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# **BLIND BEAMFORMING FOR COLLABORATIVE ARRAY PROCESSING IN SENSOR NETWORKS**

**Regents of the University of California**

**Sponsored by**  
**Defense Advanced Research Projects Agency**  
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## Table of Contents

|   |                |
|---|----------------|
| <i>I A comparison of actual accomplishments with the goals and objectives established for the period, the findings of the investigators, or both.</i> | <i>_____ 1</i> |
| <i>II Reasons why established goals were not met, if appropriate.</i>   | <i>_____ 5</i> |
| <i>III A cumulative chronological list of written publications in technical journals.</i>   | <i>___ 5</i>   |
| <i>IV A list of professional personnel associated with the research efforts.</i>  | <i>_____ 7</i> |
| <i>V Papers presented at meetings, conferences, and seminars.</i>   | <i>_____ 7</i> |
| <i>VI Consultative and advisory functions to other laboratories and agencies.</i>   | <i>_____ 7</i> |
| <i>VII New discoveries, inventions, and patent disclosures and specific applications.</i>   | <i>___ 8</i>   |

## **I. A comparison of actual accomplishments with the goals and objectives established for the period, the findings of the investigators, or both.**

The detection, localization, tracking, and identification of a single target by acoustical/seismic measured data are fairly well understood. Many of the methods considered in the SensIT program proven in various ways for a single target in an open-air environment, will not be applicable to multiple targets. In the proposal, we advocated a new algorithm based on an efficient computational Approximate Maximum-Likelihood (AML) method using alternate projection to tackle the multiple target cases. The idea is that instead of performing the AML search in high dimensions for  $M$  targets, we first perform the ML estimate for the strongest target, then by fixing that target, we perform the ML estimate for the second strongest target, until the  $M$ -th target, and then iterate with the first target again

In this final report (covering the period from June 28, 2002 to September 30, 2003), we have completed all the objectives originally established for this program. We summary our work on advances made both at the algorithmic understanding, simulation verification, and experimental measurement levels of the objectives.

In August 2002, our basic AML algorithm work for multiple targets was published in the prestigious IEEE Transactions on Signal Processing. We wrote Matlab codes to verify the use of AML algorithm for multiple targets by simulations. In the summer of 2002, we visited Parc, our partner in applying the AML algorithms to physical single and multiple target measuring scenarios. After technical discussions with Jim Reich and Dr. Feng Zhao of Parc, we wrote C language codes of the AML algorithm for implementation on their acoustical testbed system. In addition, we have worked with Prof. Deborah Estrin's group in the Computer Science Department at UCLA, on applying the AML algorithm to her wireless acoustical testbed system utilizing iPAQs. These iPAQs have self-contained microphones, advanced signal processing microprocessors, and 802.11 wireless communication PC cards. Results showed the AML algorithm worked very well with the measured data. Some of these results have been presented in an IEEE CAS Workshop on Wireless Communications and Networking on September 6, 2002.

On October 7, 2002, we provided an audio/video teleconference presentation (using the real-time capability of the VNC capability) from UCLA to Dr. D. Shephard and Dr. S. Kumar of DARPA in Arlington, VA. We gave a vu graph presentation entitled "Multi-Target Detection, Localization, and Classification: Concepts and Software Demos" and real-time Matlab demonstrations. In this teleconference, we first demonstrated the Approximate Maximum-Likelihood (AML) direction-of-arrival (DOA) bearing estimation method is applicable for localization of multiple targets. Then we demonstrated some basic concepts of association for detection and localization of multiple targets from DOAs. Finally, we demonstrated the AML method is applicable to perform space-frequency classification of multiple targets. The AML space-frequency

classification method was novel and we proposed continuing work on the basic understanding and verification of this method in the coming months.

On November 6-8, 2002, we attended and participated fully in the SensIT PI Review Meeting held at Waltham, MA. On Nov. 7<sup>th</sup>, we made a presentation entitled “Optimal/Sub-Optimal Multi-Target Recognition.” In this presentation, we first discussed the limitation of existing algorithms based on amplitude/power levels of sensors as essentially only for single target detection and localization. When a large number of such sensors using these algorithms are employed, multiple targets can be detected and localized only if there are minimal interferences among themselves. In other words, for each target a collection of sensors adjacent to that target is able to resolve that target only if there is minimal interferences from other targets. This condition implies the multiple targets are not too closely spaced. Thus, under this scenario, multiple target detection and localization are just a collection of single target detection and localization performed at each local neighborhood. However, in realistic battlefield conditions, multiple targets may not appear under such assumptions. Our proposed AML DOA estimation technique does not require such stringent assumption that the targets are necessarily widely spaced. Then we continue with the introduction of the AML method in which for P targets, instead of performing a P-dimensional parameter ML search, we perform only a sequence of alternating one-dimensional parameter ML searches for each of the P target DOAs. In general, the total computational effort of the sequence of one-dimensional parameter ML searches is less than the full P-dimensional parameter ML search. In the presentation, we present various specific simulations and measured data to support the claim of the advantages of the AML detection and localization method for multiple targets. Finally, we present the space-frequency target classification method. The AML method is able to estimate the DOAs of multiple targets using the dominant spectral contents of the target data. The spectral signature of each target at a given DOA provides information for its classification. A simple example was given to justify this method. In the afternoon of Nov. 6<sup>th</sup>, we also participated in the poster session with a poster entitled, “MIMO-AML Method for Multiple Target DOA, Localization, and Identification.” In this poster, we presented more examples on the use of the AML method to treat the multiple target problems.

