Modern Signal Processing Methods in Passive Underwater Surveillance

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Abstract

This research work concerns the application of modern signal processing methods, based on sparse modeling and convex optimization, to the problems arising in passive underwater surveillance. Starting from recently proposed sparse methods for direction of arrival (DOA) estimation we have constructed greedy sparse algorithms for estimation of wideband sources and we further introduced a number of criteria based on minimum description length (MDL) principle for the selection of the number of sources. Simulations show that the new methods perform well. The developed methods were also tested using real data collected in underwater surveillance experiments. Further tuning of the methods for the difficult cases where there are several sources having closely spaced directions is possible when more data containing such difficult cases will be available. The standard methods for wideband DOA estimation that are based either on minimum variance distortion-less response (MVDR) or on the high resolution method MUSIC and the developed methods perform equally well for relatively high SNR and for far-apart targets but the new methods have somewhat higher complexity. However, for close targets, the performance of the standard methods degrades rapidly but the newly introduced methods show better performance in these cases while maintaining a relatively low computational complexity.

1. Introduction

The direction of arrival of underwater sounds can be determined by the time differences of the incoming signals as received by different sensors. The subject is already wide and complex, as it relates to noisy signals received at the sensors with additional problems of coherence loss, multiple reflections, and deformations. This subject has been extensively studied, and the early systems are about one hundred years ago. Digital signal processing rapid development over the last couple decades has made it possible to implement in practice more sophisticated methods than before. In particular, the rapid development of the convex optimization-based technologies enables a more efficient optimization of the arrays formed of hydrophone antennas. The benefits are greatest when the design constraints, such as strong noise, power consumption, the number of hydrophones, and the uncertainty about their precise locations are critical. Especially when using independently moving underwater monitoring devices all these problems are present.

The advances in signal processing and pattern recognition methods allow to determine the location of the underwater sound sources by exploiting phenomena which were not possible to be used before, due to prohibitive implementation complexity or in cases where signal-to-noise is very low. One such phenomenon is the so-called Lloyds’ mirror effect, which is already familiar in optics from early 1800’s, and long known in underwater sound processing, but which has been considered mainly in signal processing as a phenomenon causing difficulties and as a distraction. This phenomenon can enable a full estimation of location parameters or at least a partial location assessment (floating target versus submersed target).

Convex optimization is the part of the optimization theory which is studying the minimi-
zation of convex functions. Convexity allows the usage of many in-depth mathematical tools and very efficient optimization algorithms exist in case of convex problems. Convex optimization is particularly suitable for control theory and for the design of signal processing algorithms. Convex optimization relies on efficient and reliable software libraries like SeDuMi which are publicly available. A particularly interesting library called CVXGEN, which is still in its developing stages, addresses real time computation; it is able to speed-up even 1000 times some classes of convex optimization by tuning an individualized algorithm for the problem at hand; hence, the real-time use of programs with hundreds of variables can be envisaged. This opens new possibilities for advancing the processing tools usable for array beamforming.

Another emerging field, connected to convex optimization by some of its basic methods, is that of sparse approximation (or sparse modeling) theory. Its goal is to find for complex problems such models that depend only on a small number of parameters. Sparse methods have produced impressive results in image processing applications and recently they have been applied to beamforming as well.

2. Research objectives and accomplishment plan

The main theme is the application of sparse methods and convex optimization to processing of hydrophone array data and recognition of interference patterns. In particular, the main problem of estimating the angle of arrival is made more difficult in the case of a towed array of sensors due to (i) noise from towing vehicle; (ii) relative movement of individual hydrophones in the towed array. The main efforts have concentrated on obtaining robust sparse method for DOA estimation, especially to resolving closely spaced targets. This is the case where traditional methods do not perform well at low values of the SNR.

3. Materials and methods

The standard methods for DOA estimation considered in this report are: beamforming, MVDR and MUSIC. Direction of Arrival (DOA) estimation is a spatial signal processing problem where the directions (angles) of sources (for example boats emitting sound) are estimated using the measurements from an array of sensors. Figure 1 illustrates the situation. Conventional methods originating in spectrum estimation include Minimum Variance Distortion-less Response (MVDR) and Multiple Signal Classification (MUSIC).

Below are shown two typical examples showing the accuracy in detecting narrowband targets of various strengths (two different SNR values, the first very high, 122 dB, the second a typical one for surveillance situations, close to 0 dB). In the high SNR case both MVDR and MUSIC perform very well, in the second case the distant targets are correctly
identified, while the close sources are not separated. Beamforming method performs poorly in both cases.

**Figure 2** Estimation of four targets, at very high SNR: three located closely, at 40, 41, and 41.5 degrees, and one at 60.2 degrees. (Top) the whole range of angles (-90,90), (Middle) zoom in the range of the three close DOAs; (Bottom) zoom near the forth target, at 60.1 degrees. Beamforming has very flat maxima at the targets and cannot resolve the three close targets, while MVDR and MUSIC perform very well.

**Figure 3** Estimation of four targets, at low SNR: three located closely, at 40, 41, and 41.5 degrees, and one at 60.2 degrees. (Top) the whole range of angles (-90,90), (Middle) zoom in the range of the three close DOAs; (Bottom) zoom near the forth target, at 60.1 degrees. Both MVDR and MUSIC identifies one target at 60 degrees and one target at 41 degrees.
In our underwater case the sensors are hydrophones and they receive wideband signals. Wideband DOA estimation is accomplished by splitting the wideband signal into narrow-band signals with e.g. the Fourier transform.

