SELECTED ANNOTATED BIBLIOGRAPHIES FOR ADAPTIVE FILTERING OF DIGITAL IMAGE DATA

By Margaret Mayers and Lynnette Wood

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by Margaret Mayers[1/] and Lynette Wood[2/]

INTRODUCTION

Digital spatial filtering is an important tool both for enhancing the information content of satellite image data and for implementing cosmetic effects which make the imagery more interpretable and appealing to the eye. Spatial filtering is a context-dependent operation that alters the gray level of a pixel by computing a weighted average formed from the gray level values of other pixels in the immediate vicinity.

Traditional spatial filtering involves passing a particular filter or set of filters over an entire image. This assumes that the filter parameter values are appropriate for the entire image, which in turn is based on the assumption that the statistics of the image are constant over the image. However, the statistics of an image may vary widely over the image, requiring an adaptive or "smart" filter whose parameters change as a function of the local statistical properties of the image. Then a pixel would be averaged only with more typical members of the same population.

This annotated bibliography cites some of the work done in the area of adaptive filtering. The methods usually fall into two categories, (a) those that segment the image into subregions, each assumed to have stationary statistics, and use a different filter on each subregion, and (b) those that use a two-dimensional "sliding window" to continuously estimate the filter either the spatial or frequency domain, or may utilize both domains. They may be used to deal with images degraded by space variant noise, to suppress undesirable local radiometric statistics while enforcing desirable (user-defined) statistics, to treat problems where space-variant point spread functions are involved, to segment images into regions of constant value for classification, or to "tune" images in order to remove (nonstationary) variations in illumination, noise, contrast, shadows, or haze.

1/ TGS Technology, Inc. Work performed under U.S. Geological Survey contract 14-08-0001-22521.

2/ Environmental Research Institute of Michigan (ERIM).

Since adpative filtering, like nonadaptive filtering, is used in image processing to accomplish various goals, this bibliography is organized in subsections based on application areas. Contrast enhancement, edge enhancement, noise suppression, and smoothing are typically performed in order imaging process, (for example, degradations due to the optics and electronics of the sensor, or to blurring caused by the intervening atmosphere, uniform motion, or defocused optics). Some of the papers listed may apply to more than one of the above categories; when this happens the paper is listed under the category for which the paper's emphasis is greatest. A list of survey articles is also supplied. These articles are general discussions on adaptive filters and reviews of work done. Finally, a short list of miscellaneous articles are listed which were felt to be sufficiently important to be included, but do not fit into any of the above categories. This bibliography, listing items published from 1970 through 1987, is extensive, but by no means complete. It is intended as a guide for scientists and image analysts, listing references for background information as well as areas of significant development in adaptive filtering.

CONTRAST ENHANCEMENTS

Alparslan, Erhan, and Ince, Fuat, 1981, Image enhancement by local histogram stretching: IEEE Transaction on Systems, Man, and Cybernetics, v. SMC-11, no. 5, May 1981, p. 376-385.

An image enhancement algorithm that makes use of local histogram stretching is introduced. This algorithm yields considerable improvements in human observation of details in an image, compared to straightforward histogram equalization and a number of other enhancement techniques. The algorithm is especially suitable for producing hard copies of images on electrostatic plotters with limited gray levels, as shown in applications to a digitized photograph of a girl and a Landsat image.

Dorst, L., 1982, A local contrast enhancement filter: IEEE International Conference on Pattern Recognition, 1982, Munich, Germany, Proceedings: v. 1, p. 604-605.

A non-linear filter for the enhancement of the contrast in an image is described. The proposed filter is based on a stretching of the local histograms. The filter is rather insensitive to noise, as local outliers are discarded.

Harris, James L., Sr., 1977, Constant variance enhancement: a digital processing technique: Applied Optics, May 1977, v. 16, no. 5, p. 1268-1271.

An image enhancement process is one in which the image is manipulated for the purpose of increasing the information extractable by the human visual system. Constant variance enhancement is a technique that employs a high-pass filter to reduce the local average to zero for all regions of the picture, and then applies a gain factor equal to the reciprocal of the local standard deviation to produce an output picture in which all local regions have equal variance. An example of a constant variance enhancement is presented with pictures illustrating the various mathematical stages of the processing operations. The concept of differential luminance gain is introduced as a crude measure of enhancement effectiveness and is numerically evaluated for the illustrative processing. The significance of negative differential luminance gain is considered, and ways of dealing with these spurious results are considered.

Ketcham, David J., 1976, Real-time image enhancement techniques: Journal of Photo-Optical Instrumentation Engineers (SPIE), Image Processing, February 1976, v. 74, p. 120-125.

Most image enhancement techniques are not suitable for real-time applications. This paper presents two contrast enhancement techniques that can work at TV rates with fairly simple hardware.

Narendra, Patrenahalli M., and Fitch, Robert C., 1981, Real-time adaptive contrast enhancement: IEEE Transactions on Pattern Analysis and Machine Intelligence, November 1981, v. PAMI-3, no. 6, p. 655-661.

A recursive filter approach is introduced to simplify real-time implementation of an adaptive contrast enhancement scheme for imaging sensors. With this scheme, even scenes possessing large global dynamic ranges (>40 dB) can be accommodated by the limited dynamic range (20 dB) of a display without losing the local contrast essential for image interpretation. This paper describes the recursive filter implementation of the local area contrast enhancement scheme using charge-coupled devices and the resultant real-time hardware capable of processing standard 525 and 875 line TV-compatible video (from vidicons, videotape recorders, etc.). Several examples from video imagery are included to demonstrate the filter's effectiveness.

Peli, Tamar, and Lim, Jae S., 1982, Adaptive filtering for image enhancement: Optical Engineering, January-February 1982, v. 21, p. 108-112.

An image enhancement algorithm that modifies the local luminance mean of an image and controls the local contrast as a function of the local-luminance mean of the image is discussed. The algorithm first separates an image into its low (low-pass filtered form) and high (high-pass filtered form) components. The low component then controls the amplitude of the high component to increase the local contrast. The local luminance mean of the image is modified by a point non-linearity and is combined with the processed high component. The performance of this algorithm when applied to enhance typical undegraded images, images with large shaded areas, and also images degraded by cloud cover, is illustrated by examples.

Pizer, Stephen M., and others, 1987, Adaptive histogram equalization and its variations: Computer Vision, Graphics, and Image Processing, v. 39, 1987, p. 355-368.

