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Distributed Low-cost Microphone Array for 3D Localization for Bio-acoustic Applications

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Abstract—In this paper we present a multi-scale microphone array aimed at 3D source localization, with applications in bioacoustic animal tracking. We propose a hardware architecture for wirelessly synchronized sensor nodes consisting of small 5-element microphone arrays. Using this distributed sensor array we set up a probabilistic source localization problem, which we subsequently demonstrate to be able to estimate the position of a bat-like sound source in three dimensions. The proposed hardware architecture allows scalable source localization in a wide variety of application domains.

I. INTRODUCTION

Acoustic localization using sensor arrays has been thoroughly studied over the past decades [1]–[4]. In this paper we describe a low-cost approach for the localization of an acoustic source in 3D space using a Wireless Sensor Network (WSN) which consists of multiple sensor sub-arrays. Each individual sub-array is positioned in the environment with a known location and orientation. Many existing solutions to acoustic 3D localization of sources (e.g. animals like bats) use large-scale arrays of single-element microphones [1], [2]. The position of the acoustic source can be derived by analyzing the Time Difference of Arrival (TDOA) of the received signals at all array elements [3]. By introducing small-scale sub-arrays in the large-scale array, each node can first perform an estimate of the arrival angle. Several of these arrival angle estimates can lead to a 3D source position [4]. In this paper we present a probabilistic framework to combine the small-scale and large-scale TDOA measurements to perform accurate 3D localization of an acoustic source using a wirelessly synchronized sensor array. The remainder of this paper is structured as follows: in section II the probabilistic source localization algorithm is explained. Section III gives more details on our system and shows some experimental results. We discuss these results and indicate directions for future work in the final section.

II. PROBABILISTIC SOURCE LOCALIZATION

The goal of source localization is to retrieve the position $\vec{P}_s$ of a sound source:

$$\vec{P}_s = [x_s, y_s, z_s]^T$$

To this end we use a probabilistic localization technique that results in not only a most likely position, but will retain information on the likelihood of this and other possible locations.

Fig. 1. Panel a) is the 2D representation of small-scale TDOA estimation on a single node (essentially Angle-of-arrival estimation). The resulting likelihood function is cone-shaped, and can be seen in panel b). Panel c) illustrates the combination of several local small-scale AOA estimates into a single 3D position estimate. The resulting likelihood function is shown in panel d). This likelihood function can be used to estimate the position of a sound source in 3D.

A microphone array can record the source's sound at different locations so that TDOA techniques can be used to locate the source. We refer to this approach as large-scale TDOA estimation of the source's position. The microphone array is divided in multiple sub-arrays consisting of several closely-spaced (orders of centimeters) microphones (fig 1a). In this way, these sub-arrays form the nodes of a larger WSN as illustrated in figure 1c. Each of these individual nodes can perform an estimate of the arrival angle of the impinging sound wave (fig 1b), which is referred to as small-scale TDOA estimation. Localization in 3D can then be performed using the entire network by combining multiple sub-arrays into a larger super-array through the combination of several Angle of Arrival (AOA) estimates. The resulting location estimate can be seen in figure 1d.

A. Small-scale Source Localization

Our nodes each contain a sub-array of 5 microphones and an Analog to Digital Converter (ADC) able to sample six channels synchronously. Since the data-acquisition on a single node is done using a simultaneous sampling ADC we assume the individual microphone recordings to be accurately

synchronized. When a sound is received, the relative arrival times can be calculated (for example through generalized cross correlation [5]) and a local measurement vector $\vec{M}_L$ can be constructed by comparing differences in arrival time between all microphone pairs. To keep the formulas below compact, we restricted ourselves to 3 microphones:

$$\vec{M}_L = [d_1 - d_2, d_1 - d_3, d_2 - d_3]^T$$

with d_j the relative arrival time for microphone j . Using the individual location and orientation information of each sensor node, we can calculate $\vec{M}_L$ for each source location $\vec{P}_s$. This prediction is used to construct a distance vector $\vec{D}(\vec{P}_s)$ as a function of $\vec{P}_s$:

$$\vec{D} = [d_1 - d_2, d_1 - d_3, d_2 - d_3]^T$$

The likelihood $\mathcal{L}_L$ of the measurement vector $\vec{M}_L$ given a proposed source position $\vec{P}_s$ can be expressed for each node i as:

$$\mathcal{L}_{L,i}(\vec{M}_L|\vec{P}_s) = \exp\left[-(\vec{M}_{L,i} - \vec{D})^T \cdot \Sigma_L^{-1} \cdot (\vec{M}_{L,i} - \vec{D})\right]$$

with Σ_L the expected covariance matrix of the measurement errors. By multiplying the likelihoods of each microphone pair together we get a combined likelihood estimate for the measurement over all nodes in the array:

$$\mathcal{L}_L(\vec{M}_L|\vec{P}_s) = \prod_{i=1}^n \mathcal{L}_{L,i}(\vec{M}_L|\vec{P}_s)$$

