Guest Editorial
Introduction to the Special Issue on Nonlinear Image Processing

THE need for nonlinear image and video signal processing arises as a result of the following phenomena:

1) The physics laws of image formation are nonlinear.
2) There is strong evidence that many stages of human visual perception are nonlinear.
3) Stochastic components of image and video signals are inherently nonstationary and non-Gaussian random processes for which linear processing is not optimum.

Thus, many tasks required for image processing, visual communications, and computer vision such as geometrical feature extraction, noise filtering, and image segmentation, can all be made more efficient by the use of nonlinear algorithms.

While the field of digital image processing has matured within the framework of linear systems, novel areas of nonlinear signal processing continue to appear. The response of the scientific community to nonlinear signal processing is perhaps well described by the success of the first two IEEE Workshops on Nonlinear Signal Processing held in Finland and in Greece in 1993 and 1995, respectively. We expect that novel research areas and applications will continue to appear in the broad domain of nonlinear signal processing.

The goal of the issue is to bring together the latest advances in several established methodologies of nonlinear image processing as well as developments in some emerging nonlinear methods. The contributions to this Special Issue gather around the following themes:

1) order-statistic-based signal processing
2) mathematical morphology
3) higher order statistics
4) radial basis functions
5) emerging nonlinear methods.

Order-statistic and morphological signal processing represent two large classes of nonlinear systems that avoid several problems introduced by linear filtering. Specifically, blurring and shifting important image features such as edges and other characteristics of the objects' geometry are among the problems caused by linear filters. The morphological class stems historically from set/lattice theory and stochastic/integral geometry, whereas the order-statistic class comes from robust statistics. These two classes are related, have a rich theoretical framework, and have been applied extensively in image processing.

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On a related front, many image analysis and computer vision tasks such as feature extraction, motion detection and segmentation, and object recognition often need a multiscale formulation, where features/objects are more easily detected at coarse scales rather then at their original resolution. Whereas early approaches in computer vision used linear lowpass filters, e.g., Gaussian convolutions, for multiscale analysis, the linear scale space suffers from its shifting and blurring of important image features across scales. In contrast, morphological and order-statistic smoothing filters have recently been used to create a nonlinear scale-space for multiscale image analysis that has as rich a theory as the Gaussian scale space and can exactly preserve vertical edges and the outline and location of object shapes up to the maximum scale at which they exist.

Higher order statistics (HOS) is another important approach to the nonlinear processing of images. HOS can offer significant advantages over conventional second-order statistics due to the fact that most image processes are non-Gaussian in nature. Thus, system identification, noise suppression, and signal synthesis are all imaging tasks that can be improved from the use of HOS. Polynomial and Volterra filters that use polynomial transformations of the input signal space are related to HOS systems. Thus, this class of nonlinear filters exploits the HOS of an underlying signal to provide improved estimates.

We have opted not to include neural networks or, in general, low-dimensional expansion methods that represent nonlinear functionals as a series of low-dimensional nonlinear functions. Although neural networks constitute an important class of nonlinear signal processing algorithms, these have been appropriately addressed by other Special Issues in the literature. We do, however, include papers with less established theories of nonlinear systems and papers in which the application of a nonlinear method is novel to image processing. A brief introduction to the papers follows.

The papers in this Special Issue that present advances on order-statistic-based signal processing cover various topics such as space-scale representation, time/scale/rank image decompositions, filter design, and vector processing.