Sparsity in general has been an active field in signal processing for the last decade. It has also attracted interest in DOA estimation. For example $l1$-SVD introduced by Malioutov in "Sparse Signal Reconstruction Perspective for Source Localization with Sensor Arrays" is a widely known narrowband method that uses $l1$-optimization. It, however, suffers from complexity issues when it comes to the wideband problem. Greedy algorithms such as Orthogonal Matching Pursuit (OMP) alleviate the complexity and are easier to control. Novel results with greedy algorithms are published in the paper "An alternating descent algorithm for the off-grid DOA estimation problem with sparsity constraints" by Gretsistas and Plumbley, for example. Yet, few publications deal with the wideband problem. There is a paper with promising results with wideband signals and aliasing by Tang et al called "Aliasing-Free Wideband Beamforming Using Sparse Signal Representation", but only result for fairly far sources are presented in there. Also, the detection of close sources or the number of sources has not been covered in the literature.

Our research focused on using OMP and its variants on the wideband DOA problem. OMP is an iterative algorithm that uses a dictionary (matrix) consisting of steering vectors. At each step it selects the steering vector that minimizes the difference of the measured signal and the signal estimate with the given steering vector.

We notice that OMP is robust and simple and is able to see well separated sources as well or better than MVDR (See Fig. 4 in Results). To attack the problem of close sources a regression model similar to the one used in OMP was used. The difference is that instead of selecting only one steering vector from the dictionary we also choose two (or three) close steering vectors in a single step and use an information theoretic criterion to determine the number of sources. For the narrowband problem this method is able to separate sources better than conventional methods such as MVDR or MUSIC.

Close source detection is sensitive to the method used in combining the narrowband results into the wideband result. Instead of using plain averages over all subbands, we have developed and tested a method consisting of clustering using heuristic decisions regarding the number of sources as identified in each subband.

The final developed algorithm, named Sparse regression, has the following main steps:

1. For each frequency band:
   - Use MVDR to get initial spatial spectrum.
   - Use the regression model to get the signal power estimate and see if there are two or three sources in a single MVDR peak.
   - For each pair of close sources save the angle in the middle of them.
2. Decide the existence of close sources:
   - If enough many middle points are close to each other set a boundary to the average of the middle points.
3. Cluster all the DOA estimations utilizing the boundaries.
4. Output the cluster centers as the DOA estimates and the summed values of clusters as the magnitudes of the DOAs.
4. Results and discussion

Results over simulated data are shown in Fig. 4, where the mean squared error (MSE) between the true angles and the estimations is plotted as a function of signal-to-noise ratio (SNR). The plot marked "sparse" refers to OMP. The sources were at 50 and 120 degrees. MSE is the average of 300 trials.

![Figure 4](image)

Figure 4 The precision of detecting well separated sources.

Figures 5 and 6 illustrate the performance of the Sparse regression algorithm when dealing with close sources. The leftmost figure is the ground truth, the middle is MVDR and the rightmost Sparse regression. The SNR is 6 dB for the first and -5 dB for the second figure.
Figure 5. Simulated data for two crossing targets, at 6dB, crossing each other at the times 20, 60, and 100 s. The sparse regression algorithm outperforms the MVDR when the targets are very close.
Figure 6 Simulated data as in Figure 5, at very low SNR, equal to -5 dB. Again the sparse regression algorithm outperforms MVDR method at the times of crossing between the two targets.

The use of Lloys’s mirror phenomenon in detecting midwater sources in shallow water environments was studied by comparing the interference patterns in spectrograms between simulated and measured data. It was observed that a reasonably good matching between simulated and real data cannot be obtained without more realistic modeling of sound propagation. Thus, more emphasis was directed to include both properties of the bottom and sound speed gradient in simulations. The results show that more realistic interference patterns were obtained when these factors were included.

5. Conclusions

The standard signal processing methods were shown to perform in general reasonably good for the estimation of the direction in surveillance applications; however there are situations where the capacity of discriminating between two close targets is small. The newly introduced methods based on sparse regression were shown to perform well using simulated data and also they were found to perform well with preliminary experimental data. Further tuning of the methods for the difficult cases of closed targets is possible when more data containing such difficult cases will be available. The standard methods for wideband DOA estimation based on minimum variance distortion-less response (MVDR) and on the high resolution method MUSIC are shown to behave well for relatively high SNR and for distant targets, while for close targets the performance degrades rapidly. The newly introduced methods are comparable with the standard ones in most cases, and furthermore they improve over the standard ones in difficult situations, while maintain a relatively low computational complexity.

For the use of Lloyd’s mirror phenomenon it was observed that a realistic modeling of the sound propagation is essential in shallow water situation, especially when there is a strong temperature gradient, as is often the case in the Finnish coast.

6. Scientific publishing and other reports produced by the research project

The following publications are in preparation and will be submitted in the following three months:

P. Helin, MSc Thesis, Department of Signal Processing, Tampere University of Technology, to be submitted in March 2013.