Introduction to the Special Issue on Information-Theoretic Imaging

THE idea for this Special Issue of the IEEE TRANSACTIONS ON INFORMATION THEORY on the topic of Information-Theoretic Imaging grew out of plans for a workshop on Detection, Estimation, Classification, and Imaging. That workshop was sponsored by the IEEE Information Theory Society and held in Santa Fe, New Mexico, in February 1999. The five Guest Editors met at the 1998 International Symposium on Information Theory held in Cambridge, MA, to finalize plans. The resulting call for papers appeared in the TRANSACTIONS in November 1998.

The last decade has seen some impressive advances in statistical imaging and in statistical, model-based image processing in general. Recent research has addressed two categories of problems: novel applications of fundamental statistical and information-theoretic principles to imaging; and exploring optimal and suboptimal methods for extracting information from intrinsically high-dimensional image data. In the first category are topics such as hierarchical image modeling and representation, minimax analysis, robustness analysis, learning theory, statistical pattern recognition and pattern matching, image compression, inference from compressed image data, and fundamental performance bounds on estimation, detection, classification, and compression. In the second category are topics such as approximation theory for multidimensional objects, multiresolution data analysis, content-based indexing of image databases, projection pursuit methods, and image reconstruction from incomplete and noisy data, for example, from magnitude-only Fourier data or tomographic projections.

The first goal of this Special Issue is to publish papers addressing fundamental theoretical and computational aspects of such problems and at the same time to raise the awareness for such research within the information theory community. Our long-term goal, beyond this Special Issue, is to encourage a broad, high-quality forum for addressing imaging problems of fundamental information-theoretic significance and to help bridge the current significant gap between emerging, advanced theoretical concepts and image processing practice.

The topic of information-theoretic imaging, interpreted broadly, includes all aspects of imaging system modeling, design, and analysis in which information theory plays a role. A more narrow interpretation would focus on the traditional domain of information theory in the development of performance bounds, the design of systems based on data likelihoods, and image compression. As editors we adopted the broader view.

The design and analysis of many imaging systems starts with a model for the available data based on the physics of the sensing modality and an underlying scene, image, or function. Images are usually functions of two variables, but can be multidimensional as in hyperspectral imaging and three-dimensional image reconstruction. These models are quantitative, including statistical uncertainties in the measurements. Such models are required in order to quantify the amount of information about an underlying function that the measurements give. A goal of this Special Issue was to present new models and application areas to the readers of this TRANSACTIONS. Doerschuk and Johnson describe an estimation-theoretic approach to cryo electron microscopy, including a detailed physical model and the unique symmetry properties that constrain solutions. They derive an expectation-maximization algorithm and do experiment design based on a Cramér–Rao bound. Radio-astronomical imaging is an application where traditional and novel imaging algorithms may be used, as discussed by Leshem and van der Veen. These images must be estimated while simultaneously suppressing interfering radio signals. Tsihrintzis and Devaney give a detailed description of models for data in diffraction tomography. The model is in the form of a nonlinear Rytov series, and they present methods for solving the resulting inverse problem. Other papers in this issue include applications in Poisson imaging (Nowak and Kolaczyk, Chrétien and Hero), radar imaging (Chiang, Moses, and Potter, and Caprari), hyperspectral imaging (Schweizer and Moura, and Chang), and optical imaging (Cooper and Miller, Shusterman, Miller, and Rimoldi, and Permuter and Francos).

Given a model of an imaging system, image formation problems are often stated as inverse problems. An inherent challenge in such problems is dealing with ill-posedness which, arises in most image formation problems. Most often, the image to be reconstructed takes values in an infinite-dimensional space. If the measurements are finite-dimensional, then in the absence of a prior distribution on the image, the problem is ill-posed. More rigorous definitions of ill-posedness are available in the literature and in papers in this Special Issue, including the paper by Solo. Some form of regularization is required for such problems. Complexity regularization methods are discussed in the paper by Hansen and Yu and by Moulin and Liu. Hierarchical image models provide a framework for image representation that is often exploited in imaging problems. Li, Gray, and Olshen address classification problems using hierarchical, multiresolution Markov models. They use an expectation-maximization algorithm to estimate model parameters. Hansen and Yu apply Rissanen's minimum description length principle to wavelet coefficients of images. They show that this method also provides good image compression. Moulin and Liu apply complexity regular-

