Digital Signal Processing

Academic and Research Staff
Professor Alan V. Oppenheim, Professor Arthur B. Baggeroer, Dr. Charles E. Rohrs.

Visiting Scientists and Research Affiliates
Dr. Dan E. Dudgeon[1], Dr. Yonina Eldar[2], Dr. Ehud Weinstein[3], Dr. Maya R. Said[4]

Graduate Students
Thomas Baran, Zahi Karam, Jon Paul Kitchens, Jeremy Leow, Shay Maymon, Melanie Rudoy, Joseph Sikora III, Dennis Wei.

Technical and Support Staff
Eric Strattman

Introduction

The Digital Signal Processing Group develops signal processing algorithms that span a wide variety of application areas including speech and image processing, sensor networks, communications, radar and sonar. Our primary focus is on algorithm development in general, with the applications serving as motivating contexts. Our approach to new algorithms includes some unconventional directions, such as algorithms based on fractal signals, chaotic behavior in nonlinear dynamical systems, quantum mechanics and biology in addition to the more conventional areas of signal modeling, quantization, parameter estimation, sampling and signal representation. When developing new algorithms, we often look to nature for inspiration and as a metaphor for new signal processing directions.

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[1] BAE Systems IEWS, Senior Principal Systems Engineer, Nashua, New Hampshire.
[2] Department of Electrical Engineering, Faculty of Engineering, Technion-Israel Institute of Technology, Israel.
[3] Department of Electrical Engineering, Systems Division, Faculty of Engineering, Tel-Aviv University, Israel; adjunct scientist, Department of Applied Ocean Physics and Engineering, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts.
[4] Visiting Scientist, Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts.

1. The Thermodynamics of Signal Processing

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Texas Instruments, Inc. Leadership University Program

Project Staff
Thomas Baran, Professor Alan V. Oppenheim

In circuit theory, many useful properties emerge from the thermodynamic principles underlying the physical implementation of a system. These properties include, for example, system invertibility and various forms of stability and robustness. In the design of digital signal processing systems, however, the particular way that a signal is processed is often rather distinct from the physical laws underlying the implementation of the system. This suggests that there may be opportunity in applying thermodynamic principles to signal processing settings that are traditionally far-removed from the effects of thermodynamics. This project explores the application of thermodynamic principles to the design of new signal processing algorithms and examines the thermodynamic principles that underlay existing signal processing settings.

Recent focus has been directed toward the problem of nonlinear system inversion. We first derive a class of signal flow graphs for which a notion of conjugate variables analogous to voltage and current exists, and we demonstrate that the ensemble of results from circuit theory that are stated in terms of Tellegen's Theorem apply in a straightforward way to the proposed class of structures. In circuit theory, Tellegen's Theorem is applicable to generally nonlinear networks, and the theorem may similarly be applied to the proposed structures. The concept of network duality from circuit theory in turn implies a notion of system inverses for the proposed class of structures, and we generalize the concept to a broader class that includes familiar discrete-time filter topologies.

2. Robust SVM/GMM Systems

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Project Staff
Zahi Karam, Dr. William Campbell (Lincoln Labs), Professor Alan V. Oppenheim

The use of parameters derived from generative models, such as Gaussian mixture models (GMMs), as features for support vector machine (SVM) classifiers has resulted in powerful SVM/GMM systems, specifically in speaker and language identification tasks. Recently, a method that performs likelihood-ratio scoring between two GMMs, discriminatively trained using parameters of the SVM optimization, has performed well in language identification. Our work examines the connection between SVM scoring in the SVM/GMM systems and likelihood-ratio scoring with GMMs, and identifies a framework that both theoretically and empirically connects the two scoring techniques.

In every classification task one must deal with two types of variability the good and the bad. The good is the variability needed to perform the classification, the bad is the variability that confuses the classifier. Our work proposes a method, which we call variability compensated support vector machines (VCSVM), to deal with this problem in SVM classifiers. VCSVM incorporates the variability compensation directly into the SVM optimization in an attempt to ensure that the good variability is used in the classification while the bad is ignored.

