imaging is conducted using wideband MIMO radar with a monostatic planar array (cross array or square array) [12–14] or narrowband MIMO radar with bistatic rectangular arrays [15]. All of the studies above require a uniform array and large numbers of antennas, especially for 3D imaging and cases where high-resolution is required. In practice, a sparse antenna array is more flexible for station distribution and has lower hardware cost. In this paper, we consider MIMO radar with a sparse planar array which is built on the uniform planar array proposed in [13]. For simplicity, only the 2D imaging case is studied herein by transmitting narrowband orthogonal waveforms, which can be easily extended to the 3D case by using wideband waveforms.

Compressive sensing (CS) [16,17] has been introduced into sparse imaging via MIMO radar in past years [18–20]. However, for the 2D case, CS-based methods have to convert 2D data into a vector and then construct a high-dimensional measurement matrix which imposes a heavy burden on the storage and computation. Furthermore, the inherent problem of basis mismatch [21,22] is inevitable in CS-based methods. The matrix completion (MC) theory proposed recently [23–25] provides a new way of solving the problems above. With the MC theory, a matrix, which is low-rank and satisfies certain conditions [23], can be obtained exactly from a small number of randomly selected entries from the matrix. MC differs from CS by directly operating on a matrix rather than a vector and is more suitable for 2D cases. Several studies have recently applied MC in MIMO radar [26–30]. In [26–29], the authors investigate the applicability of MC theory on reduced data matrices that arise in co-located MIMO radar systems using two sampling schemes. The full data matrices are recovered via MC, and then used for target detection and estimation. In [30], a sub-

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Nyquist sampling strategy in bistatic MIMO radar is explored. Therein, the data matrix is recovered from a small subset of matrix elements via an enhanced matrix completion. Then, the data matrix is used to estimate the direction-of-arrival (DOA) and the direction-of-departure (DOD) of each target. All of the above studies investigate the problem of target parameter estimation and assume there are more receiving antennas than targets.

In this paper, we introduce MC into MIMO radar imaging with a sparse planar array. Two types of sparse array are considered herein to obtain the reduced samples. For the parameter estimation case, targets are usually limited and separated in the space, however, the target in the imaging case is usually composed of numerous scatterers which are not well-separated from each other. Practical imaging scenarios may result in high-rank or full-rank data matrices which will not meet the low-rank property in MC theory. Additionally, for the type of sparse array in which some rows or columns of the planar array have no antennas, the traditional MC theory is invalid for recovery of the unobserved data in the absent antennas. Both of the two problems above greatly restrict the application of MC in MIMO radar imaging. An initial attempt at under-sampled SAR imaging via MC has been completed in [31]. In that attempt, a simple imaging scenario containing several scatterers is considered to ensure the low-rank property. Moreover, the problem in the MC-based method is not solved in [31] when entries of a row or column in the matrix are all missing. In this paper, we propose a MIMO radar imaging method with a sparse planar array based on the Enhanced Matrix Completion (EMaC) theory. The EMaC theory was recently proposed in [32] to recover multidimensional frequency models using nuclear norm minimization of a low-rank enhanced matrix pencil constructed from the data. In our work, we investigate the imaging problem with a sparse MIMO array and utilize the EMaC theory to solve the imaging problem. A structured data matrix is produced by constructing a two-fold Hankel matrix, which can significantly improve the low-rank property and effectively remove the rows and columns that contain no entries. In other words, the proposed method is very suitable for the complex target imaging scenario using MIMO radar with different types of sparse planar arrays. To distinguish from EMaC theory, we describe the MIMO imaging method with sparse planar array as the StMC-based method in this paper. In this paper, the main contributions can be summarized as:

