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13. ABSTRACT (Maximum 200 words)

This work investigates the use of Bayesian multiscale techniques for image analysis and automatic target recognition. We have developed two new techiques. First, we have develop a wavelet-based approach to image restoration and deconvolution problems using Bayesian image models and an alternating-maximization method. Second, we have developed a wavelet-based framework for target modeling and recognition that we call TEMPLAR (TEMPlate Learning from Atomic Representations). TEMPLAR is can be used to automatically extract low-dimensional wavelet representations (or templates) of target objects from observation data, providing robust and computationally efficient target classifiers. On a more theoretical level, we have developed a framework for multiresolution analysis of likelihood functions, which extends wavelet-like analysis to a wide class of non-Gaussian processes. In another line of investigation, we are exploring a new imaging application known as network tomography. The goal of this work is to characterize the internal performance of communication networks based only on external measurements at the edge (sources and receivers) of the network. In the coming year, we plan to focus on four key research areas. First, we will develop theoretical bounds on the performance of multiscale/wavelet estimators in non-Gaussian environments including Poisson imaging applications. Second, we will study the use of complex wavelets in image restoration and target recognition problems. Third, we will develop automatic methods for segmenting imagery (SAR, FLIR, LADAR) based on complexity-regularization methods. Fourth, we will continue to develop a unified framework for communication network tomography and investigate new tools for network performance visualization.

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1. List of Papers Submitted or Published under ARO Sponsorship During this Reporting Period

(a) Manuscripts Submitted

E. Kolaczyk and R. Nowak**, "Multiscale Generealized Linear Models for Nonparametric Function Estimation**", submitted to Biometrika, 2003.

R. Willett and R. Nowak, "**Multiscale Density Estimation**," submitted to IEEE Transactions on Information Theory, May 2003.

Y. Tsang, M. Coates, and R. Nowak, "**Network Delay Tomography**," to appear in IEEE Transactions on Signal Processing, Special Issue on Signal Processing in Networking, 2003.

R. Nowak, "**Distributed EM Algorithms for Density Estimation and Clustering in Sensor Networks**," to appear in IEEE Transactions on Signal Processing, Special Issue on Signal Processing in Networking, 2003.

(b) Papers Published in Peer-Reviewed Journals

R. Willett and R. Nowak, "**Platelets: a multiscale approach for recovering edges and surfaces in photon-limited medical imaging**," IEEE Transactions on Medical Imaging, Volume: 22 Issue: 3, March 2003, Pages: 332 –350.

E. Kolaczyk and R. Nowak, ``**Complexity Penalized Estimation using Multiscale Likelihood Factorizations: Risk Bounds and Asymptotics**,'' to appear The Annals of Statistics, 2003.

M. Figueiredo and R. Nowak**, "An EM Algorithm for Wavelet-Based Image Restoration**", *IEEE Transactions on Image Processing*. To appear in July 2003.

(c) Papers Published in Non-Peer-Reviewed Journals or in Conference Proceedings

Boundary Estimation in Sensor Network: Theory and Methods, R. Nowak and U. Mitra, 2nd International Workshop on Information Processing in Sensor Networks, Palo Alto, CA, April 22-23, 2003.

Platelets: a multiscale approach for recovering edges and surfaces in photon-limited medical imaging *Willett, R.M.; Nowak, R.D.;* Medical Imaging, IEEE Transactions on , Volume: 22 Issue: 3 , March 2003 Page(s): 332 -350

Wavelet-based adaptive image deconvolution *Figueiredo, M.A.T.; Nowak, R.D.;* Acoustics, Speech, and Signal Processing, 2002. Proceedings. (ICASSP '02). IEEE International Conference on , Volume: 2 , 2002 Page(s): 1685 -1688

Multiresolution nonparametric intensity and density estimation *Willett, R.M.; Nowak, R.D.;* Acoustics, Speech, and Signal Processing, 2002. Proceedings. (ICASSP '02). IEEE International Conference on , Volume: 2 , 2002 Page(s): 1493 -1496