3. Acoustic Vector-Sensor Array Processing

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Project Staff
Jon Paul Kitchens, Professor Arthur Baggeroer

For acoustic pressure-sensor arrays, existing theory yields useful performance criteria and techniques for both fixed and data-adaptive processing. By measuring particle velocity in addition to pressure, acoustic vector-sensor arrays offer tremendous potential but complicate analysis and processing.

The research underway shows that substantial performance gains can be achieved with vector-sensor arrays despite their added complexity. It addresses three key problems encountered in vector-sensor array processing. First, it analyzes the performance dimension along which vector-sensor arrays excel: resolving signals that are ambiguous with classical arrays. Two alternative performance bounds under examination illustrate vector-sensor array performance along this new dimension. Second, the research provides techniques for designing robust fixed weights for non-adaptive processing. The added complexity of vector-sensors makes closed-form solutions impossible for some design criteria, but convex optimization provides a numerical alternative. Third, the research develops approaches for data-adaptive processing in high-dimensional spaces. Because vector-sensors quadruple the dimension of the problem, data-adaptive processing must be both efficient and robust.

4. Reconstruction from Non-uniform Samples

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Project Staff
Jeremy Leow, Professor Alan V. Oppenheim

The research is concerned with the reconstruction of signals from their non-uniform samples. The complexity of non-uniform sampling theory lies in its inability to adopt a linear time-invariant system for the reconstruction. We have focused on working with deterministic sequences of samples. Two key approaches were taken: time-warping formulation of the signal and its reconstruction process, and approximate reconstruction methods.

A delay modulation interpretation of time-warping has been used for non-harmonic Fourier analysis of non-uniformly sampled signals. Since the Lagrange interpolation formula is a method for reconstructing bandlimited signals from their non-uniform samples, an analysis of the Lagrange formula has been done to understand its properties. This has thus led to the formulation of a range of approximate reconstruction methods, including the use of sine functions and splines. In addition, studies have been made on the reconstruction of non-uniform samples from out-of-band signals, and the error resulting from the assumption that the samples lie on the uniform grid.

5. Randomized Sinc Interpolation of Nonuniform Samples

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Project Staff
Shay Maymon, Professor Alan V. Oppenheim

This research develops and compares simpler approximate methods for signal reconstruction from nonuniform samples.

We treat nonuniform samples as a stochastic perturbation from a uniform grid. With respect to second-order statistics, nonuniform sampling with stochastic perturbations can be modeled as uniform sampling of the signal pre-filtered by the Fourier transform of the pdf of the sampling perturbation. With this approach, the characteristic function of the perturbation error plays a role similar to that of an anti-aliasing filter. Of course the stochastic perturbation still manifests itself through an additive white noise. Thus, this model suggests that aliasing can be traded off with uncorrelated white noise by appropriate design of the pdf of the sampling perturbation.

Using this model, several approaches are suggested and analyzed for approximate reconstruction from nonuniform samples. These methods, based on the uniform sampling reconstruction and its Taylor's series expansion, lead to sinc interpolation of the nonuniform samples treated as though they are on a uniform grid, and alternatively sinc interpolation applied to the samples on the nonuniform grid. A generalized reconstruction method is also proposed, which incorporates both methods as special cases. This generalized method consists of locating the samples randomly around the uniform grid with the characteristics of the random perturbations designed to minimize the reconstruction error.

6. Multistage Mean-Variance Portfolio Selection in Cointegrated Vector Autoregressive Systems

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Project Staff
Melanie B. Rudoy, Dr. Charles E. Rohrs

The problem of portfolio choice is an example of sequential decision making under uncertainty. Investors must consider their attitudes towards risk and reward in face of an unknown future, in order to make complex financial choices. Often, mathematical models of investor preferences and asset return dynamics aid in this process, resulting in a wide range of portfolio choice paradigms, one of which was considered in this research. Specifically, it is assumed that the investor operates so as to maximize his expected terminal wealth, subject to a risk (variance) constraint, in what is known as mean-variance optimal (MVO) portfolio selection, and that the log-prices of the assets evolve according a simple linear system known as a cointegrated vector autoregressive (VAR) process. While MVO portfolio choice remains the most popular formulation for single-stage asset allocation problems in both academia and industry, computational difficulties traditionally limit its use in a dynamic, multistage setting. Cointegration models are popular among industry practitioners as they encode the belief that the log-prices of many groups of assets are not WSS, yet move together in a coordinated fashion. Such systems exhibit temporary states of disequilibrium or relative asset mis-pricings that can be exploited for profit.