Bayes' theorem can then be used to assess the posterior distribution probability $\mathcal{P}$ of each position $\vec{P}_s$ given the measurement $\vec{M}_L$:

$$\mathcal{P}(\vec{P}_s|\vec{M}_L) = \frac{\mathcal{L}_L(\vec{M}_L|\vec{P}_s) \cdot \mathcal{P}(\vec{P}_s)}{\mathcal{P}(\vec{M}_L)}$$

with $\mathcal{P}(\vec{P}_s)$ the prior distribution for position $\vec{P}_s$ and $\mathcal{P}(\vec{M}_L)$ the marginal of the posterior distribution. Since the microphones of a single node are spaced relatively close together in a single plane, $\mathcal{L}_{L,i}(\vec{M}_L|\vec{P}_s)$ does not result in a unimodal shape around the true source position, but rather in a cone shape where all 3D points that have equal azimuth and elevation with respect to the local node have an equal likelihood, which can be interpreted as an estimate of the arrival angle. In other words, the likelihood $\mathcal{L}_L$ is range independent with respect to the node's spherical coordinate system (see figure 1b). The product of all the individual likelihoods, $\mathcal{L}_L(\vec{M}_L|\vec{P}_s)$, will have a (unimodal) peak around the true source position in the case of Gaussian measurement errors (see figure 1d).

B. TDOA between Nodes

At network scale, multiple sub-arrays are combined into a larger WSN, which we have previously referred to as large-scale TDOA estimation. One or more channels from each sub-array are combined and the TDOA can be calculated. At this point it is quintessential that the individual sub-arrays are accurately synchronized. In previous work [6]

we described how the simultaneous generation of pseudo-random numbers across different nodes can be used for post measurement synchronization using cross correlation of the pseudo-random signal. The synchronization is performed in a distributed network of pulse-coupled oscillators inspired by the synchronization approach followed by many species of fireflies. A global measurement vector $\vec{M}_G$ is constructed as follows:

$$\vec{M}_G = [d_1 - d_2, d_1 - d_3, d_2 - d_3]^T$$

where d_i can be any microphone of any sub-array. Again, for notational clarity, we restricted ourselves to 3 microphones. Similar to the small-scale TDOA approach, we can create a vector $\vec{D}_G$ for each source position $\vec{P}_s$, allowing us to calculate the likelihood $\mathcal{L}_G$ for measurement $\vec{M}_G$, given $\vec{P}_s$:

$$\mathcal{L}_G(\vec{M}_G|\vec{P}_s) = \exp\left[-(\vec{M}_G - \vec{D}_G)^T \cdot \Sigma_G^{-1} \cdot (\vec{M}_G - \vec{D}_G)\right]$$

As the large-scale array has a much larger size than the local curvature of the arriving wavefronts, the probability of any point $\vec{P}_s$ being the point of origin of the sound then becomes:

$$\mathcal{P}(\vec{P}_s|\vec{M}_G) = \frac{\mathcal{L}_G(\vec{M}_G|\vec{P}_s) \cdot \mathcal{P}(\vec{P}_s)}{\mathcal{P}(\vec{M}_G)}$$

This posterior distribution has a unimodal peak around the true source position in case of unbiased Gaussian measurement errors.

C. Combining Local and Global Measurements

Having obtained a posterior position estimate for the source in two separate ways (small-scale and large-scale TDOA), we can combine both posterior distributions into a single distribution for the source position:

$$\mathcal{P}(\vec{P}_s|\vec{M}) = \frac{\mathcal{P}(\vec{P}_s|\vec{M}_G) \cdot \mathcal{P}(\vec{P}_s|\vec{M}_L)}{\sum_{\forall \vec{P}_s} (\mathcal{P}(\vec{P}_s|\vec{M}_G) \cdot \mathcal{P}(\vec{P}_s|\vec{M}_L))}$$

In a single-measurement source estimation problem, the best guess for the sound location can be found as:

$$\tilde{\vec{P}}_s = \operatorname{argmax}_{\vec{P}_s} \mathcal{P}(\vec{P}_s|\vec{M})$$

which can be solved using a non-linear constrained maximization algorithm. Alternatively, in a path-tracking application, the posterior distribution can be fed into a particle filter together with a motion model of the source that is to be tracked to arrive at a recursive path-tracking solution. In this paper however we will focus on single-snapshot localization experiments.

