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Three-dimensional acoustic imaging with planar microphone arrays and compressive sensing

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ABSTRACT

For obtaining super-resolution source maps, we extend compressive sensing (CS) to three-dimensional acoustic imaging. Source maps are simulated with a planar microphone array and a CS algorithm. Comparing the source maps of the CS algorithm with those of the conventional beamformer (CBF) and Tikhonov Regularization (TIKR), we find that the CS algorithm is computationally more effective and can obtain much higher resolution source maps than the CBF and TIKR. The effectiveness of the CS algorithm is analyzed. The CS algorithm can locate the sound sources exactly when the frequency is above 4000 Hz and the signal-to-noise ratio (SNR) is above 12 dB. The location error of the CS algorithm increases as the frequency drops below the threshold, and the errors in location and power increase as SNR decreases. The further from the array the source is, the larger the location error is. The lateral resolution of the CS algorithm is much better than the range resolution. Finally, experimental measurements are conducted in a semi-anechoic room. Two mobile phones are served as sound sources. The results show that the CS algorithm can reconstruct two sound sources near the bottom of the two mobile phones where the speakers are located. The feasibility of the CS algorithm is also validated with the experiment.

1. Introduction

Planar microphone arrays and beamformers have been indispensable techniques for two-dimensional acoustic imaging [1,2]. With the help of two-dimensional acoustic imaging, one can estimate locations and powers of sources in the observation zone, which is a plane parallel to the array plane. The conventional beamformer (CBF) is originally derived from plane-wave model [3], but it has been extended to acoustic imaging applications based on point-source model [4,5]. However, CBF is characterized by poor spatial resolution and pronounced side lobes contamination [6,7]. In order to improve the spatial resolution and suppress the effect of side lobes, a variety of deconvolution beamformers have been proposed. DAMAS [6], DAMAS2 [7], Non-Negative Least-Squares(NNLS) [8], Richardson-Lucy (RL) [9,10], CLEAN [11,12] and CLEAN-SC [13] are among the typical deconvolution beamformers. These beamformers can guarantee relatively good performances in two-dimensional imaging and present highly resolved and unambiguous maps. Sparse regularization beamformers [14–16] have also been widely developed by using ℓ_1-norm. These sparse methods enforce the sparsity of the solution and improve the spatial resolutions greatly. Apart from beamformers, least squares methods such as Truncated Singular Value Decomposition (TSVD) [17] and Tikhonov Regularization (TIKR) [18] can also be used to tackle acoustic imaging issues.

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Nevertheless, for two-dimensional acoustic imaging, it is necessary to obtain a priori knowledge of the distance between the source plane and the array plane [19], which implies that all sources under estimation must sit on the same plane. Unfortunately, actual sources do not always necessarily sit on a plane. Therefore, it is of great significance to study three-dimensional acoustic imaging.

A simple method to extend two-dimensional imaging to three-dimensional imaging is to define grids on several planes that are parallel to the array [20]. Then the observation zone will be expanded from a plane to a rectangular box, and the number of nodes will be increased dramatically. However, the extension of the CBF to three-dimensional application also shows some intrinsic limitations as it does in two-dimensional acoustic imaging. The map is affected by poor spatial resolution and contaminated by side lobes. Furthermore, compared with the lateral resolution, the range resolution is quite disappointing [20,21]. In addition, the three-dimensional beamformers can be computationally expensive due to the explosive increase in the number of nodes [19,20,22].