A set of multiperiod trading strategies are developed and studied. Both static and dynamic frameworks are considered, in which rebalancing is prohibited or allowed, respectively. Throughout this work, the relationship between the resulting portfolio weight vectors and the geometry of a cointegrated VAR process is demonstrated. In the static case, the performance of the MVO solution is analyzed in terms of the use of leverage, the correlation structure of the inter-stage portfolio returns, and the investment time horizon. In the dynamic setting, the use of inter-temporal hedging enables the investor to further exploit the negative correlation among the inter-stage returns. However, the stochastic parameters of the per-stage asset return distributions prohibit the development of a closed-form solution to the dynamic MVO problem, necessitating the use of Monte Carlo methods. To address the computational limitations of this numerical approximation, a set of four approximate dynamic schemes are considered. Each relaxation is suboptimal, yet admits a tractable solution. The relative performance of these strategies, demonstrated through simulations involving synthetic and real data, depends again on the investment time horizon, the use of leverage and the statistical properties of the inter-stage portfolio returns.

7. Sound Wave Propagation around Underwater Seamounts

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Project Staff

Joseph Sikora III, Professor Arthur B. Baggeroer

In the ocean, low frequency acoustic waves propagate with low attenuation and cylindrical spreading loss over long-ranges, making them an effective tool for underwater source localization, tomography, and communications. Underwater mountains, or seamounts, are ubiquitous throughout the world’s oceans and can absorb and scatter acoustic energy, offering many interesting acoustic modeling challenges. The goal of this research is to measure the acoustic scattered field of a large, conical seamount at long-range, and reconcile observations with 2-D range-dependent acoustic models, for the purpose of understanding the effects of highly range-dependent bathymetry.

The Basin Acoustic Seamount Scattering Experiment (BASSEX) was conducted to measure the scattered fields of the two seamounts which form the Kermit-Roosevelt Seamount Complex in the Northeast Pacific Ocean during September and October of 2004. The experiment used fixed and ship-deployed acoustic sources transmitting m-sequence signals at 68.2 and 250 Hz carrier frequencies, with 35 and 83 Hz bandwidth, respectively. The receiver was a towed hydrophone array with 3 m sensor spacing, cut for 250 Hz. BASSEX is the first experiment to measure acoustic arrival patterns in the scattered field of a seamount at many locations at sound path ranges of order 500 km, utilizing a rich bathymetry and sound velocity database.

Convergence zones in the forward-scattered field of seamounts at long-range are observed, created by higher order mode coupling and blockage. Acoustic ray arrival angles, travel times, and amplitudes show good agreement with parabolic equation (PE) acoustic modeling results inside the forward-scattered fields; in particular, simulated results are fairly accurate for weak surface-reflected-bottom-reflected acoustic rays. The width of the forward-scattered field is shown to span the projected width of a seamount. Temporal coherence of ray amplitude inside a seamount scattered field could not be determined due to array movement issues, and should be the focus of future research to determine the stability of scattered acoustic rays for applications such as acoustic tomography.

Robust adaptive beamforming methods are used to process hydrophone array data gathered in the BASSEX experiment. Non-stationarity in the observed noise field caused by array fluctuations and data acquisition system malfunctions motivate the use of a time-varying Capon adaptive beamformer, and strong acoustic harmonics from ship operations motivate the use of a frequency and steering angle dependent white noise gain constraint. In an effort to process snap-shot deficient data sets, the novel physically constrained maximum likelihood (PCML) beamformer was further developed and applied. By using orthonormal trigonometric eigenvector bases to determine the maximum likelihood spectral covariance matrix, the PCML beamformer computational efficiency is significantly increased.

8. Design of Discrete-Time Filters for Computational Efficiency

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Project Staff
Dennis Wei, Professor Alan V. Oppenheim

This research addresses the design of discrete-time filters with the explicit objective of reducing computational complexity, both as an end in itself and as a means toward improving other cost metrics such as power consumption and hardware usage. The current focus is on the design of sparse filters, i.e., filters with few non-zero coefficients relative to conventional designs. Our work is also applicable to designing linear sensor arrays where sparse designs allow for the elimination of array elements.