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ization to several data models and bound performance using an index of resolvability. They also study the relationship to image compression by an analogy between minimizing the expected index of resolvability and rate-distortion theory. Nowak and Kolaczyk use a novel multiscale, conjugate prior distribution on Poisson intensities. Solo presents regularization issues for stochastic inverse problems, defines the modulus of continuity as a measure of the difficulty of a problem, and obtains minimax performance bounds in terms of this measure.

Characterizations of scenes may be more sophisticated if more information is known. This information may be included in prior distributions on the scenes or in deterministic constraints. In object recognition problems, the possible objects may be completely or partially known. For rigid objects, the position and orientation (pose) constitute the only uncertainty in the characterization of the object, and likelihoods for observations are specified conditioned on the object and its position and orientation. Shusterman, Miller, and Rimoldi take this view of object recognition and describe a methodology for optimal object model (or codebook) design using rate-distortion theory; the distortion function is on the estimated orientation of the object. If the objects are not from a known finite set, but are constrained in some other way, then inference over that constraint set is appropriate. Permuter and Francos derive a model for the perspective projection of periodic patterns on flat surfaces, and estimate parameters within this framework. Traditionally, nonparametric models have been used for many imaging problems. The model of Nowak and Kolaczyk is of this type. Schweizer and Moura present a Markov random field model for hyperspectral images, give estimation algorithms for the model parameters, and present performance analyses for applications to detection problems.

Given models for or prior distributions on scenes, and models for the sensors, the derivation of algorithms often has a strong information- theoretic background. Nowak and Kolaczyk derive an alternating minimization algorithm for Poisson inverse problems. Their multiscale model uses conjugate priors for the Poisson rates, yielding closed-form expressions for their algorithms; these priors have hyperparameters that are selected in problem-specific ways. Chrétien and Hero derive new iterative algorithms for maximum-likelihood estimation that converge faster than expectation-maximization algorithms. They add a Kullback penalty, scaled by a relaxation parameter, to the likelihood function and incorporate a trust region approach.

The performance of estimation problems is often quantified using Fisher information and Cramér–Rao bounds. Several papers refer to such bounds, including Permuter and Francos. Permuter and Francos estimate the orientation of planar surfaces that have periodic patterns on them and compare the performance to Cramér–Rao bounds. A new class of bounds for shape estimation is presented by Ye, Bresler, and Moulin. They find confidence regions for the true shape around estimated shapes. The probability that the true shape is in the confidence region is bounded using level-crossing statistics. Cooper and Miller describe a framework for using mutual information to quantify the information about target orientation obtained by a sensor, and apply their results to infrared and video imaging. As mentioned above, Solo derives limits on estimation performance in ill-posed, stochastic, inverse problems.

Image data sets are often very large, motivating the use of compression methods for storage and transmission. Wee Sun Lee develops a universal source coding approach to image compression by optimally tiling subbands and selecting a probability model for each tile from a finite class of models. As mentioned above, Hansen and Yu and Moulin and Liu discuss the connection between complexity regularization and compression.

Images are used for many purposes. An important application is classification. Li, Gray, and Olshen use nonparametric models based on a multiscale Markov mesh for classification. Chiang, Moses, and Potter tackle the difficult problem of classification using radar data. For many objects of interest, a scattering center model for radar data is appropriate. They describe such a model for radar data, derive likelihood-based classification algorithms based on their model, and present simulation results showing feasability of the approach.

Detection problems often must be solved using image data. For Schweizer and Moura, their estimation problem is a step in the process of solving a detection problem. Chang is also interested in detection using hyperspectral imaging data, and compares the use of discrepancy measures based on squared error and relative entropy (discrimination). Caprari derives a novel approach for target detection using a generalized matched filter followed by an optimal detector for the output of that filter; the approach is applied to both synthetic-aperture radar and infrared data, using parameters and distributions estimated from training sets.