Tabus, Petrescu, and Gabbouj present a general training framework for stack and boolean filters. These methods can prove useful in a wide range of applications requiring the robust design of this class of filters, which include weighted median filters. Arce and Tian develop a time-scale/rank filtering framework where an input signal, in addition to being decomposed into a set of subbands, is also decomposed into a set of rank orderings. Thus, subband decomposition and rank ordering is accomplished jointly. This framework is then applied to improve the learning characteristics of adaptive order-statistic filters. Yu and Chen propose to generalize stack filters by replacing the traditional crisp boolean functions with fuzzy boolean operators applied on each threshold decomposed signal. The fuzzy decisions result in improved estimates. An extension of selection permutation filters is presented by Hardie and Barner. They show that if the sample mean is included in the permutation space, the resultant class of filters exhibit excellent edge-enhancement properties. It turns out that most rank-order based enhancers can be formulated as subclasses of the proposed framework. Trahanias, Karakos, and Venetsanopoulos extend the theory of vector directional filters, which offer a good alternative in processing color images as the direction of the input vectors signifies the chromaticity of a given color; thus, results that are more appealing to human perception can be attained. Bangham, Ling, and Young propose a scale-space decomposition algorithm based on recursive running medians. The algorithm is fast and has a close relationship to morphological sieves. Pitas *et al.* modify the update procedure of Kohonen's likelihood vector quantizers to attain more robust learning characteristics. Finally, Koivunen presents a multivariate filter algorithm that minimizes a robust error criterion; this algorithm is applied to the smoothing of color images.

The papers in this Special Issue that deal with morphological image processing focus on various topics such as applications to image/video coding and template matching, multiscale analysis, segmentation, image representation, stochastic geometry and image restoration, system representation in the space and slope transform domain, and nonlinear dynamics. Since mathematical morphology is a shape/size-oriented approach to signal processing, it offers many powerful tools for region-based image coding. The paper by Salembier *et al.* describes many such morphological tools (ranging from shape-preserving smoothing by morphological reconstruction to multiscale watershed segmentation) and successfully demonstrates their applications in image and video segmentation and contour and texture coding. A powerful methodology for image segmentation is the watershed approach implemented by various morphological algorithms. The paper by Jackway deals with multiscale watershed segmentation and contributes a theoretical analysis related to the monotonicity of the number of catchment basins for sequences of appropriately filtered gradient images. A frontier and interesting area of morphological image processing is the modeling and processing of random images using stochastic morphology. The paper by Sivakumar and Goutsias makes some theoretical contributions in this area by analyzing continuous-space binary random fields via random sets and mathematical morphology and by studying their discretization. In the same area, the paper by Sidiropoulos, Meleas, and Stragas theoretically analyzes the MAP estimation of morphologically smooth images in sequences of noisy observations and investigates the relationship between the number of observation images and the error of signal reconstruction using morphological estimation rules.

Morphological image processing has traditionally used geometry and set/lattice algebra to analyze morphological operators in the space domain. The paper by Maragos provides a unified view and systems analysis tools for a recently growing part of morphology that is based on ideas from calculus and dynamical systems. Examples include differential/difference equations that model distance propagation or multiscale processes and slope transforms that analyze these systems in a transform domain in ways conceptually similar to using Fourier transforms for linear systems. The paper by Kosravi and Schafer studies a morphological signal correlation and investigates its application to template matching and its advantages over standard linear correlation. The paper by Ko, Morales, and Lee uses the morphological basis representation theory to develop some fast recursive algorithms for discrete morphological operations using a basis matrix formulation. Finally, the paper by Wang and Ronsin studies compact representations for gray-level images using ideas from morphological skeletonization and explores their applications.

Within the area of HOS, this Special Issue contains papers contributing to image modeling and its applications, image and edge enhancers, and the application of HOS to image sequence motion analysis. In particular, Hall and Giannakis use higher and second-order statistics for ARMA image modeling. Their technique is subsequently used for texture classification and synthesis. Thurnhofer and Mitra present a general framework for quadratic Volterra filters for edge enhancement that exploits the characteristics of the human visual system. The use of HOS in motion estimation is presented in the paper by Sayrol, Gasull, and Fonollosa. A fourth-order cost function of the displaced frame difference is used for motion detection when the sequence is severely corrupted by noise.