In November 2002, we completed a manuscript entitled, “Theory and Implementation of Beamforming on a Distributed Sensor Network,” submitted the invited paper for review to a Special Issue of the IEEE Proceedings. The purpose of this manuscript is to provide a tutorial treatment of beamforming on a distributed sensor network and present some recent experimental results on its implementation over a wireless network using iPAQs with PCMCIA radio Ethernet cards.

In December 2002, we completed a manuscript entitled, “Array Processing for Target DOA, Localization and Classification based on AML and SVM Algorithms in Sensor Networks,” submitted for review for consideration of the 2<sup>nd</sup> International Workshop on Information Processing in Sensor Networks (IPSN’03) to be held at Palo Alto Research Center, Palo Alto, CA, April 22-23, 2003.

On January 14, 2003, we presented a technical seminar entitled, "Theory and Application of Acoustical Beamforming on a Distributed Sensor Network," in the ECE Department Seminar of the University of California, San Diego. In this seminar, we first reviewed the basis of narrowband and wideband beamforming. Then various aspects of coherent processing for source localization based on time-delayed and least-squares estimation and cross bearings of direction-of-arrival estimation were presented. Finally, the use of distributed wireless sensor networking to perform these beamforming operations was given.

On January 20, 2003, the P.I. and one graduate student visited Drs. Jim Reich, Feng Zhao, and Patrick Cheung, of PARC Research Center at Palo Alto, CA, to conduct experimental acoustical array measurements. Data were collected for outdoor environments, indoor reverberant room scenarios, and semi-anechoic room scenarios for single and multiple source localization purposes.

In January of 2003, we revised our previously submitted paper, "Theory and Implementation of Beamforming on a Distributed Sensor Network," with the new title of, "Coherent Acoustic Array Processing and Localization on Wireless Sensor Networks." This revised invited paper has been accepted for publication in a Special Issue of the IEEE Proceedings.

In February 2003, we revised a previously submitted manuscript entitled, "Array Processing for Target DOA, Localization and Classification based on AML and SVM Algorithms in Sensor Networks," that has been accepted for presentation to the 2<sup>nd</sup> International Workshop on Information Processing in Sensor Networks (IPSN'03) to be held at Palo Alto Research Center, Palo Alto, CA, April 22-23, 2003.

We (K. Yao, D. Estrin, and Y.H. Hu) were the guest editors of the March 2003 "Special Issue on Sensor Networks," for EURASIP Journal on Applied Signal Processing. In our Editorial, we described the recent interest and importance of sensor networks and briefly reviewed the significance of the seven papers in the issue. In this Special Issue, our paper, "Acoustic Source Localization and Beamforming: Theory and Practice," considered the theoretical and practical aspects of locating acoustic sources using an array of microphones. Many experimentally measured acoustic data was used to verify various algorithms.

The paper, "A Wireless Time-Synchronized COTS Sensor Platform: Applications to Beamforming," was supposed to be presented at the International Conference on Speech and Signal Processing, April 6-10, 2003, to be held at Hong Kong. Due to the SARS problem, this conference has been cancelled, but the papers in the have appeared in the Proceedings. In this paper, we considered the use of Compaq iPAQ 3760s, equipped with a built-in microphone and an external wireless card, for acoustic acquisition and processing to perform a distributed acoustical beamforming. Time synchronization among the microphones is achieved by the Reference-Broadcast Synchronization method. Two beamforming algorithms, based on the time difference of arrivals (TDOAs) among the microphones and least-squares estimation of the TDOAs method, and the maximum-

likelihood (ML) parameter estimation method, are used to perform source detection, enhancement, localization, delay-steered beamforming, and direction-of-arrival estimation. Experimental beamforming results using the iPAQs and the wireless network were reported.