Adaptive histogram equalization (AHE) is a contrast enhancement method designed to be broadly applicable and having demonstrated effectiveness. However, slow speed and the overenhancement of noise produced in relatively homogeneous regions are two problems. Algorithms designed to overcome these and other concerns are reported. These algorithms include interpolated AHE, to speed up the method on general-purpose computers; a version of interpolated AHE designed to run in a few seconds on feedback processors; a version of full AHE designed to run in under 1-second on custom VLSI hardware; weighted AHE, designed to improve the quality of the result by emphasizing pixels' contribution to the histogram in relation to their nearness to the resultant pixel; and clipped AHE, designed to overcome the problem of overenhancement of noise contrast. The authors conclude that clipped AHE should become a method of choice in medical imaging and probably also in other areas of digital imaging, and that clipped AHE can be made adequately fast to be routinely applied in the normal display sequence.

Schreiber, William F., 1978, Image processing for quality improvement: IEEE, Proceedings, December 1978, v. 66, no. 12, p. 1640-1651.

In order to encourage the development of computer-based methods that produce better quality pictures, the long and successful history of image processing in photography and graphic arts is called to the attention of the computer fraternity. Studies of contrast sensitivity and of the relationships among illumination, object reflectance, and image luminance are presented. Homomorphic filtering is analyzed in this light. Adaptive filtering methods that exploit perceptual phenomena, as well as the physical properties of imaging systems, are given. These methods attempt to permit the attainment of a very high degree of sharpening equally visible throughout the tone scale, as well as in image areas of quite different character, without the concomitant appearance of quality-destroying artifacts such as haloes or overshoots. Results are compared with linear and homomorphic nonadaptive sharpening.

Winkler, G., and Vattrodt, K., 1978, Measures of conspicuousness: Computer Graphics and Image Processing, v. 8, p. 355-368.

Using combinatorial analysis and local filtering, measures for optical conspicuousness are developed. They take into consideration contrast and contour properties of a picture, and may be useful for detecting, recognizing, and tracking interesting objects in images where conventional pattern recognition and correlation techniques fail because of lacking information. These measures permit one to associate values with any section of a picture, assigning larger values to picture sections that are more conspicuous. The mathematical expressions obtained for the measures are in their analytic form very similar to statistical entropy. An account is given of the properties of the measures and of primary applications to real images.

NOISE SUPPRESSION OR SMOOTHING

Anderson, G. Leigh, and Netravali, Arun N., 1976, Image restoration based on a subjective criterion: IEEE Transactions on Systems, Man, and Cybernetics, v. SMC-6, no. 12, December 1976, p. 845-853.

The problem of removing random noise from gray-tone images without significantly sacrificing the subjective resolution is considered. Based on a subjective visibility function, which gives the relationship between the visibility of a unit noise and a measure of local spatial detail (spatial masking), two procedures are developed to adapt continuously the finite impulse response of a two-dimensional, noncausal, linear digital filter. At sharp transitions in the image intensity, the filter operator is strongly peaked to preserve the resolution, whereas in flat areas, it is flat to effectively average out the random noise. The first procedure (S-filter) is computationally more efficient, but does not perform as well as the second method (SD-filter), which requires solution of a new optimization problem at every picture element. Results of several simulations are presented to demonstrate the feasibility of our approach. Extensions are pointed out to incorporate different adaptation procedures and psychovisual criteria other than the type of spatial masking used here.

Arensault, Henri H., and Levesque, Martin, 1984, Combined homomorphic and local-statistics processing for restoration of images degraded by signal-dependent noise: Applied Optics, v. 23, no. 6, March 15, 1984, p. 845-850.

The generalized homomorphic transformation to make signal-dependent noise independent of the signal is combined with a local-statistics image restoration technique to process images degraded by signal-dependent noise. Experimental results are given for images degraded by film-grain and by multiplicative noise.

Azimi-Sadjadi, Mahmood R., 1987, Speckled image restoration by adaptive block Kalman filtering: Proceedings, IGARSS '87 Symposium, Ann Arbor, Michigan, May 18-21, 1987, p. 1449-1455.

The speckle effect is commonly observed in images generated with highly coherent light as a multiple of tiny spots (or speckles) of varying intensity superimposed on the original image. In airborne synthetic aperture radar (SAR) systems the effect of this degradation reduces the accuracy of detecting a target. Thus the elimination of this noise is an important task in SAR imaging systems. A two-dimensional recursive processing scheme using adaptive block Kalman filtering is developed. New Kalman filtering equations are derived that incorporate not only the effect of multiplicative noise (speckle) but also the additive thermal noise and blur. Local stationarity within one block is assumed, whereas the image can be assumed to be globally nonstationary. A recursive identification process is also proposed which can be used on-line to estimate the filter parameters based upon each new block of data received, in contrast to more conventional adaptive filters that adjust the filter parameters with each received data point. The effectiveness of the proposed adaptive block Kalman filtering method has been examined on SEASAT SAR images.

Bednar, J. Bee, and Watt, Terry L., 1984, Alpha-trimmed means and their relationship to median filters: IEEE Transactions on Acoustics, Speech, and Signal Processing, v. ASSP-32, no. 1, p. 145-152.

Suppose that X is a finite set of N numbers. The alpha-trimmed mean of X is obtained by sorting X into ascending order, removing (trimming) a fixed-fraction alpha (0<=alpha<=0.5) from the high and low ends of the sorted set, and computing the average of the remaining values. When applied to a sliding window, the alpha-trimmed mean of a set is the median of the set and the filtering operation is called median filtering. Repeated application of a median filter to the output of a previous median filter of the same length eventually produces a signal that is invariant to median filtering. This final signal is called the root signal. This paper explains the relationship between alpha-trimmed means and median filters, derives a simple, straightforward, and fast algorithm for employing a median filter, and provides a new explanation of the convergence of repeated median filtering to the root signal. The latter result incorporates an approach that permits generalization of the associated concepts to a larger class of "index map" filters.

Biemond, Jan, and Gerbrands, Jan J., 1979, An edge-preserving recursive noise smoothing algorithms for image data: IEEE Transaction on Systems, Man, and Cybernetics, v. SMC-9, no. 10, October 1979, p. 622-627.

Recursive Kalman filters are often used for noise reduction in image data. These linear filters are based on the second-order statistics of image and noise. The noise is effectively reduced by the filtering operation, but the edges in the image are blurred and image contrast is reduced as well. These effects decrease the subjective quality of the image. A simple and computationally fast scan-ordered one-dimensional Kalman filter is derived, which is then provided with additional structural information about the edges in the noisy image. This filter behaves like the original noise-smoothing Kalman filter if no edges are present but has a greatly improved step response. In this way the edge-blurring phenomenon is effectively reduced. Results of several experiments are presented to demonstrate the feasibility of the approach.

Bovik, Alan C., Huang, Thomas S., and Munson, David C., Jr., 1983, A generalization of median filtering using linear combinations of order statistics: IEEE Transactions on Acoustics, Speech, and Signal Processing, v. ASSP-31, no. 6, p. 1342-1350.