Many researchers have made an effort to improve the performance of three-dimensional acoustic imaging. Brooks and Humphreys [20] investigated the three-dimensional application of DAMAS to point sources and landing gears. DAMAS can render relative clean and unambiguous maps, specifically for larger array at sufficiently higher frequency, but its primary drawback is that it is too slow. DAMAS2 is a spectral deconvolution algorithm and can improve the computational efficiency significantly [7,21]. Xenaki et al. [21] applied DAMAS2 algorithm combined with a coordinate system transformation and scanning technique to three-dimensional mapping. The method proposed by Xenaki et al. [21] improved the shift invariance and thus gave rise to clear and sidelobe-free maps. Furthermore, the range resolution can also be improved, but it is at the expense of side lobes contamination. DAMAS2 implies that the beamformer's point spread function be shift invariant [7,21]. Since this is not always the case in engineering applications, the deconvolution results would then be limited in applications [23]. CLEAN-SC does not need to solve a huge system of equations as DAMAS does [13,19,22], so it is more efficient. Its performance relies on the property of the spatial beamformer filters, which are governed by the steering vectors [13,24]. Sarradj [24] applied CLEAN-SC method for three-dimensional point sources mapping and examined its performance with four different steering vectors. However, none of the steering vectors provided satisfactory results: two of the steering vectors (refer to Eqs. (7) and (12) in Ref. [24]) led to the correct location at the cost of error in the strength estimation; the other two (refer to Eqs. (6) and (10) in Ref. [24]) estimated the correct strength, but failed to estimate the location correctly.

To summarize, the beamformers have their own merits in three-dimensional acoustic imaging as well as some inherent limitations. For the CBF, the limitations that show up in two-dimensional beamformer maps become more severe in three-dimensional acoustic imaging. Deconvolution beamformers suffer from the drawbacks of its computationally expensiveness and the poor range resolution.

Compressive sensing (CS), a recently developed revolutionary theory in signal processing [25–29], has been used in a wide range of applications, including medical [25,30] and ultrasound imaging [31], error correction in channel coding [28], radar detection [32], seismic imaging [33,34] and image reconstruction [35]. The basic idea of CS is to reconstruct sparse signals from very few measurements with help of convex optimization algorithms or greedy algorithms. In the field of acoustics, CS has been applied to the acoustic source localization problem using the direction-of-arrival estimation [15,36–38], acoustic response reconstruction in the reverberant environments [39,40], and acoustic imaging [41–43]. In particular, Simard and Antoni [41] employed the basis pursuit algorithm developed in the context of CS in two-dimensional acoustic source identification from a limited number of measurements by a microphone array. Bai and Chen [44] examined the application of CS+convex optimization (CVX) method to acoustical array signal processing. Bai and Kuo [45] formulated the acoustic sources separation issue into a CS problem and solved it with CVX. Zhong et al. [43] proposed a CS beamforming method based on sampling covariance matrix for the two-dimensional acoustic imaging. Boufounos et al. [42] extended CS for locating multiple broadband sources with joint and group sparsity models. As a drawback of the current CS techniques, mismatch between the assumed and the actual basis may cause the signal to appear as incompressible [46].

By comparing with beamformers, the researchers have found that robust and super-resolution are the main characteristics of CS for the acoustic imaging. Up to now, CS is only employed for two-dimensional acoustic imaging. The purpose of this work is to extend CS to three-dimensional acoustic imaging and analyze the effectiveness and the limitations of CS for obtaining super-resolution acoustic maps in three dimensions. We find, by comparing the maps of CS with that of CBF, that CS can suppress side lobes and enhance main lobes and has much less computational cost. We examine the applicability of CS in acoustic imaging under different settings. In addition, we have performed physical experiments to verify the validity of the CS algorithm in the practical application of three-dimensional acoustic imaging.

The rest of this paper is organized as follows. In Section 2, we provide the observation model based on planar microphone arrays. In Section 3, we describe an overview of CS, the restricted isometry property, coherence measures of the measurement matrix, and a CS algorithm used in this work. In Section 4, we apply the CS algorithm to simulate the acoustic maps in a three-dimensional rectangular box. The effects of the frequency, the signal-to-noise ratio (SNR), the lateral resolution, and the range resolution on three-dimensional acoustic imaging are discussed in this section. Then, we conduct experimental measurements to investigate the performance of the CS algorithm in practical applications. Finally, we present our conclusions in Section 5.

2. Observation model

Fig. 1 illustrates a three-dimensional rectangular box with P observation planes and a numerically optimized random planar array [2] with M microphones distributed within a circular aperture of diameter D on the ground. The origin of the