The issue also contains several papers presenting emerging nonlinear methods for image processing. The article by Cha and Kassam describes the application of radial basis functions (RBF's) to image processing. RBF's offer local approximations to fit local regions using a parametric function. The fit is in regions where data exists, and therefore, it is immune to modeling errors that may occur in regions other than the one being approximated. Holt, Huang, and Netravali describe a set algebraic methods that are useful in the study of polynomial system equations; these methods are then applied to the important problem of motion estimation. A general algorithm for the L1-minimization of total image variation is presented in the paper by Li and Santosa. This algorithm is then applied to the restoration of blurred and noisy images. Schultz and Stevenson describe how an edge-preserving image model can be used to extract high-resolution imagery from a low-resolution image sequence. A filtering approach based on conditioning on a state variable is described in the paper by Lightstone, Abreu, Mitra, and Arakawa. Based on the state variable, the filter performs as an identify or as a rank-order mean filter. Krieger *et al.* introduce the concept of intrinsic dimensionality as a description of image content and use this concept to show that quadratic filters can extract image information structures better than linear filters. Friedlander and Francos consider a polynomial phase model for non-homogeneous 2-D signals and develop an algorithm for estimating its parameters. Finally, Bovik *et al.* extend image modulation models and related demodulation algorithms to the case of multicomponent superposition.

In closing we would like to acknowledge the efforts of the authors who submitted papers to this Special Issue. Special thanks go to the referees for working within the tight schedule required for special issues. Our sincere thanks to Dave Munson, whose constant support has been instrumental in the completion of this project. We also extend our thanks to Pierce Wheeler for his support through the various stages of the project.

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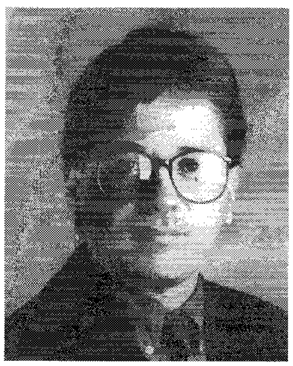

Gonzalo R. Arce (SM'93) was born on September 20, 1957 in La Paz, Bolivia. He received the B.S.E.E. degree with the highest honors from the University of Arkansas, Fayetteville, USA, in 1979, and the M.S. and Ph.D. degrees in electrical engineering from Purdue University, West Lafayette, IN, USA, in 1980 and 1982, respectively.

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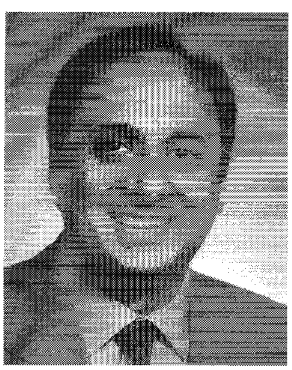
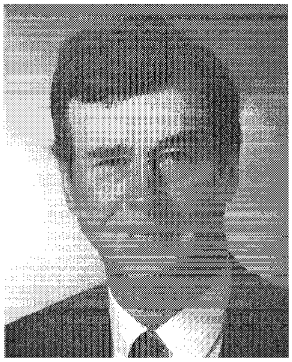
Dr. Arce has served three consecutive terms as Associate Editor of the IEEE TRANSACTIONS ON SIGNAL PROCESSING and is a member of the Digital Signal Processing Technical Committee of the Circuits and Systems Society. He has served as Chair, Co-Chair, and on the advisory committees of several conferences on nonlinear signal processing.



Petros Maragos (S'81–M'85–SM'91–F'95) received the Diploma degree in electrical engineering from the National Technical University of Athens, Athens, Greece, in 1980 and the M.S.E.E. and Ph.D. degrees from the Georgia Institute of Technology (Georgia Tech), Atlanta, in 1982 and 1985.

In 1985, he joined the faculty of the Division of Applied Sciences at Harvard University, Cambridge, MA, where he worked as first as Assistant (1985–1989) and then as Associate Professor (1989–1993) of electrical engineering. In 1993, he joined the faculty at Georgia Tech, where he is currently an Associate Professor of electrical and computer engineering. During parts of 1992 and during 1995 to 1996, he has been a visiting professor at the National Technical University of Athens. He has consulted for several industry research groups including Xerox at PARC and the Institute for Language and Speech Processing in Athens. His research activities have been in the general areas of signal processing, systems theory, communications, pattern recognition and their applications to image processing and computer vision, and computer speech processing and recognition.