As Guest Editors for this Special Issue, we wish to thank all those who submitted manuscripts for consideration. Thanks also to the many individuals who served as referees of the submitted manuscripts. Priority has been given to manuscripts that reflect in some way the influence of information theory and which we hope will motivate those with interests in information theory to apply their skills to imaging science.

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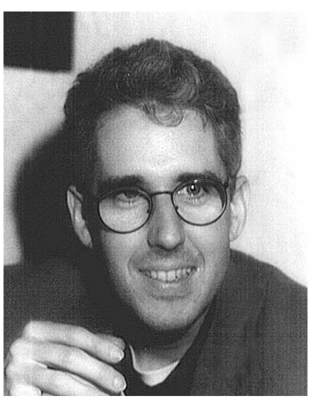
From 1966 to 1969, he was on the faculty of MIT. Since 1969, he has been on the electrical engineering faculty of Washington University, St. Louis, MO. He served as Chairman of the Department of Electrical Engineering from 1976 to 1986 and as Associate Director of the Biomedical Computer Laboratory, Washington University School of Medicine. He is the founding Director of the Electronic Systems and Signals Research Laboratory (ESSRL) in the Department of Electrical Engineering, and he served as director of this laboratory from 1986 to 1998. ESSRL is involved with research in information-theoretic imaging, with applications to biomedical imaging, hyperspectral imaging, automatic object recognition, dynamic vision, etc. He is the Samuel C. Sachs Professor of Electrical Engineering and Professor of Radiology. He is the author of papers on the theories of random processes, estimation, decision, and systems and the application of these theories to practical problems. Most recently, his interest has been in the development and application of random point process models in optical and radiological imaging. He is coauthor with M. Miller of *Random Point Processes in Time and Space*, published by Springer-Verlag.

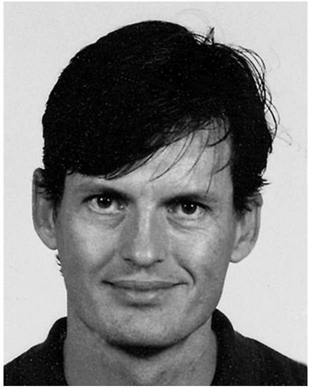
Dr. Snyder served as Associate Editor for random processes for the IEEE TRANSACTIONS ON INFORMATION THEORY and was the 1981 President of the IEEE Information Theory Society.



Alfred O. Hero III (S'79–M'80–SM'96–F'98) was born in Boston, MA, in 1955. He received the B.S. degree in electrical engineering (*summa cum laude*) from Boston University, Boston, in 1980 and the Ph.D. degree from Princeton University, Princeton, NJ, in 1984, both in electrical engineering. While at Princeton he held the G.V.N. Lothrop Fellowship in engineering.

Since 1984, he has been with the Department of Electrical Engineering and Computer Science at the University of Michigan, Ann Arbor, where he is currently Professor and Director of the Communications and Signal Processing Laboratory. He has held positions of Visiting Scientist at MIT Lincoln Laboratory (1987–1989), Visiting Professor at Ecole Nationale des Techniques Avancees (ENSTA), Ecole Supérieure d'Electricite, Paris, France (1990), Ecole Normale Supérieure de Lyon, Lyon, France (1999), and Ecole Nationale Supérieure des Télécommunications, Paris (1999), and was William Clay Ford Fellow at Ford Motor Company (1993). His current research interests are in the area of estimation and detection, statistical communications, signal processing, and image processing.