On April 22, 2003, we presented a technical paper, "Array Processing for Target Localization, and Classification Based on AML and SVM Algorithms in Sensor Networks," at the Second International Workshop on Information Processing in Sensor Networks (IPSN'03), held at Palo Alto, CA. In this paper, we proposed to use the Approximate Maximum-Likelihood (AML) method to estimate the direction-of-arrival (DOA) of multiple targets from various spatially distributed sub-arrays, with each sub-array having multiple acoustical/seismic sensors. Localization of the targets can with possibly some ambiguity be obtained from the cross bearings of the sub-arrays. Spectra from the AML-DOA estimation of the target can be used for classification as well as possibly to resolve the ambiguity in the localization process. We use the Support Vector Machine (SVM) supervised learning method to perform the target classification based on the estimated target spectra. The SVM method extends in a robust manner to the non-separable data case. In the learning phase, classifier hyperplanes are generated off-line via a primal-dual interior point method using the training data of each target spectra obtained from a single acoustical/seismic sensor. In the application phase, the classification process can be performed in real-time involving only a simple inner product of the classifier hyperplane with the AML-DOA estimated target spectra vector. Analysis based on Cramer-Rao bound (CRB) and simulated and measured data is used to illustrate the effectiveness of AML and SVM algorithms for wideband acoustical/seismic target DOA, localization, and classification.

On June 20, 2003, we presented a demonstration on, "Real-Time Acoustical Beamforming Using Wireless iPAQs", at the Global Digital Technology and Media Conference, Mountain View, CA. In this demo, we used four iPAQs place on a square of about 30 cm on each side to collect waveforms from an acoustical source. The waveforms collected by the microphones are synchronously sampled and converted to digital data and by an 802.11b wireless radio system to a central processor. The propagation time delay differences from the source to the microphones are processed to estimate the direction-of-arrival (DOA) of the source to the array. If two or more such arrays are used, cross bearing of these DOAs can be used to locate the acoustical source. This work is noted for two novel advanced digital processing and distributed computing algorithms for the wireless synchronous time stamping for the collected acoustical data for coherent array processing as well as the DOA estimations based on approximate maximum-likelihood (AML) method. C-codes running on Linux OS in these iPAQs have been optimized for real-time processing and demonstration. Many potential practical applications of this technology were described.

On July 9, 2003, we sent two PowerPoint files (DOA1.ppt and DOA2.ppt) to Dr. Sri Kumar and Mr. David Shepherd on two demonstrations of a real-time acoustical beamformer. In the first file, using the AML algorithm running on one subarray with four iPAQs, we can estimate the Direction-Of-Arrival (DOA) of a source in real-time.

The AML algorithm has been presented at various SensIT meetings and described in various publications. In the second file, using two of these subarrays, the cross bearing of the two DOAs yields the location of the target in real-time.

In August 2003, our paper, “Coherent Acoustic Array Processing and Localization on Wireless Sensor Networks,” appeared at the first paper in an invited Special Issue of the August 2003 IEEE Proceedings. In this paper, we first discussed advances in microelectronics, array processing, and wireless networking, have motivated the analysis and design of low-cost integrated sensing, computing, and communicating nodes capable of performing various demanding collaborative space-time processing tasks. Then we considered the problem of coherent acoustic sensor array processing and localization on distributed wireless sensor networks. We first introduce some basic concepts of beamforming and localization for wideband acoustic sources. A review of various known localization algorithms based on time-delay followed by LS estimations as well as maximum likelihood method was given. Issues related to practical implementation of coherent array processing including the need for fine-grain time synchronization were discussed. Then we described the implementation of a Linux-based wireless networked acoustic sensor array testbed, utilizing commercially available iPAQs with built in microphones, codecs, and microprocessors, plus wireless Ethernet cards, to perform acoustic source localization. Various field-measured results using two localization algorithms showed the effectiveness of the proposed testbed.

On September 9, 2003 and on September 12, 2003, we presented the seminar, “Theory and Application of Acoustical Beamforming on Sensor Networks,” at the Department of Electrical and Computer Engineering of Cornell University and Columbia University, respectively. In that seminar, we first discuss some motivations and recent advances in wireless distributed sensor networks. Then we provided a brief introduction to UCLA's new National Science Foundation Center for Embedded Networked Sensing (CENS) and the use of beamforming in some applications at CENS. Various basic issues and theory of wideband acoustical beamforming were then considered. Applications to various DOA and localization problems were given. Implementation issues of beamforming on various platforms including a recent effort on a wireless acoustical testbed using iPAQs were also presented.

## **II. Reasons why established goals were not met, if appropriate.**

As described in part (i), we have completed 100% of the objectives and there was not any goal not met in this period.

## **III. A cumulative chronological list of written publications in technical journals.**

J.C. Chen, R. E. Hudson, and K. Yao, “Maximum-Likelihood Source Localization and Unknown Sensor Location Estimation for Wideband Signals in the Near-Field,” IEEE Trans. on Signal Processing, vol. 50, Aug. 2002, pp. 1843-1854.