Dr. Maragos's work in signal, image, and speech processing has received several awards, including a National Science Foundation Presidential Young Investigator Award (1987), the IEEE Signal Processing Society's 1988 Paper Award for the paper "Morphological Filters," IEEE Signal Processing Society's 1994 Senior Award (corecipient), and the 1995 IEEE Baker Award for the paper "Energy Separation in Signal Modulations with Application to Speech Analysis." (corecipient). He has also served as associate editor for the IEEE TRANSACTIONS ON SIGNAL PROCESSING, and as general chairman for the 1992 SPIE Conference on Visual Communications and Image Processing. He is a member of two IEEE DSP Committees and is president of the International Society for Mathematical Morphology.



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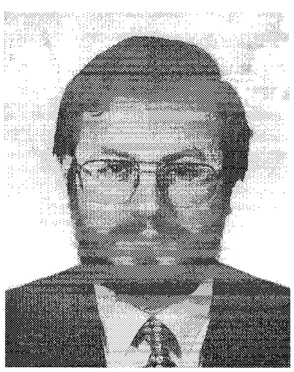
He held various research and teaching positions at the Helsinki University of Technology, the Academy of Finland, and Cornell University, from 1968 to 1976. Since 1976, he has been a Professor of Electrical Engineering at the Tampere University of Technology, Tampere, Finland. During the academic year 1981-1982, he was with the University of California, Santa Barbara, USA, as a Visiting Professor. Since 1984, he has held the position of National Research Professor at the Academy of Finland. Since 1993, he has been with Nokia Corporation, Espoo, Finland, currently as Senior Vice President of research and development at Nokia Mobile Phones. His main research interests are in digital signal and image processing algorithms and their implementations.

Dr. Neuvo is a member of EURASIP, Phi Kappa Phi, the Finnish Academy of Technical Sciences, the Foreign Member of the Royal Swedish Academy of Technical Sciences, and Academiae Europae. He holds an Honorary Doctor of Medicine degree from Tampere University. He is member of the Editorial Board of *Signal Processing*, an Associate Editor of *Circuits, Systems and Signal Processing*, and is an Associate Editor of the IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS FOR VIDEO TECHNOLOGY. He serves as a member of the Signal Processing Committee of the IEEE Circuits and Systems Society. He is a member of EU's Science and Technology Assembly (1994–). He was Distinguished Lecturer of IEEE Circuits and Systems Society from 1991 to 1995. He was a member of the Committee for the Development of Science and Technology in Europe from 1990 to 1994. He was the President of the Society of Electronics Engineers in Finland from 1978 to 1980. He was the General Chairman of the 1988 IEEE International Symposium on Circuits and Systems held in Helsinki, Finland.



Ioannis Pitas received the Diploma of Electrical Engineering in 1980 and the Ph.D. degree in electrical engineering in 1985 both from the University of Thessaloniki, Greece.

He is full Professor in the Department of Informatics at the same University. From 1980 to 1994, he served as Scientific Assistant, Lecturer, Assistant, and Associate Professor at the same University. He served as a Visiting Research Associate at the University of Toronto, Canada, the University of Erlangen-Nuernberg, Germany, Tampere University of Technology, Finland, and as Visiting Assistant Professor at the University of Toronto. He was lecturer in short courses for continuing education. His current interests are in the areas digital image processing, multidimensional signal processing, and computer vision. He has published over 180 papers and contributed in eight books in his area of interest. He is the co-author of the book *Nonlinear Digital Filters; Principles and Applications* (Boston, MA: Kluwer, 1990). He is the author of the book *Digital Image Processing Algorithms* (Englewood Cliffs, NJ: Prentice-Hall, 1993). He edited the book *Parallel Algorithms and Architectures for Digital Image Processing, Computer Vision and Neural Networks* (New York: Wiley, 1993).

Dr. Pitas has been a member of the European Community ESPRIT Parallel Action Committee. He has also been invited speaker and/or member of the program committee of several scientific conferences and workshops. He is associate editor of IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS and of *Multidimensional Systems and Signal Processing*. He was chair of the 1995 IEEE Workshop on Nonlinear Signal and Image Processing.