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Multiple wideband source detection and tracking using a distributed acoustic vector sensor array: A random finite set approach

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A B S T R A C T

In the past, distributed acoustic vector sensor (AVS) arrays have been employed to localize the source in a three dimensional space. Least-squares approaches were introduced to triangulate the source position by using the direction of arrival (DOA) measurements extracted at each AVS. However, such approaches: (1) cannot detect and localize multiple sources; and (2) can be seriously degraded due to inaccurate DOA estimates. In this paper, a practical scenario that the source existence and the number of sources are assumed to be unknown is considered. A random finite set (RFS) approach is developed to jointly detect and track multiple wideband acoustic sources. RFS is able to characterize the randomness of the state process (i.e., the source dynamics and the number of active sources) as well as the measurement process (i.e., DOA measurements generated by real sources and false alarms). Since the relationship between DOAs and source position is highly nonlinear, a particle filtering approach is employed to arrive at a computationally tractable approximation of the RFS densities. Simulations under different acoustic environments demonstrate the performance of the proposed approach and show a significant improvement on position estimation over the least squares approaches.

1. Introduction

Detection, localization and tracking of acoustic sources in a three dimensional (3-D, *x*-, *y*-, *z*-coordinate) space are important topics both in civilian and military missions such as sonar and radar array signal processing [1], autonomous underwater vehicle positioning and navigation [2], and room speech enhancement [3]. The tasks are traditionally performed by using a number of hybrid vertical and horizontal arrays equipped with acoustic pressure sensors [1]. In recent years, a new technology namely acoustic vector sensor (AVS) [4,5] has been widely employed for acoustic source detection and localization, and different signal processing algorithms have been developed accordingly [6]. Acoustic vector sensor employs a co-located sensor structure and measures acoustic pressure as well as particle velocity at sensor position. Compared to the traditional pressure sensors, it has following advantages: (1) it enables 2-D (azimuth and elevation) DOA estimation with a single AVS; (2) it allows elevation angle estimation unambiguously; and (3) its manifold vector is independent of the source's signal frequency and thus AVS is suitable for wideband source signal processing or scenarios where the source signal's frequency is unknown *a priori*. A full description of AVS in signal processing problems can be found in [6].

Due to its advantages described above, both the theoretical aspects and the applications of AVS array have been

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widely studied. DOA estimation using a single AVS has been investigated in [7–12]. For linear AVS array configuration (as shown in Fig. 1(a)), different DOA estimation approaches such as Capon beamforming [13], MUSIC [14,15], ESPRIT [14,16–18], and subspace intersection based approach [19,20,21] have been investigated. A circular AVS array configuration (as shown in Fig. 1(b)) is studied in [22], which conducts beamforming using decomposition in the acoustic mode domain. Tracking the DOA of a single acoustic source has been recently studied in [9–12] by developing different particle filtering approaches. Also, applications of AVS in room acoustic environments and underwater acoustic communication are investigated in [23,24] respectively. However, most existing localization approaches focus on the 2-D DOA estimation rather than the 3-D position estimation.

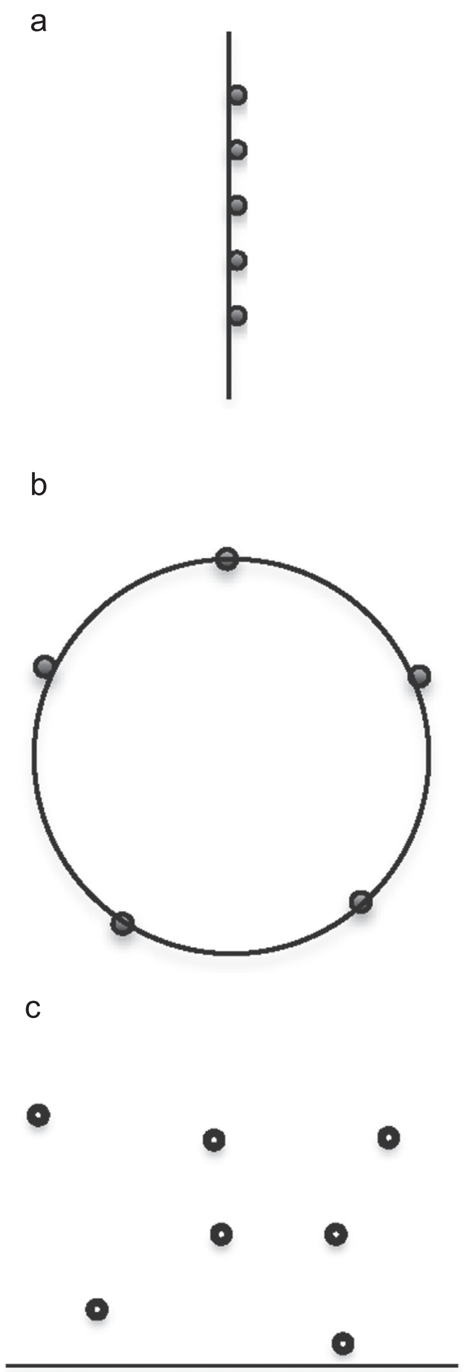

Fig. 1. Illustration of different AVS array configurations. (a) linear array; (b) circular array; and (c) distributed array.

Recently, advances in distributed sensor arrays in providing unprecedented capabilities for target detection and localization have motivated the deployment of distributed sensor arrays for acoustic source detection and localization [18,25]. Such an array is configured by using a number of randomly distributed but with known position AVSs, as shown in Fig. 1(c). In [18], least square approaches have been developed for 3-D source position estimation. At each AVS, Capon beamforming is employed to estimate the 2-D DOAs of the source. These DOA estimates are then employed to triangulate a 3-D location by using weighted least-squares (WL) and re-weighted least-squares (RWL) based approaches. The advantage of this array configuration is that each AVS needs only to transmit the DOA estimates to the central processor. Hence, the communication cost is very low. However, such approaches assume the existence of a single source and cannot be applied for multiple source position estimation. Also, the accuracy of the triangulation can be seriously degraded by undesired DOA estimates at each AVS.

In this paper, the problem of joint detection and tracking of multiple wideband acoustic sources using a distributed AVS array is considered. Such a consideration is more practical since, usually the source existence is unknown and the number of sources may be time-varying in the tracking scene. Hence, more advanced approaches should be employed to fuse the DOA information extracted from distributed AVSs and estimate the number of sources as well as the state of each source. Recently, random finite set (RFS) approaches have been widely employed for multitarget detection and tracking problem [26–28]. In essence, an RFS is a random process that is random in cardinality as well as in values of each element. It is thus able to naturally characterize the randomness of the state and measurement processes when target appearance and measurement origination are unknown. Generally, RFS framework neglects the intrinsic data association between sources and measurements, and has been found promising for multi-object tracking problem [26–30]. For rigorous mathematical discipline of RFS framework and its application in multi-object tracking problem, the reader is referred to [26–30].

An RFS approach is developed to detect and track a time-varying number of acoustic sources in this paper. In the state model, each element of an RFS is employed to describe the motion dynamics of acoustic sources, and its cardinality is used to model the time-varying number of sources. At each time step, the DOA measurement is extracted by using Capon beamforming that is exactly the same as that in [18]. When the signal to noise ratio (SNR) is low and the number of snapshots is small, the Capon beamforming response may be distorted and spurious peaks may be present. Also, acoustic source signals may