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13. ABSTRACT (Maximum 200 words)

This research includes the development and analysis of signal processing estimation algorithms. The main areas of application are sensor array processing for source localization, adaptive signal processing, system identification, and estimation.

In the sensor array processing area we developed algorithms for: source localization with decentralized array processing, sensor localization, passive range and bearing estimation, and source localization in multipath and short data applications. We introduced statistical tools that were used to provide compact expressions of the asymptotic variances of source localization algorithms and to obtain, for the first time, concrete analytical performance comparisons. Performance bounds of the Cramér-Rao type were found and used to analyze statistical efficiency.

We introduced the use of electromagnetic and acoustic vector sensors for passive source localization and for active target localization and identification. We derived performance bounds and investigated the potential advantages of methods using vector sensors. Simple algorithms for estimating source direction with a vector sensor were proposed along with their statistical performance analysis.

In the adaptive signal processing and system identification area we developed algorithms for root factorization and nonlinear filtering. We analyzed the tracking properties of our previously introduced adaptive notch filter for nonstationary signals.

In the general estimation area we derived concentrated Cramér-Rao bound (CRB) expressions applicable to a large class of estimation problems, CRB formulae in the frequency domain, and CRB for transient signals.

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This research includes the development and analysis of signal processing estimation algorithms. The main areas of application are sensor array processing for source localization, adaptive signal processing, system identification, and estimation.

Sensor Array Processing

We developed optimal sensor fusion algorithms for decentralized direction of arrival (DOA) estimation [1], [2], algorithms for passively estimating the ranges and bearings of near field sources [3], [4], and algorithms for DOA estimation in applications of multipath and short data [5], [6]. Using our statistical tools, we analyzed the performance of these algorithms, compared their performance with one another and with the optimal Cramér-Rao bound (CRB). We introduced new calibration methods for sensor position estimation with active source signals and derived the Cramér-Rao bound for this problem [7], [8]. Additionally, we analyzed the performance of the conditional and unconditional maximum likelihood estimators (MLEs) [9], [10], beam-space MUSIC [11] and subspace rotation estimators [12], [13], and DOA estimators using large arrays and short data [14]. In [15] we presented a derivation of the concentrated stochastic likelihood function for the array processing problem. Some of our results will also appear in a chapter of a book, [16].

We obtained several significant results on electromagnetic source direction and polarization estimation in [17], [18] and [19]. We introduced new methods for this problem using *vector* sensors that measure the complete electric and magnetic data. We showed that with one lumped vector sensor it is possible to find the direction to two sources. Conventional methods require distributed sensors to solve this problem. New quality measures including mean-square angular error (MSAE) and covariance of vector angular error (CVAE) were introduced and their lower bounds were derived. The advantage of using vector sensors was highlighted by explicit evaluation of the MSAE and CVAE bounds for source localization with a *single* vector sensor. A simple algorithm for estimating the source DOA with this sensor was presented along with its statistical performance analysis.

The source resolution of vector sensor arrays is not limited by Rayleigh's principle, which is unlike conventional scalar sensor arrays. For closely-spaced sources the resolution of vector sensors is extremly good if the sources have small differences in their polarization state. Conventional scalar sensor arrays are not sensitive to such differences and hence, by Rayleigh's principle, need larger array aperture (in wave lengths) to resolve the sources as they get closer to each other.

We extended the electromagnetic vector sensor approach to actively localizing and identifying targets in [20]. Target dependent parameters were proposed that provide a natural parametrization of the statistics of the target's reflection characteristics (scattering matrix) to arbitrarily polarized transmitted signals. Cramér-Rao bounds on the variance of unbiased estimators of these variables were derived to show how an estimator's expected performance depends on the target's state and the transmitted signal. The new parameters were shown to have physical interpretations and to represent characteristics intrinsic to the target.

It may be worth noting that electromagnetic vector sensors are currently being developed at the national institute of standards and technology (NIST) and by Flam & Russell Inc.

In [21], [22], the vector sensor processing approach was applied to localization of acoustic sources. An array of sensors for which the measurement of each sensor is a *vector* consisting of the acoustic pressure and acoustic particle velocity was used. Two simple algorithms for estimating the source DOA with this sensor were developed along with their statistical performance analyses.

Adaptive Signal Processing and System Identification

We analyzed the accuracy of our previously introduced adaptive notch filter in the presence of unknown colored noise [23], its tracking properties for nonstationary inputs [24], [25], and the convergence of its pseudolinear regression version [26]. We developed several efficient recursive algorithms for polynomial root factorization [27]. These algorithms were applied to temporal frequency and direction-of-arrival estimation problems. We also developed exact recursive algorithms for nonlinear filtering via Gauss transform eigenfunctions [28]. We provided a unique analysis of minimum bias priors for the estimation of parameters which appear nonlinearly in state space models [29]. A new adaptive power spectrum estimation algorithm was derived and applied on-line for heart rate variability analysis [30].