A class of nonlinear filters whose output is given by a linear combination of the order statistics of the input sequence is discussed. Assuming a constant signal in white noise, the coefficients in the linear combination are chosen to minimize the output mean squared error for several noise distributions. It is shown that the optimal order statistic filter (OSF) tends toward the median filter as the noise becomes more impulsive. The optimal OSF is applied to an actual noisy image and is shown to perform well, combining properties of both the averaging and median filters. A more general design scheme for applications involving nonconstant signals is also given.

Chan, Philip, and Lim, Jae S., 1983, One-dimensional processing for adaptive image restoration: IEEE International Conference on Acoustics, Speech, and Signal Processing, San Diego, California, March 1983, Proceedings, p. 3731-3734.

A one-dimensional approach to the problem of image restoration is presented. The approach involves a cascade of four one-dimensional adaptive filters oriented in the four major correlation directions of the image, with each filter treating the image as a one-dimensional signal. The objective of our one-dimensional approach is to improve the performance of the more general two-dimensional approach. This differs considerably from previous one-dimensional approaches; the objectives of which have been typically to approximate a more general two-dimensional approach for computational reasons and not to improve its performance. To illustrate this point, this approach is applied to an existing two-dimensional image restoration algorithm. Experiments with images at low signal-to-noise ratios show that the one-dimensional approach performs better than the two-dimensional approach for the specific image restoration algorithm. The one-dimensional approach preserves edges while removing noise in all regions of the image including the edge regions.

Chaudhuri, Bidyut B., 1983, A note on fast algorithms for spatial domain techniques in image processing: IEEE Transactions on Systems, Man, and Cybernetics, v. SMC-13, no. 6, p. 1166-1169.

The redundancy in computation for median filtering, mean filtering, and point and line detection in two-dimensional images is considered. Fast algorithms are described for median evaluation with 3x3 and 5x5 window sizes. The algorithms are compared with existing ones, and the test result on a picture is given. Extension of the algorithms for mean filtering, and point and line detection is also described.

Chen, C., 1979, Adaptive image filtering: Proceedings, IEEE Computer Society Conference on Pattern Recognition and Image Processing, Chicago, Illinois, August 6-8, 1979, p. 32-37.

The adaptive image filtering considered in this paper includes a Kalman filter for noisy image enhancement and a generalized likelihood ratio technique to detect and estimate the jumps corresponding to object boundaries. The filter is adjusted when the jump is detected. When the transition matrix of the filter is unknown, it is determined by a method of simultaneous on-line estimation of parameters and states. Both the mathematical analysis and computer results are presented in detail. The procedures involved are highly effective and flexible, and computationally efficient.

Chin, Roland T., and Yeh, Chia-Lung, 1983, Quantitative evaluation of some edge-preserving, noise-smoothing techniques: Computer Vision, Graphics, and Image Processing, v. 23, p. 67-91.

A quantitative evaluation of several edge-preserving, noise-smoothing techniques is presented. All of the techniques evaluated are devised to preserve edge sharpness, while achieving some degree of noise cleaning. They are based on local operations on neighboring points and all of them can be iterated. They are unweighted neighbor averaging (AVE), K-nearest neighbor averaging (KAVE), the edge and line weights method (EDLN), gradient inverse weighted smoothing (GRADIN), maximum homogeneity smoothing (MAXH), slope facet model smoothing (FACET), and median filtering (MEDIAN). The evaluation procedure involves two steps. First, the image is partitioned into regions based on the amount of spatial activity in a neighborhood of a pixel, where spatial activity is defined as local gradient. In the second part of the procedure, an objective measure, the mean-square error, for each region of the partitioned image is obtained to evaluate the performance of the smoothing scheme at the corresponding level of spatial activity content. This evaluation procedure provides a convenient way to compare both the edge-preserving and noise-smoothing abilities of different schemes. The smoothing schemes were tested on a specially generated image with varying degrees of added noise and different edge slopes. The results of the comparison are presented.

Fitch, J. Patrick, Coyle, Edward J., and Gallagher, Neal C., Jr., 1984, Median filtering by threshold decomposition: IEEE Transactions on Acoustics, Speech, and Signal Processing, v. ASSP-32, no. 6, p. 1183-1188.

Median filters are a special class of ranked order filters used for smoothing signals. Repeated application of the filter on a quantized signal of finite length ultimately results in a sequence termed a root signal, which is invariant to further passes of the median filter. In this paper, it is shown that median filtering an arbitrary level signal to its root is equivalent to decomposing the signal into binary signals, filtering each binary signal to a root with a binary medial filter, and then reversing the decomposition. This equivalence allows problems in the analysis and implementation of median filters for arbitrary-level signals to be reduced to the equivalent problems for binary signals. Since the effects of median filters on binary signals are well understood, this technique is a powerful new tool.

Heckbert, Paul S., 1986, Filtering by repeated integration: Computer Graphics, v. 20, no. 4, p. 315-321.

Many applications of digital filtering require a space variant filter--one whose shape or size varies with position. The usual algorithm for such filters, direct convolution, is very costly for wide kernels. Image prefiltering provides an efficient alternative. One prefiltering technique, repeated integration, which is a generalization of Crow's summed-area table, is explored.

Convolution of a signal with any piecewise polynomial kernel of degree n-1 can be computed by integrating the signal n times and point sampling it several times for each output sample. The use of second- or higher-order integration permits relatively high-quality filtering. The advantage over direct convolution is that the cost of repeated integration filtering does not increase with filter width. Generalization to two-dimensional image filtering is straightforward. Implementations of the simple technique are presented in both preprocessing and stream processing styles.

Heygster, George, 1982, Rank filters in digital image processing: Computer Graphics and Image Processing, v. 19, p. 148-164.

Rank filters operating on images assign the Kth value of the gray levels from the window consisting of M pixels arranged according to their value to the center point of the window. The special cases K=1, K=M (MIN and MAX filter) and K=(M+1)/2 (medium filter), which have already been applied in image processing, are investigated in systematic connection with all rank filters. Some of their properties can be formulated analytically. They commute with monotonic transforms of the gray scale. In the one-dimensional case (also valid for line-like structures in images), the output functions of monotonic input functions can be calculated directly. The alternating application of MIN and MAX filters leads, if repeated more than once, to the same result as a single application. The application of the rank filters to a set of test images shows that there is no simple way to describe their action on the spectrum by means of a transfer or autocorrelation function. In particular, the smoothing of the median filter cannot be described in terms of a low-pass filter, but rather by the reduction of the mean local variance. As shown on real and statistical model images, rank filters smooth less than linear filters, but preserve edges.