Dr. Hero has served as Associate Editor for the IEEE TRANSACTIONS ON INFORMATION THEORY. He was also Chairman of the Statistical Signal and Array Processing (SSAP) Technical Committee of the IEEE Signal Processing Society. He served as treasurer of the Conference Board of the IEEE Signal Processing Society. He was Chairman for Publicity for the 1986 IEEE International Symposium on Information Theory (Ann Arbor, MI). He was General Chairman for the 1995 IEEE International Conference on Acoustics, Speech, and Signal Processing (Detroit, MI). He was Co-Chair for the 1999 IEEE Information Theory Workshop on Detection, Estimation, Classification, and Filtering (Santa Fe, NM) and the 1999 IEEE Workshop on Higher Order Statistics (Caesaria, Israel). He is currently a member of the Signal Processing Theory and Methods (SPTM) Technical Committee and Vice President (Finances) of the IEEE Signal Processing Society. He is also currently Chair of Commission C (Signals and Systems) of the U.S. National Commission of the International Union of Radio Science (URSI). He is a member of Tau Beta Pi, the American Statistical Association (ASA), and Commission C of the International Union of Radio Science (URSI). He received the 1998 IEEE Signal Processing Society Meritorious Service Award, the 1998 IEEE Signal Processing Society Best Paper Award, and the IEEE Third Millenium Medal.



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He was a Researcher at the Faculté Polytechnique de Mons during 1984–1985 and at the Ecole Royale Militaire in Brussels, Belgium, during 1986–1987. He was a Research Scientist at Bell Communications Research, Morristown, NJ, from 1990 until 1995. In 1996, he joined the University of Illinois at Urbana-Champaign, where he is currently an Associate Professor in the Department of Electrical and Computer Engineering and a Research Associate Professor in the Beckman Institute and in the Coordinated Science Laboratory. His fields of professional interest are image and video processing, compression, statistical signal processing and modeling, nonparametric function estimation, information theory, and the application of multiresolution signal analysis, optimization theory, and fast algorithms to these areas.

During 1996–1998, Dr. Moulin served as an Associate Editor of the IEEE TRANSACTIONS ON INFORMATION THEORY. He was Co-Chair of the 1999 IEEE Information Theory Workshop on Detection, Estimation, Classification, and Imaging and is currently a Guest Associate Editor of the IEEE TRANSACTIONS ON INFORMATION THEORY's 2000 Special Issue on Information-Theoretic Imaging, an Associate Editor of the IEEE TRANSACTIONS ON IMAGE PROCESSING, and a member of the IEEE IMDSP Technical Committee. He received a 1997 CAREER award from the National Science Foundation and the IEEE Signal Processing Society 1997 Senior Best Paper award for a September 1995 paper on nonorthogonal subband coding.

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Dr. Moura serves as Vice-President for Publications and as a member of the Board of Governors of the IEEE Signal Processing Society. He is also Vice-President for publications for the IEEE Sensors Council. He has been on the Editorial Board of PROCEEDINGS OF THE IEEE since January 1999. He chairs the IEEE Signal Processing Society Publications Board. He was the 1995–1999 Editor in Chief for the IEEE TRANSACTIONS IN SIGNAL PROCESSING, and he is currently a member of the Multimedia Signal Processing technical committee, a founding member of the Sensor Array and Multichannel technical committee, and a past member of the Underwater Accoustics technical committee. He was a member of the IEEE Press Board from 1991 to 1995, an Associate Editor for several journals, and has been on the program committee for several IEEE international conferences and workshops. He is a corresponding member of the Academy of Sciences of Portugal. He is affiliated with several IEEE societies, Sigma Xi, AMS, IMS, and SIAM. In 2000, he received an IEEE Third Millennium Medal.

Joseph A. O'Sullivan (S'83–M'85–SM'92) was born in St. Louis, MO, on January 7, 1960. He received the B.S., M.S., and Ph.D. degrees, all in electrical engineering, from the University of Notre Dame, Notre Dame, IN, in 1982, 1984, and 1986, respectively.

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Dr. O'Sullivan was the Publications Editor for the IEEE TRANSACTIONS ON INFORMATION THEORY from 1992 to 1995, and is currently Associate Editor for Detection and Estimation. He has served on the organizing and program committees for several conferences and workshops. He was Co-Chair of the 1999 Information Theory Workshop on Detection, Estimation, Classification, and Imaging, and was in charge of travel grants and registration for the 1995 Information Theory Workshop on Information Theory, Multiple Access, and Queueing. He is active in local IEEE activities as well, including being Chair of the St. Louis Section of the IEEE in 1994. He received the IEEE Third Millenium Medal. He is a member of Eta Kappa Nu, and a member of SPIE.