As part of ongoing work on sparse filter design under a minimax constraint on the frequency response, we have developed a method based on solving a sequence of minimization problems involving the p-norms for $0 < p < 1$ (more properly, the extension of the p-norms to $0 < p < 1$). The p-norms have the desirable property of being an asymptotically exact measure of sparsity as p approaches zero. The lack of convexity is partially overcome by appropriately initializing each minimization. To solve the p-norm minimization problems, an efficient local search algorithm has been devised based on a certain optimality condition. Examples demonstrate that the method is capable of producing filters with near-optimal sparsity for a given set of specifications.

We are also investigating the design of sparse filters under a quadratic or least-squares constraint, which has additional applications in estimation and detection problems. Although the design problem is computationally difficult in the general case, promising progress has been made in obtaining efficiently solvable relaxations that yield close lower bounds on the true optimal cost. These relaxations can be incorporated in a branch-and-bound algorithm for solving the exact problem.

Publications

Journal Articles, Submitted

T. Baran, D. Wei, A.V. Oppenheim, “Linear Programming Algorithms for Sparse Filter Design,” submitted to IEEE Transactions on Signal Processing.

M.S. Willsey, K.M. Cuomo, A.V. Oppenheim, “Quasi-Orthogonal Wideband Radar Waveforms Based on Chaotic Systems,” submitted to IEEE Transactions on Aerospace and Electronic Systems.

Meeting Papers, Published

S.R. Dey, A.V. Oppenheim, "Coefficient Dither in Fixed-Point FIR Digital Filters," in thein the Proceedings of the 42nd Annual Asilomar Conference on Signals, Systems, and Computers, (Asilomar, CA), October 26-29, 2008.

M.B. Rudoy, C.E. Rohrs, "Optimal Mean-Variance Portfolio Construction in Cointegrated Vector Autoregressive Systems," 2008 American Control Conference, (Seattle, WA), June 11-13, 2008.

M.B. Rudoy, C.E. Rohrs, "A Dynamic Programming Approach to Two-Stage Mean-Variance Portfolio Selection in Cointegrated Vector Autoregressive Systems," in the Proceedings of the 47th IEEE Confernece on Decision and Control, (Cancun, Mexico), December 9-11, 2008.

Meeting Papers, Accepted

W.M. Campbell, Z.N. Karam, “A Framework for Discriminative SVM/GMM Systems for Language Recognition”, to appear in Proceedings of INTERSPEECH09, Brighton, UK, 2009.

Z.N. Karam, W.M. Campbell, “Variability Compensated Support Vector Machines; Applied to Speaker Verification”, to appear in Proceedings of INTERSPEECH09, Brighton, UK, 2009.

S. Maymon, A.V. Oppenheim, “Randomized Sinc Interpolation of Nonuniform Samples,” submitted to 17th European Signal Processing Conference (EUSIPCO 2009), August 24 – 28, 2009, Glasgow, Scotland.

D.E. Sturim, W.M. Campbell, Z.N. Karam, D.A. Reynolds, F. Richardson, “The MIT-LL 2008 Speaker Recognition System”, to appear in Proceedings of INTERSPEECH09, Brighton, UK, 2009.

D. Wei, “Non-Convex Optimization for the Design of Sparse FIR Filters”, accepted for presentation at the 2009 IEEE Workshop on Statistical Signal Processing, Cardiff, Wales, UK, August 31 – September 3, 2009.

Meeting Papers, Submitted

T. Baran, B. Lee, R.W. Schafer, “A Real-Time Frequency-Domain Algorithm For Single-Channel Blind Dereverberation” submitted to 2009 IEEE Workshop on Applications of Signal Processing to Audio and Acoustics, October 18-21, 2009, New Paltz, NY.

Theses

J.P. Kitchens, "Acoustic Vector-Sensor Array Performance", Master's Thesis, June 2008.

M.B. Rudoy, "Multistage Mean-Variance Portfolio Selection in Cointegrated Vector Autoregressive Systems", Doctoral Thesis, February 2009.

J. J. Sikora, "Sound Propagation around Underwater Seamounts", Doctoral Thesis, February 2009.