Hodson, E. K., Thayer, D. R., and Franklin, C., 1981, Adaptive Gaussian filtering and local frequency estimates using local curvature analysis: IEEE Transactions on Acoustics, Speech, and Signal Processing, v. ASSP-29, no. 4, p. 854-859.

An adaptive filtering technique for smoothing noisy sampled data is presented. Due to the adaptive nature of the process, distortion of the information content is significantly reduced. Each point of the smoothed output is the result of a central convolution of the noisy data with a Gaussian weight. Gaussian weights of different widths are used to produce each point of the smoothed output. The width of each Gaussian weight is selected, following local curvature estimates of the data, so that the smoothed points contain a nearly constant and acceptable error resulting from the smoothing process. Since each Gaussian weight has its half-power frequency equivalent, it is possible to infer the system of narrowest bandwidth that can be tolerated in transmitting the signal. The rationale used to determine the convolving Gaussians is developed along with brief discussions of applications.

Jian-hus, Xu, 1980, An adaptive filtering approach of digital image enhancement: Proceedings, 5th International Conference on Pattern Recognition, v. 2, December 1-4, 1980, p. 930-032.

A new recursive algorithm for digital image enhancement is presented. Making use of the innovation sequence, different texture and structure of the image were detected, and the Kalman estimation of the image gray levels of the different texture and structure was corrected directly. The simulation experiments on the computer proved that this algorithm was effective.

Kasturi, Rangachar, Walkup, John F., and Krile, Thomas F., 1985, Adaptive point estimation in signal-dependent noise: IEEE Transactions on Systems, Man, and Cybernetics, v. SMC-15, no. 3, p. 352-359.

Images corrupted by signal-dependent film grain noise are restored using spatially adaptive point estimators. Optimal Bayesian estimators are obtained assuming a spatially nonstationary model for the image signal. Computationally simple, suboptimal estimators are also described. The performance of various estimators are compared using computer simulations and several measures for image quality.

Kitchen, Leslie, Pietkikainen, Matti, Rosenfeld, Azriel, and Wang, Cheng-Ye, 1983, Multispectral image smoothing guided by global distribution of pixel values: IEEE Transactions on Systems, Man, and Cybernetics, v. SMC-13, no. 4, p. 626-631.

Multispectral images can be effectively smoothed by using the global distribution of pixel values to guide a local, selective averaging process. After several iterations of this process, a typical image is virtually segmented into regions of constant value while significant edges in the image are preserved.

Lee, Jong-Sen, 1978, Digital image processing by use of local statistics, Proceedings of the IEEE Computer Society Conference on Pattern Recognition and Image Processing, Chicago, Illinois, May 31 - June 2, 1978, p. 55-61.

Computational techniques involving contrast enhancement and noise filtering on two-dimensional image arrays are developed based on their local mean and variance. These algorithms are non-recursive and do not require the use of any kind of transform. They share the same characteristics in that each pixel is processed independently. Consequently, this approach has an obvious advantage when used in real time digital image processing applications and where parallel processors can be used. For both the additive and multiplicative noise, the a priori mean and variance of each pixel is derived from its local mean and variance. Then, the minimum mean square error estimator in its simplest form is applied to obtain the noise filtering algorithms. For multiplicative noise a statistical optimal linear approximation is made. Experimental results show that such an assumption yields a very effective filtering algorithm. Examples on images containing 256 x 256 pixels are given. Results show that in most cases the techniques developed in this paper are readily adaptable to real-time image processing.

Lee, Jong-Sen, 1980, Digital image enhancement and noise filtering by use of local statistics: IEEE Transactions on Pattern Analysis and Machine Intelligence, v. PAMI-2, no. 2, p. 165-168.

Computational techniques involving contrast enhancement and noise filtering on two-dimensional image arrays are developed based on their local mean and variance. These algorithms are nonrecursive and do not require the use of any kind of transform. They share the same characteristics in that each pixel is processed independently. Consequently, this approach has an obvious advantage when used in real-time digital image processing applications, and where a parallel processor can be used. For both the additive and multiplicative cases, the a priori mean and variance of each pixel is derived from its local mean and variance. Then, the minimum mean-square error estimator in its simplest form is applied to obtain the noise-filtering algorithms. For multiplicative noise, a statistical optimal linear approximation is made. Experimental results show that such an assumption yields a very effective filtering algorithm. Examples on images containing 256 x 256 pixels are given. Results show that in most cases the techniques developed in this paper are readily adaptable to real-time image processing.

Lee, Jong-Sen, 1981, Refined filtering of image noise using local statistic: Computer Graphics and Image Processing, v. 15, p. 380-389.

An effective algorithm for digital image noise filtering is presented. Most noise-filtering techniques such as Kalman filter and transform domain methods require extensive image modeling and produce filtered images with considerable contrast loss. The algorithm proposed is an extension of Lee's local statistics method modified to utilize local gradient information. It does not require image modeling, and it will not smear edges and subtle details. For both the additive and multiplicative noise cases, the local mean and variance are computed from a reduced set of pixels depending on the orientation of the edge. Consequently, noise along the edge is removed, and the sharpness of the edge is enhanced. For practical applications when the noise variance is spatially varying and unknown, an adaptive filtering algorithm is developed. Experiments show its good potential for processing real-life images. Examples on images containing 256 x 256 pixels are given to substantiate the theoretical development.

Lee, Jong-Sen, 1983, Digital image smoothing and the sigma filter: Computer Vision, Graphics, and Image Processing, v. 24, p. 255-269.

A conceptually simple, but effective noise-smoothing algorithm is described. This filter is motivated by the sigma probability of the Gaussian distribution, and it smooths the image noise by averaging only those neighborhood pixels that have the intensities within a fixed sigma range of the center pixel. Consequently, image edges are preserved, and subtle details and thin lines, such as roads, are retained. The characteristics of this smoothing algorithm are analyzed and compared with several other known filtering algorithms by their ability to retain subtle details, preserving edge shapes, sharpening ramp edges, etc. The comparison also indicated that the sigma filter is the most computationally efficient filter among those evaluated. The filter can be easily extended into several forms, which can be used in contrast enhancement, image segmentation, and smoothing signal-dependent noisy images. Several test images 128 x 128 and 256 x 256 pixels in size are used to substantiate its characteristics. The algorithm can be easily extended to three-dimensional image smoothing.

Lee, Jong-Sen, 1986, Speckle suppression and analysis for synthetic aperture radar: Optical Engineering, v. 25, no. 5, p. 636-643.

Speckle appearing in synthetic-aperture radar (SAR) images is generated by coherent interference of radar echoes from target scatters. Basically, speckle noise has the nature of a multiplicative noise. Procedures for defining and verifying a statistical noise model are developed, and two multiplicative noise-smoothing algorithms are presented. These two algorithms are computationally efficient and have the potential of achieving real-time or near-real-time processing. Several SEASAT SAR and SIR-B (Shuttle Image Radar) images are used for illustration.