H. Wang, L. Yip, D. Maniezzo, J.C. Chen, R.E. Hudson, J. Elson, and K. Yao, "A Wireless Time-Synchronized COTS Sensor Platform: Applications to Beamforming," IEEE Proc. of CAS Workshop on Wireless Communications and Networkings, Sept. 2002, 8 journal pages. (Exact pagination not known presently).

K. Yao, D. Estrin, and Y.H. Hu, "Editorial – Special Issue on Sensor Networks," Eurasip Journal on Applied Signal Processing, vol. 2003, no. 4, March 2003, pp. 319-320.

J.C. Chen, K. Yao, and R.E. Hudson, "Acoustic Source Localization and Beamforming: Theory and Practice," Eurasip Journal on Applied Signal Processing, vol. 2003, no. 4, March 2003, pp. 359-370.

J.C. Chen, H. Wang, L. Yip, D. Maniezzo, R.E. Hudson, J. Elson, K. Yao, and D. Estrin, "A Wireless Time-Synchronized COTS Sensor Platform: Applications to Beamforming," Proceedings of the International Conference on Speech and Signal Processing, April 2003, pp. II-597-II-600.

L. Yip, K. Comanor, J.C. Chen, R.E. Hudson, K. Yao, and L. Vandenberghe, "Array Processing for Target DOA, Localization and Classification based on AML and SVM Algorithms in Sensor Networks," Proc. of the 2<sup>nd</sup> International Workshop on Information Processing in Sensor Networks (IPSN'03), April 2003, pp. 269-284.

J.C. Chen, L. Yip, J. Elson, H. Wang, D. Maniezzo, R.E. Hudson, K. Yao, and D. Estrin, "Coherent Acoustic Array Processing and Localization on Wireless Sensor Networks," Proc. of the IEEE, vol. 91, August 2003, pp. 1154-1162.

#### **IV. A list of professional personnel associated with the research efforts.**

1. PI – Prof. Kung Yao, Electrical Engineering Dept., UCLA. (Summer 30%, school year 15%).
2. List of investigators on this project.
  - a. Prof. Kung Yao, Electrical Engineering Dept., UCLA. Analysis and design of multiple target detection, localization, tracking, and identification algorithms. (Summer 30%; school year 15%).
  - b. Dr. Ralph E. Hudson, Research Engineer, Electrical Engineering Dept., UCLA. Analysis and design of multiple target detection, localization, tracking, and identification algorithms. (25%)
  - c. Dr. Joe C. Chen, Research Engineer, Electrical Engineering Dept., UCLA. Analysis and simulation of multiple target detection and localization algorithms. (10%)
  - d. Len Yip, Ph.D. candidate, Electrical Engineering Dept., UCLA. Analysis and design of multiple target detection, localization, tracking, and identification algorithms. (30%)
3. Prof. K. Yao, Dr. R.E. Hudson, Dr. J.C. Chen, Mr. L. Yip are all U.S. citizens.

#### **V. Papers presented at meetings, conferences, and seminars.**

L. Yip, K. Comanor, J.C. Chen, R.E. Hudson, K. Yao, and L. Vandenberghe, “Array Processing for Target DOA, Localization and Classification based on AML and SVM Algorithms in Sensor Networks,” Proc. of the 2<sup>nd</sup> International Workshop on Information Processing in Sensor Networks (IPSN’03), April 22, 2003.

P. Bergamo, D. Maniezzo, and K. Yao, “Real-Time Acoustical Beamforming using Wireless iPAQs”, at the Global Digital Technology and Media Conference, Mountain View, CA, June 20, 2003.

K. Yao, “Theory and Application of Acoustical Beamforming on Sensor Networks,” seminars presented at the Department of Electrical and Computer Engineering of Cornell University and Columbia University, Sept. 9<sup>th</sup> and Sept. 12<sup>th</sup>, 2003, respectively.

#### **VI. Consultative and advisory functions to other laboratories and agencies.**

None.

## **VII. New discoveries, inventions, and patent disclosures and specific applications.**

1. Demonstrated the Approximate Maximum-Likelihood (AML) direction-of-arrival (DOA) bearing estimation method is applicable for localization of multiple targets.
2. Demonstrated basic concepts of association for detection and localization of multiple targets from DOAs.
3. Demonstrated off-line processing of AML DOA and cross-correlation-time delay and least-squares estimation methods for real-time data collection of target localization in a wireless network using iPAQs with a PCMCIA radio Ethernet cards.
4. Demonstrated the AML method with the SVM method is able to perform complex target classification of multiple targets.
5. Demonstrated the real-time processing of AML DOA and cross-correlation-time delay and least-squares estimation methods for real-time data collection of target localization in a wireless network using iPAQs with a PCMCIA radio Ethernet cards.