III. HARDWARE PROTOTYPE AND EXPERIMENTAL RESULTS

To demonstrate the efficacy of the proposed localization approach we designed and developed a Printed Circuit Board (PCB) with a 5 microphone sub-array as seen in figure 2a. All 5 microphones are sampled at a sample rate of 285 kHz by a 6-channel simultaneous sampling ADC which ensures that the local microphone data is synchronized. When a recording is made we use a matched filter to determine if and when a

Fig. 2. Panel a): Our single-board microphone sub-array. This PCB contains 5 ultrasonic microphones placed at the edges of the board and a 433 MHz antenna for wireless synchronization. The PCB stacks on top an ADC module and a SBC (Single Board Computer). Panel b): Overview of the hardware stack. The SBC at the bottom manages digital communication with the ADC above i.e. data offload and when to start or stop a capture. The ADC only receives analog data from the microphone array. The synchronization signal is sent as a 6th analog channel to the ADC. Panel c): Experimental AOA estimates made by a single sub-array in an office-like environment. The likelihood function $\mathcal{L}_{L,i}(\vec{M}|\vec{P}_s)$, sampled on a hemisphere, is plotted using a Lambert Equal Area projection. Gridlines spaced at 30° , contour lines spaced at 10% of the maximum probability.

certain reference sound (e.g. a prerecorded bat call) is present in the measurement. The 6th channel of the ADC is reserved as a synchronization channel to record the XOR-ed state of the synchronized pseudorandom generator (see [6] for details). The RF-based synchronization is performed over a 433 MHz communication link based on a Texas Instruments CC430 RF-SoC through the SimpliciTI communication protocol.

As shown in figure 2b we built a hardware stack with on top the microphone array. The array stacks on top of the ADC board, which sits on top of a Single Board Computer (SBC), in this case a BeagleBone Black (BBB). The BBB runs a general purpose Linux OS and is equipped with a Programmable Real-Time Unit (PRU). The PRU is a 200 MHz, 32 bit real-time core that can be programmed directly in assembler and guarantees single-clock IO operations. Therefore, the PRU is ideally suited to perform timing-critical tasks such as interfacing with a high-speed ADC, as the control of this ADC is very timing sensitive.

We placed our node in a room together with an ultrasonic speaker. The speaker emits an imitation of a bat call, i.e. a frequency sweep from 60 kHz to 20 kHz in 3 ms [7]. As explained in section II-A a single node can estimate the AOA in azimuth and elevation. Figure 2c shows the likelihood $\mathcal{L}_{L,i}(\vec{M}|\vec{P}_s)$ of a single measurement for a single node. The points $\vec{P}_s$ were distributed uniformly over a hemisphere with a radius of 5 meters, allowing the creation of the Lambert Equal Area Projections of the likelihood function.

To illustrate the full 3D localization of a sound source, we simulated an array consisting of 3 nodes, with each node being identical to the nodes described in the previous section. We placed the nodes in an array as shown in figure 1c. We simulated an acoustic source following a typical trawling-bat flight path (e.g. *Myotis daubentonii*). The snapshot-based

Fig. 3. Tracking a typical simulated flight path of a trawling bat like *Myotis daubentonii*. The red line is the true flight path, the red dots indicate the estimated position. The remaining colored dots illustrate the width of the a-posteriori probability function of each position estimate. The error in Euclidean distance between our best guess and the actual source position ranges between 5 mm and 19 cm with a mean of 5 cm. The nodes lie on a single plane at $x = 0$, their locations have been marked in blue.

localization algorithm is capable of reconstructing the sources flight-path as shown in figure 3.

IV. CONCLUSION AND FUTURE WORK

In this paper we introduced a multi-scale microphone array for 3D sound source localization aimed at bioacoustics. We proposed a probabilistic framework in which a source can be localized in 3D through a combination of small-scale TDOA (i.e. the implicit combination of multiple AOA estimates) and large-scale TDOA. We introduced a hardware architecture which supports this distributed localization technique through a synchronized wireless sensor network, and demonstrated the feasibility of the proposed localization algorithm for bio-acoustic tracking applications. As future work, we plan to introduce the probabilistic formulation of the source's position in a recursive Bayesian filter to accurately track the path of the source in three dimensions over time.

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