Connexions: DSP education for a networked world *Baraniuk, R.G.; Burrus, C.S.; Hendricks, B.M.; Henry, G.L.; Hero, A.O., III; Johnson, D.H.; Jones, D.L.; Kusuma, J.; Nowak, R.D.; Odegard, J.E.; Potter, L.C.; Ramchandran, K.; Reedstrom, R.J.; Schniter, P.; Selesnick, I.W.; Williams, D.B.; Wilson, W.L.;* Acoustics, Speech, and Signal Processing, 2002. Proceedings. (ICASSP '02). IEEE International Conference on , Volume: 4 , 2002 Page(s): 4144 -4147

Platelets for multiscale analysis in medical imaging *Willett, R.M.; Nowak, R.D.;* [Engineering in Medicine and Biology, 2002. 24th Annual Conference and the Annual Fall Meeting of the Biomedical Engineering Society] EMBS/BMES Conference, 2002. Proceedings of the Second Joint , Volume: 2 , 2002 Page(s): 1023 -1024 vol.2

Image restoration under wavelet-domain priors: an expectation-maximization approach *Figueriedo, M.A.T.; Nowak, R.D.;* Image Processing. 2002. Proceedings. 2002 International Conference on, Volume: 1 , 2002 Page(s): 337 -340

Satellite and aerial image deconvolution using an EM method with complex wavelets *Jalobeanu, A.; Nowak, R.D.; Zerubia, J.; Figueiredo, M.A.T.;* Image Processing. 2002. Proceedings. 2002 International Conference on , Volume: 1 , 2002 Page(s): 333 -336

Platelets for multiscale analysis in photon-limited imaging *Willett, R.M.; Nowak, R.D.;* Image Processing. 2002. Proceedings. 2002 International Conference on , Volume: 1 , 2002 Page(s): I-365 -I-368 vol.1

An efficient algorithm for frame-based signal processing *Yi Wan; Nowak, R.D.;* Circuits and Systems, 2002. MWSCAS-2002. The 2002 45th Midwest Symposium on , Volume: 3 , 2002 Page(s): 243 -246

Multiscale maximum penalized likelihood estimators *Nowak, R.D.; Kolaczyk, E.D.;* Information Theory, 2002. Proceedings. 2002 IEEE International Symposium on , 2002 Page(s): 156 -156

`(d) Papers Presented at Meetings, but Not Published in Conference Proceedings`

`None.`

2. Scientific Personnel Supported by the Project

Clayton Scott, Ph.D. Candidate (expected December 2003)
Thesis Title: New Results on Classification Trees

3. Report of Inventions

None.

4. Scientific Progress and Accomplishments
[1]
Multiscale Density Estimation
The nonparametric density estimation method proposed in this paper is computationally fast, capable of detecting density discontinuities and singularities at a very high resolution, spatially adaptive, and offers near minimax convergence rates for broad classes of densities including Besov spaces. At the heart of this new method lie multiscale signal decompositions based on piecewise-polynomial functions and maximum penalized likelihood estimation. Upper bounds on the estimation error are derived using an information-theoretic risk bound based on squared Hellinger loss. The method and theory share many of the desirable features associated with wavelet-based density estimators, but also offers several advantages including guaranteed non-negativity, bounds on the L1 error (instead of L2), small-sample quantification of the estimation errors, and additional flexibility and adaptability. In particular, the method proposed here can adapt the degrees as well as the

locations of the polynomial pieces. For a certain class of densities, the error of the variable degree estimator converges at nearly the parametric rate. Experimental results demonstrate the advantages of the new approach compared to traditional density estimators and wavelet-based estimators.

Spatially Adaptive Classification and Decision Trees
Classification trees are one of the most popular types of classifiers, with ease of implementation and interpretation being among their attractive features. Despite the widespread use of classification trees, theoretical analysis of their performance is scarce. In this work, we show that a new family of classification trees, called dyadic classification trees (DCTs), are near optimal (in a minimax sense) for a very broad range of classification problems. This demonstrates that other schemes (e.g., neural networks, support vector machines) cannot perform significantly better than DCTs in many cases. We also show that this near optimal performance is attained with linear (in the number of training data) complexity growing and pruning algorithms. Moreover, the performance of DCTs on benchmark datasets compares favorably to that of standard CART, which is generally more computationally intensive and which does not possess similar near optimality properties. Our analysis stems from theoretical results on structural risk minimization, on which the pruning rule for DCTs is based.