Lee, Jong-Sen, 1987, Statistical modelling and suppression of speckle in synthetic aperture radar images: Proceedings, IGARSS '87 Symposium, Ann Arbor, Michigan, May 18-21, 1987, p. 1331-1339.

Speckel appearing in synthetic-aperture radar (SAR) images is generated by coherent interference of radar echoes from target scatterers. The author's research in the area of statistical modelling and suppression of speckels in SAR images are reviewed. Comments are also made to recent papers of other researchers. Speckles are modelled with multiplicative noise models and verified with SEASAT SAR and SIR-B data. Using the developed statistical noise model, two multiplicative noise-smoothing algorithms are presented. These two algorithms are computationally efficient and have the potential of achieving real-time or near real-time processing. Several SAR images are used for illustration.

Lim, Jae L., and Nawab, Hamid, 1981, Techniques for speckle noise removal: Optical Engineering, v. 20, no. 3, p. 472-480.

Several techniques to reduce speckle noise (more generally signal-independent multiplicative noise) in images are studied. The techniques include gray-scale modification, frame averaging, low-pass filtering in the intensity and density domains, and application of the short-space spectral subtraction image restoration technique in the density domain. Some discussions on the theoretical basis of the techniques studied are given and their performances are illustrated by way of examples.

Maeda, Junji, and Murata, Kazumi, 1986, Local-statistics algorithm for smoothing noisy images with low signal-to-noise ratio: Optics Communications, v. 59., no. 1, pp. 11-16.

A digital method for smoothing noisy images is described. The smoothing procedure is a local-statistics algorithm composed of median filtering and mean filtering. This method is suitable for noisy images that have low signal-to-noise ratio and strong edges. Some results of computer simulations that demonstrate the effectiveness of the proposed algorithm are presented.

Nago, Makoto, and Matsuyama, Takashi, 1979, Edge preserving smoothing: Computer Graphics and Image Processing, v. 9, p. 394-407.

A new smoothing algorithm is proposed that looks for the most homogeneous neighborhood around each point in a picture, and then gives each point the average gray level of the selected neighborhood. It removes noise in a flat region without blurring sharp edges, or destroying the details of the boundary of a region. This smoothing also has the ability to sharpen blurred edges.

Narayanan, K. A., and Rosenfield, Azriel, 1981, Image smoothing by local use of global information: IEEE Transaction on Systems, Man, and Cybernetics, v. SMC-11, no. 12, December 1981, p. 826-831.

There exists a class of iterative local image-smoothing techniques in which a neighborhood of each pixel is examined, and the pixel is replaced by an average of a selected set of its neighbors chosen so as to make it likely that they belong to the same region as the pixel, that is, on the basis of their resemblance to it. Thus these methods choose the neighbors to be averaged on the basis of information local to the neighborhood. A more powerful approach in which the neighbors are chosen based on global information derived from the histogram of the image is described. This approach attempts to choose neighbors that belong to the same histogram peak as the given pixel, but are more typical of that peak. Smoothing using this approach gives dramatically better results than smoothing based only on local information in cases where the noise in a region belongs to the same histogram peak as the region's mean.

Narendra, Patrenahalli M., 1981, A separable median filter for image noise smoothing: IEEE Transactions on Pattern Analysis and Machine Intelligence, v. PAMI-3, no. 1, p. 20-29.

Some properties of the separable filter resulting from successive applications of a one-dimensional median filter on the rows and columns of an image are investigated. Although the output of this separable filter is not identical to the corresponding, nonseparable, two-dimensional median filter with a square window, its performance in image noise smoothing is close. In particular, its effectiveness in smoothing noise and its behavior with edges are characterized and compared with those of the two-dimensional median filter. It is shown that the separable filter has a much simpler implementation in real-time hardware (at video rates, for examples).

Nieminen, Ari, and Neuvo, Yrjo, 1987, A new class of detail-preserving filters for image processing: IEEE Transactions on Pattern Analysis and Machine Intelligence, v. PAMI-9, no. 1, p. 74-90.

A new class of median type filters for image processing is proposed. In the filters, linear finite impulse response (FIR) substructures are used in conjunction with the median operation. The root signals and noise attenuation properties of the FIR-median hybrid filters are analyzed and compared to representative edge-preserving filtering operations. The concept of multilevel median operation is introduced to improve the detail-preserving property of conventional median and the FIR-median hybrid filters. In the multilevel filters, there exists a tradeoff between noise attenuation and detail preservation. The analysis and examples indicate that FIR-median hybrid filters preserve details better and are computationally much more efficient than the conventional median and the K-nearest-neighbor-averaging filters.

Nodes, Thomas A., and Gallagher, Neal C., Jr., 1983, Two-dimensional root structures and convergence properties of the separable median filter: IEEE Transactions on Acoustics, Speech, and Signal Processing, v. ASSP-31, no. 6, p. 1350-1365.

The root (signals invariant to filtering) structures of the two-dimensional separable median filter are derived and presented. In addition, it is proved that with rare exception, after repetitive passes of the separable median filter, any two-dimensional signals will be reduced to a signal containing only root structures.

Ranade, Sanjay, and Shneier, Michael, 1981, Using quadtrees to smooth images: IEEE Transaction on Systems, Man, and Cybernetics, v. SMC-11, no. 5, May 1981, p. 373-376.

Three methods for smoothing images are presented. All three use variable numbers of picture points over which the smoothing functions are defined. The first method examines the histogram of a neighborhood of each point. The subset of gray values most similar to that of the point is used in calculating the smoothing functions. The other two methods use quadtree approximation to smooth the image. One of these uses the sizes of the leaves in the quadtree to determine neighborhood sizes over which to apply a smoothing function, while the other refines the gross smoothing defined by the quadtree. All the methods perform fairly well, but the quadtree methods are particularly attractive because of the information about region sizes and homogeneity provided by the quadtree structure.

Wang, David C., Vagnucci, Anthony H., and Li, C. C., 1981, Gradient inverse weighted smoothing scheme and the evaluation of its performance: Computer Graphics and Image Processing, v. 15, p. 167-181.

An image smoothing scheme for improvement of the quality of noisy pictures is presented. It is an iterative scheme employing a 3 by 3 mask in which the weighting coefficients are the normalized gradient inverse between the center pixel and its neighbors. The smoothing operation tends to clean out noise inside a region without blurring its boundary. In order to evaluate the performance of the proposed scheme, an f statistic is adopted that is based on the analysis of variance. Simulation studies show that this method reduces the gray level scattering within a region, and keeps its mean relatively unchanged. Applications to several images are illustrated.