Estimation

A method that simplifies the analytical computation of the Cramér-Rao bound was found in [31]. The method circumvents calculations involving so-called nuisance parameters, the bounds for which are not themselves needed. The technique avoids having to evaluate potentially complicated expectations and can significantly lower the analytical complexity as compared to traditional methods. The dimension of a matrix that requires computation and inversion is reduced to the length of the parameter vector of interest. We applied the results to processes having densities in the exponential family and found a particularly simple closed form result for Gaussian processes. We also found closed form expressions of the CRB in the frequency domain for Gaussian processes [32] and of the CRB for transient signals modeled as damped sine waves [33].

Applications

The array processing results have turned out to be fundamental in the establishment of the correct model to use for the problem of source localization. It was shown that the "*unconditional*" *model yields consistent parameter estimates* while at the same time being the most general. The results on the Cramér-Rao bound and the new tools we introduced in our papers have found wide acceptance in the research community and are now being employed by others on a regular basis. Additionally, our results on the performance comparisons of the various algorithms used for source localization clearly indicate in which scenario one algorithm is preferred over another. These clearly have practical significance.

The active calibration method proposed is a practical and effective way to determine the array sensor positions accurately. This is important as small errors in the array configuration can lead to large errors in the target direction of arrival estimates.

The new approach of using a *vector* sensor for source localization provides a way to determine the three dimensional bearing of a source using only *one* lumped sensor. In general, compared to scalar arrays, the use of vector sensors allows the use of a smaller array aperture while maintaining performance. The vector sensor accomplishes this by measuring the complete field information. For example, electromagnetic vector sensors measure the three dimensional electric and magnetic fields. On the other hand, traditional scalar sensors measure only parts of the fields, and therefore lose information in the process.

The results presented in [19] are far-reaching in their scope. Furthermore, the methods used therein provide a natural framework for the exploitation of the complete incoming wave information. This includes, especially, the polarization state of the wave. We show that if two sources have different polarization parameters then *only one* vector sensor is needed to uniquely identify both, simultaneously. Many traditional scalar sensors would be needed to perform this same task. It is expected that this work will be widely followed by other researchers in the field.

We expect the application of vector sensors to problems in active surface identification to have both theoretical and practical repercussions. In this work we show how the electromagnetic vector sensor can give new results in remote sensing. The reflecting surface is parametrized in a natural way, and an electromagnetic vector sensor is used to identify all of the parameters associated with the surface. The parameters we propose provide a physical interpretation of the characteristics of the surface. The vector sensor subsumes traditional two-dimensional approaches to surface identification, and provides complete observability of all of the relevant electromagnetic phenomena.

The adaptive notch filter has excellent potential as a signal tracking device (as can be used in radar, etc.) and has been generalized to work in arbitrary unknown noise conditions. This will make it a practical alternative to other types of trackers which have weaker theoretical foundations. The tracking properties of the adaptive notch filter are very important for determining its application to real problems. For example, the filter can be used for tracking of a time-varying Doppler shifted radar signal. The results obtained clearly indicate how to choose the parameters used to set up the notch filter as a function of the nonstationarities present in the input. The analysis also shows the expected convergence rates of the filter's estimates under various scenarios.

The work on minimum bias priors proposes a way to choose prior densities for stochastic state-space models when true prior information is not available. The gain from using the proposed method is a decrease in the asymptotic bias of the estimator. In the past, traditional approaches to this problem have dealt usually with information theoretic criteria for choosing priors leading to less concrete results.

The main advantage of our polynomial factorization algorithms lies in their computational efficiency. This enables, for example, the use of these algorithms for direction of arrival estimation in real time.

The results on the CRB for the damped sinusoids will prove useful to workers in the field of transient signal detection since we have derived the notion of the effective time duration of such a signal. This allows one to carefully weigh the potential gains of increasing the number of time samples of such a signal.

The concentrated CRB formulas derived in have application to any model in which there are nuisance parameters. These parameters generally complicate calculation of the CRB for the parameters of interest. We provide a way to compute the CRB for the parameters of interest *directly*, thus avoiding manipulations involving the nuisance parameters. The method is straightforward to use, especially when the data distribution is Gaussian, and can potentially save much analytical work. Other researchers should be able to use our results immediately.

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