Platelets: A Multiscale Approach for Recovering Edges and Surfaces in Photon-Limited Medical Imaging
The nonparametric multiscale platelet algorithms developed in this work, unlike traditional wavelet-based methods, are both well suited to photon-limited medical imaging applications involving Poisson data and capable of better approximating edge contours. This paper introduces platelets, localized functions at various scales, locations, and orientations that produce piecewise linear image approximations, and a new multiscale image decomposition based on these functions. Platelets are well suited for approximating images consisting of smooth regions separated by smooth boundaries. For smoothness measured in certain Hölder classes, it is shown that the error of m-term platelet approximations can decay significantly faster than that of m-term approximations in terms of sinusoids, wavelets, or wedgelets. This suggests that platelets may outperform existing techniques for image denoising and reconstruction. Fast, platelet-based, maximum penalized likelihood methods for photon-limited image denoising, deblurring and tomographic reconstruction problems are developed. Because platelet decompositions of Poisson distributed images are tractable and computationally efficient, existing image reconstruction methods based on expectation-maximization type algorithms can be easily enhanced with platelet techniques. Experimental results suggest that platelet-based meth-ods can outperform standard reconstruction methods currently in use in confocal microscopy, image restoration, and emission tomography.

Network Tomography and the Identification of Shared Infrastructure
This work investigates the problem of identifying network infrastructure that is shared by a collection of end-hosts. This identification is valuable for assessment and design of content distribution systems as well as network performance estimation and simulator design. The network routes connecting a set of sources to a set of receivers form a directed graph. This paper considers the identification of subgraphs shared by two or more sources. We take a system identification approach to the shared subgraph problem, comparing source inputs with receiver outputs. Sets of receivers are then associated with shared subgraphs using this novel multiple source probing scheme. Our methodology does not rely on special-purpose cooperation from internal network elements, and only requires end-to-end measurements that are easy to make. Experiments conducted on a local area network and the Internet demonstrate the potential of our approach.

Sensor Networks
Measurement and signal processing capabilities are inherently distributed in networks. This motivates our investigation into decentralized estimation and classification. Due to power and bandwidth constraints, the potential benefits of distributed schemes are perhaps most evident for wireless networks, and sensor networks in particular. Sensor networks have emerged as a fundamentally new tool for monitoring inaccessible environments such as non-destructive evaluation of buildings and structures; contaminant tracking in the environment; habitat monitoring in the jungle; and surveillance in military zones. The slogan ``the sensor is the

network," coined at Oakridge National Labs, aptly captures the sensor networking spirit – massively distributed, small devices, networked for communication and equipped with sensing and processing capabilities, that give us a new eye with which to explore our universe. We are developing novel frameworks for hierarchical and distributed estimation and classification in networks. They aim to answer the question: What are the basic patterns, structures, and relationships in the measured data? Such questions can also be naturally posed as estimation problems, and have been widely studied under the assumption that data are stored and processed at a central location. Here that assumption is changed; we assume that the data are not centralized, but rather are distributed across a collection of networked devices. Moreover, it is assumed that the cost (in terms of power or related resources) of computation at each node is much less than the cost of communication between nodes, which makes the option of transmitting all data to a central site for processing very expensive and unattractive.

5. Technology Transfer

- Derived a novel algorithmic method for image restoration and reconstruction. The algorithms are currently being implemented and tested by the French National Institute for Research in Computer Science and Control (INRIA) Project Ariana, under the direction of Dr. Josiane Zerubia, for satellite image restoration. This collaboration is continuing this year, and we are jointly investigating the potential of our approach for image super-resolution.

- Developed new algorithms for low-power sensor networks. We are initiating a new collaboration with CENS, a NSF Science & Technology Center aimed developing Embedded Networked Sensing Systems and applying this revolutionary technology to critical scientific and social applications. In collaboration with CENS, we plan to deploy our new sensor networking algorithms in testbed systems at UCLA.

- Introduced a framework for network tomography. The Stanford Linear Accelerator Center (SLAC) High Performance Computing and Networking research group, headed by Dr. Les Cottrell, is currently investigating potential applications of our network tomography algorithms. SLAC is interested in employing our methodology to estimate the network performance capabilities of various partners in an international, high-energy physics research consortium. This will allow SLAC to improve the transmission rates for very large (Gigabyte or larger) file transfers.

<u>MEMORANDUM OF TRANSMITTAL</u>

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