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EDGE ENHANCEMENTS

Chavez, Patrick, Jr., and Bauer, Brian, 1982, An automatic optimum kernel-size selection technique for edge enhancement: Remote Sensing of Environment, v. 12, p. 23-38.

Edge enhancement is a technique that can be considered, to a first order, a correction from the modulation transfer function of an imaging system. Digital imaging systems sample a continuous function at discrete intervals so that high-frequency information cannot be recorded at the same precision as lower frequency data. Because of this, detail much finer than the sampling interval in digital images can be lost. Spatial filtering techniques can be used to enhance the fine detail information that does exist in the digital image, but the filter size is dependent on the type of area being processed. A technique has been developed by the authors that uses the horizontal first difference to automatically select the optimum kernel-size that should be used to enhance the edges that are contained in the image.

Chiralo, Robert P., and Berdan, Leonard L., 1978, Adaptive digital enhancement of latent fingerprints: Journal of Photo-Optical Instrumentation Engineers (SPIE), Applications of Digital Image Processing, v. 149, p. 118-125.

An adaptive technique for providing effective enhancement of latent fingerprints is presented. The adaptive technique is described and examples are shown, including an enhanced print prepared for a trial exhibit. Image preprocessing considerations are discussed for obtaining optimal enhancement. Results of the adaptive technique are compared to those obtained with the conventional Fourier filtering enhancement.

Conradsen, Knut, and Nilsson, Gert, 1987, Data dependent filters for edge enhancement of Landsat images: Computer Vision, Graphics, and Image Processing, v. 38, p. 101-121.

Some two-dimensional filters that are very efficient in edge enhancement of Landsat imagery are presented. The filtered images are obtained as differences between the original images and some minimum mean-square-error predictions based on suitable chosen "predictor sets." The filters compare favorably to other high-pass filters, such as the Laplacian and Gaussian filters.

Gray, Robert T., and Hunt, Bobby R., 1979, Median masking technique for the enhancement of digital images: Journal of Photo-Optical Instrumentation Engineers (SPIE), Applications of Digital Image Processing, v. 207, 1979, p. 142-145.

A nonlinear masking technique has been developed that characterizes digital images by local measures of the median and the median absolute deviation (MAD). Space-variant enhancement is elicited by modifying the local MAD as calculated over a moving window in the original image. The method is found to be effective in edge enhancement and noise cleaning operations.

Hall, Joseph E., 1979, Real-time image enhancement using 3 by 3 pixel neighborhood operator functions: Journal of Photo-Optical Instrumentation Engineers (SPIE), Applications of Digital Image Processing, v. 207, p. 135-141.

A new type of silicon-charged coupled device imager, which provides nine simultaneous video outputs representing a 3- by 3-pixel block that scans the imaging array, has been used to emphasize edges and fine detail in various images. The device can also compensate for non-uniform scene illumination. Experimental results indicate that the device can be used to combine real-time analog image processing with subsequent digital processing to form a powerful image acquisition and processing system.

Lunscher, Wolfram H. H. J., and Beddoes, Michael P., 1986, Optimal edge detector design II: Coefficient quantization: IEEE Transactions on Pattern Analysis and Machine Intelligence, v. PAMI-8, no. 2, p. 178-187.

Digital implementation of any continuous filter requires sampling and coefficient quantization. The sampled filter was examined, but a method is proposed here for selection of a minimum coefficient work size for direct-form implementation to satisfy in-band rejection bounds.

Machuca, Raul, and Gilbert, Alton L., 1981, Finding edges in noisy scenes: IEEE Transactions on Pattern Analysis and Machine Intelligence, v. PAMI-3, no. 1, p. 103-111.

This paper examines an applications-motivated approach for solving the problem of edge detection in a noisy environment using novel techniques and presents a method developed by the authors that performs well on a large class of targets. Receiver operating-characteristics curves are used to compare this method with other well-known edge detection operators, with favorable results. A theoretical argument is presented that favors least-moment mean-squared-error filtering over median filtering in extremely noisy scenes. Simulated results of the research are presented.

Nasburg, R. E., 1981, Noise effects for edge operators: Journal of Photo-Optical Instrumentation Engineers (SPIE), v. 292, p. 277-287.

Techniques and analyses for improving the signal-to-noise performance of edge detectors are presented. A general edge-detection method is developed as a result of the noise analysis, and a wide class of edge detectors is shown to be insensitive to edge orientation. For this class, an optimal design with respect to noise statistics is found, and a comparison made between many common edge operators. Edge and noise models characteristic of typical images are presented and used in the analysis of these edge detectors.

Schau, H. C., 1980, Statistical filter for image feature extraction: Applied Optics, v. 19, no. 13, p. 2182--2190.

The use of conventional edge extractors, such as Sobel and Laplacian filters, results in images that in many cases have a high degree of clutter due to the natural spatial texture of the scene background. To overcome this difficulty, a statistical filter has been developed that enhances local gray-level activity around objects, while reducing contributions due to background. The statistical filter is employed in a neighborhood modification process where the central pixel is replaced with the third central moment computed from the surrounding neighborhood. Choice of the third central moment is due in part to the fact that it is a function of the scene within the neighborhood rather than the power spectral density (Wiener spectrum) of the neighborhood. Application of the filter requires no prior knowledge, and pixels within the filter window may be chosen in random order due to the statistical nature of the operation. Results of the filter applied to IR images show performance comparable with, and in some cases superior to, the Sobel and Laplacian filters most commonly used for feature and edge extraction.

Schenker, P. S., and Cooper, D. B., 1980, Fast adaptive algorithms for low-level scene analysis: the parallel hierarchical ripple filter: Journal of Photo-Optical Instrumentation Engineers (SPIE), Smart Sensors II, v. 252, p. 113.-123.

The development of a new class of parallel computation algorithm for low-level scene analysis is reported. The algorithm is a high-resolution, high-speed estimator for boundary extraction of simple objects imaged under noisy conditions. The algorithm structure and underlying physical models are explained and pictorial examples of application to synthetic test imagery are given. A generalization of the algorithm employs a hierarchical variable resolution search to gain major improvements in algorithm convergence speed and robustness. The importance of making the algorithm adaptive to local image statistics is discussed and show that the algorithm parallel-window topology is consonant with this goal. Further experimental results that depict the generalized algorithm applied to real data bases are presented. These results demonstrate that even simple adaptation models can substantially improve algorithm convergence accuracy.

Schwartz, A. A., and Soha, J. M., 1977, Variable threshold zonal filter: Applied Optics, v. 16, no. 7, p. 1779-1781.

Variable threshold zonal filtering, in the context discussed, is an active, nonlinear image enhancement process. The filtering technique is designed to avoid ringing artifacts, which filtering can introduce near sharp brightness transitions in the original scene. It is a variation of the simple subtractive box filter.