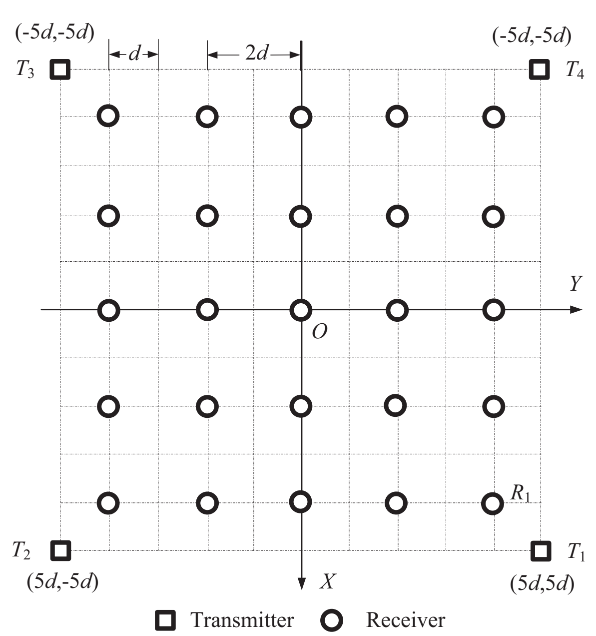

Fig. 1. Example of the planar array with 2^2 transmitters and 5^2 receivers in [13].

introduction of the MC theory into MIMO imaging with two types of sparse planar arrays, and proposal of a new imaging method based on EMaC theory which solves the difficult problems associated with MC-based MIMO imaging.

The research in this paper is developed under the following assumptions.

1) The time delay associated with the target motion can be ignored in one snapshot illumination.
2) The transmitting waveforms are ideally orthogonal, thus different transmitting waveforms can be separated via the matched filter bank at each of the receivers.
3) To simplify the investigation, array element errors, such as the gain-phase error and position error, are not considered.

This paper is organized as follows. Section 2 introduces the signal model of MIMO radar imaging with a sparse planar array. In Section 3, an MC-based MIMO radar imaging method is proposed in detail. The experimental results described in Section 4 demonstrate the effectiveness of the proposed method, and the study's conclusions are presented in Section 5.

2. Signal model of MIMO radar imaging with sparse planar array

2.1. Configuration of sparse MIMO array

In this section, a sparse MIMO array is introduced based on the M^2-transmitter N^2-receiver MIMO array proposed in [13]. An example of a MIMO array with 4 transmitters and 25 receivers is shown in Fig. 1. The 25 receivers form a 5×5 square array with an interelement distance of $2d$. The center of the square array is located at the origin of the coordinates, and the 4 transmitters are located at $(5d,\ 5d)$, $(5d, -5d)$, $(-5d, -5d)$, and $(-5d,\ 5d)$. More information about the M^2-transmitter N^2-receiver MIMO array can be found in [13]. A satisfactory target image has proven to be achievable using a planar array with enough transmitters and receivers [13], however, this usually requires a large hardware cost in practice.

In this paper, we introduce a sparse planar array that uses all of the transmitters and some of the receivers of the M^2-transmitter N^2-receiver planar array. The sparse array is divided into two types considering the distribution of receivers in the sparse planar array. One type of array is the random sparse array (r-SA). The R-SA is constructed by randomly removing several receivers from the full MIMO array. There is at least one receiver in each row or column of the sparse array. An example of R-SA is shown in Fig. 2(a), which consists of four transmitters and nine receivers of the full MIMO array in Fig. 1. The other type of array is called the row/column sparse array (R/C-SA). In R/C-SA, some rows or columns of the receiver array contain no receiver. Fig. 2(b) shows an example of R/C-SA that is built with the same receivers used in Fig. 2(a). Compared with the full array in Fig. 1, only 36% $\left(\frac{9}{25}\right)$ of the receivers are necessary for the sparse arrays in Fig. 2(a) and (b). Provided that a sparse array can produce a similar target image as the image using a full array, a great amount of cost saving may be achieved. An MC-based method is researched in this paper to produce cost savings. The division of R-SA and R/C-SA results in restriction of uniform random samples in MC which will be discussed later.

2.2. Signal model

In this section, the signal model of a full MIMO array with M^2-transmitter N^2-receiver is given and then extended to the