Shaw, Gilbert B., 1979, Local and regional edge detectors: Some comparisons: Computer Graphics and Image Processing, v. 9, p. 135-149.

Consideration of the usefulness of edge information in segmentation or other intermediate-level picture operations has motivated a comparison of the accuracy and reliability of a number of directional edge operators. The Hueckel operator is singled out for comment, and an error in its derivation is noted. Another regional edge operator is introduced as being better suited to application on discrete pictures.

Townsend, J. Keith, Shanmugan, Sam, and Frost, Victor S., 1985, Optimal frequency domain textural edge-detection filter: Applied Optics, v. 24, no. 14, p. 2067-2071.

An optimal frequency domain textural edge-detection filter is developed, and its performance is evaluated. For the given model and filter bandwidth, the filter maximizes the amount of output image energy placed within a specified resolution interval centered on the textural edge. Filter derivation is based on relating textural edge detection to tonal edge detection via the complex low-pass equivalent representation of narrow-band pass signals and systems. The filter is specified in terms of the prolate spheriodal wave functions translated in frequency. Performance is evaluated using the asymptotic approximation version of the filter. This evaluation demonstrates satisfactory filter performance for ideal and non-ideal textures. In addition, the filter can be adjusted to detect textural edges in noisy images at the expense of edge resolution.

Kasturi, Rangachar, Walkup, John F., Krile, Thomas F., 1983, Image restoration by transformation of signal-dependent noise to signal-independent noise: Applied Optics, v. 22, no. 22, p. 3537-3542.

A transformation to convert signal-dependent noise corrupting an image to additive Gaussian signal-independent noise is derived in this paper. Wiener filtering techniques using a Markovian covariance model for the image signal are applied to the transformed data followed by an inverse transformation to restore the degraded image. An ad hoc technique using contrast manipulation to adaptively convert signal-dependent noise to signal-independent noise is also described. The results of the computer simulations designed to evaluate the performance of these techniques are also presented.

Lahart, Martin J., 1979, Local image restoration by a least-squares method: Journal of Photo-Optical Instrumentation Engineers (SPIE), v. 69, no. 10, p. 1333-1339.

Restoration of individual image points by the method of least squares is investigated. Restorations computed point by point that appear the same as global restorations produced by Fourier techniques are discussed. Moreover, parameters that are related to noise, point-spread functions, or object texture can be varied easily from pixel to pixel, allowing a flexibility that is achieved only with computational difficulty in global restoration techniques. To restore individual pixels, only a few points in their neighborhood need to be considered, and the matrices that must be inverted are small enough for practical computation. The sizes of these matrices can be reduced especially if the blurring point-spread function has symmetries.

Lim, Jae S., 1980, Image restoration by short-space spectral subtraction: IEEE Transactions on Acoustics, Speech, and Signal Processing, v. ASSP-28, no. 2, p. 191-197.

A new image restoration system that is applicable to the problem of restoring an image degraded by blurring and additive noise is presented. The system is developed by attempting to estimate more accurately the frequency response of typical image restoration filters available in the literature. The resulting system combined with its short space implementation is computationally simple and appears to compare quite well in performance with other restoration techniques. Some examples are given to illustrate the performance of the new image restoration system.

Naderi, F., and Sawchuk, A. A., 1976, Nonlinear detection and estimation of images degraded by film-grain noise: Journal of Photo-Optical Instrumentation Engineers (SPIE), Image Processing, v. 74, 1976, p. 17-24.

Taking into account the chemical and optical degrading factors as well as the granularity noise results in a subjectively reasonable mathematical model for the formation and recording of photographic images. This model represents highly nonlinear observations, making the subsequent restoration difficult. When images are scanned with very small apertures on a microdensitometer, the noise is so severe that conventional estimators do not perform well. In these cases detection schemes suited to individual degraded pictures are much more effective. When the noise is not so severe, an adaptive minimum mean-square-error filter can be applied. This filter explicitly includes the nonlinear image formation effects and does not require the assumption of stationary image statistics.

Rajala, Sarah A., and De Figueiredo, Ruli J. P., 1981, Adaptive nonlinear image restoration by a modified Kalman filtering approach: IEEE Transactions on Acoustics, Speech, and Signal Processing, v. ASSP-29, no. 5, p. 1033-1042.

An adaptive nonlinear Kalman-type filter is presented for the restoration of two-dimensional images degraded by general image formation system degradations and additive white noise. A vector difference equation model is used to model the degradation process. The object-plane distribution function is partitioned into disjoint regions based on the amount of spatial activity in the image, and difference equation models are used to characterize this nonstationary object-plane distribution function. Features of the restoration filter include the ability to account for the response of the human visual system to additive noise in an image; a two-dimensional interpolation scheme to improve the estimates of the initial states in each region; and a nearest-neighbor algorithm to choose the previous state of vector for the state of pixel (i,j).

Strickland, Robin N., 1984, Digital processing of nonstationary images using local autocovariance statistics: Journal of Photo-Optical Instrumentation Engineers (SPIE), Applications of Digital Image Processing, v. 504, p. 282-293.

The problem of local/spatially-variant/adaptive image processing based on direct estimates of local autocovariance functions is addressed. In order to quantify the non-stationarity of images, and often to implement spatially-variant processing, estimates or measurements of the local image statistics are required, specifically the autocovariance function. The simplest way to achieve this is to divide the image into N- x N-pixel sub-blocks (for example, N=16), and calculate the usual biased or unbiased autocovariance function of each sub-block. In effect, each sub-block is treated as part of a wide-sense stationary field. It is well known, however, that reliable power spectral estimates require much larger amounts of data.

Nevertheless, it is possible to obtain useful maps of local autocovariance parameters by assuming simple parametric autocovariance models. Specifically, a popular first-order model, such as the non-separable exponential model, is employed. A procedure for estimating local autocovariance parameters is discussed. Resulting parameters are seen to correlate with observed signal activity. Techniques for spatially-variant image processing, coding, restoration, and enhancement based on local statistics are outlined. Processed examples are given.

Trussel, H. J., and Hunt, B. R., 1978, Sectioned methods for image restoration: IEEE Transactions on Acoustics, Speech, and Signal Processing, v. ASSP-26, p. 157-163.

Locally adaptive image processing methods are constructed by sectioning the image and applying a modified maximum a posteriori restoration algorithm. These local algorithms are shown to be effective in processing nonstationary images. The algorithms can work in both signal-independent and signal-dependent noise. The gains achieved by local and signal-dependent processing are analyzed.

Wallis, Robert, 1977, An approach to the space variant restoration and enhancement of images, in Wilde, Carroll O., and Barrett, Eamon, ed.: Western Periodicals Company, San Diego, California, Image Science Mathematics Symposium, Proceedings, pp. 107-111.

Many of the classical techniques in digital image processing fall into the category of linear space-invariant procedures. Although these methods provide the benefit of mathematical tractability and ease of analysis, they constitute a very restricted subset of approaches. This paper describes one possible avenue towards a more powerful family of nonlinear space-variant algorithms, which are based on the "tracking" of local image statistics. The statistics of the subsection of an image encompassed by a sliding perimeter or window are tracked in order to perform locally optimized enhancement or restoration. The statistics could be just two parameters, such as the local mean and variance within the window, or the entire histogram. This philosophy can be applied to the "destriping" of multispectral scanner imagery, or enhancement, with striking results.

Wells, Donald C., 1980, Nonlinear image restoration: What we have learned: Journal of Photo-Optical Instrumentation Engineers (SPIE), Applications of Digital Image Processing to Astronomy, v. 264, p. 148-156.

The first nonlinear image restoration algorithms were devised about 1970. Subsequent developments have produced rich and facinating literature, but because much of it is located in unfamiliar journals and publications, many newcomers to the astronomical field may be unaware of the work. Nonlinear image restoration techniques have pronounced performance advantages over linear restoration techniques in astronomical applications, and many of the published examples of nonlinear restorations of imagery have involved astronomical data. The new image detector systems appearing in optical astronomy, particularly CCD's, produce images of a quality that fully justifies the employment of sophisticated algorithms for the extraction of the maximum amount of information from the data. This review of the literature has been prepared to encourage new astronomical workers to enter into it.

Zhou, Y., and Rushforth, C. K., 1982, Least-squares reconstruction of spatially limited objects using smoothness and non-negativity constraints: Applied Optics, v. 21, no. 7, p. 1249-1252.

An approach to reconstructing an optical object that has been subjected to low-pass spatial frequency filtering is described. The object is assumed to be of limited and known spatial extent and is further known to be non-negative and reasonably smooth. The smoothness constraint is incorporated into a regularizing matrix in a novel way. This matrix defines a regularized version of the original imaging equation, which is then solved using least-squares estimation under a non-negativity constraint. Combining constraints in this way can lead to reconstruction of very high quality.

Ferrari, Leonard A., Sankar, P. V., and Sklansky, Jack, 1986, Efficient two-dimensional filters using B-spline functions: Computer Vision, Graphics, and Image Processing, v. 35, p. 152-169.

The use of B-spline functions in efficient, approximate implementations of spatially variant and spatially invariant image filters is discussed. The methods are extensions of techniques used in numerical integration. The concept of Duhamel integrals is extended to the spatially varying case and when combined with the B-spline approximation leads to efficient algorithms, which are more efficient than the direct computation or FFT approaches to two-dimensional filtering.

Green, William B., 1977, Computer image processing--the Viking experience: IEEE Transactions on Consummer Electronics, V. CE-23 no. 3, p. 281-299.

The primary Viking mission began in July 1977 and lasted through solar conjunction in November 1977. Both Lander spacecraft were landed safely on the surface, and a large number of black-and-white, color, and infrared images were returned from each landing site. For both landing sites, it was possible to construct black-and-white mosaics of the entire area around each spacecraft at two or three times of the Martian day. In addition, it was possible to obtain adequate stereo coverage to enable construction of three-dimensional topographic maps of the Martian surface surrounding each Lander spacecraft. The returned imagery was processed in JPL's Image Processing Laboratory (IPL) to support the science and mission operations objectives of the Viking mission. The IPL also processed a substantial number of images recorded by the vidicon camera systems on board the two Viking Orbiter spacecraft that circled the planet, recording important scientific data and serving as the main communications link between the Lander spacecraft and Earth during the primary mission. The remainder of this paper describes the basic techniques of digital image processing, using Viking imagery as illustrative examples.

McDonnell, M. J., 1981, Box-filtering techniques: Computer Graphics and Image Processing, v. 17, p. 65-70.

Box filtering involves replacing each pixel of an image with the average in a box. When it is extended in several simple ways, it becomes an efficient general-purpose tool for image processing. This paper reviews box-filtering techniques and also describes some useful extensions.

Nathan, Robert, 1970, Spatial frequency filtering: Academic Press, New York, New York, Picture Processing and Psychopictorics, p. 151-163.

Techniques for making pictorial information more accessible are discussed. The techniques are essentially digital, although most of the transformations involved may also be performed by analog means. A brief discussion of spatial frequencies is given, followed by noise removal, selective contrast stretching, and matched filtering techniques.

O'Gorman, Lawrence, and Sanderson, Arthur, 1987, A comparison of methods and computation for multi-resolution low- and band-pass transforms for image processing: Computer Vision, Graphics, and Image Processing, v. 37, p. 386-401.

The processing of images on multiple levels of resolution is often an effective and efficient tool in image analysis. For these reasons, it has met with increasing use in recent years. Past work of different authors is consolidated to introduce, review, and compare different general methods for obtaining both the multiple low-pass and multiple band-pass transformations. The methods include those using the FFT and frequency-domain filtering, and spatial-domain filtering using both separable and non-separable filter kernels. In addition, an original treatment of comparative computational costs is given for each of the methods described, as a function of image and filter sizes.

Rosenfeld, Azriel, 1985, Survey picture processing: 1984: Computer Vision, Graphics, and Image Processing, v. 30, p. 189-242.

A bibliography of over 1,250 references related to the computer processing of pictorial information, arranged by subject matter is presented. Coverage is restricted, for the most part, to a selected set of U.S. journals and proceedings of specialized meetings. The topics covered include digitization, approximation, and compression; transforms, filtering, enhancement, restoration, and reconstruction; hardware and software; pictorial pattern recognition; feature detection, segmentation, and image analysis; matching and time-varying imagery; shape and pattern; texture; formal models; and three-dimensional scene analysis. No attempt is made to evaluate or summarize the items cited; the purpose is simply to provide a convenient compendium of references.

Tom, Victor T., 1985, Adaptive filter techniques for digital image enhancement: Journal of Photo-Optical Instrumentation Engineers (SPIE), Digital Image Processing, v. 528, p. 29-42.

A survey of several adaptive techniques for image enhancement and filtering is presented within a common framework. With the proliferation of high-speed processors, such as array and image display processors, the increased computational power has shifted emphasis in image processing away from "global" to "local" techniques. These local techniques frequently use sliding windows that compute local properties of the image. The types of operations discussed encompass contrast, edge, or information enhancement; noise or artifact reduction; and feature extraction or removal. Algorithmic implementations include real-time contrast enhancement filters, zonal filters, short-space FFT filters, and a multi-dimensional adaptive least-squares technique. In this review paper, an adaptive framework, discussions on various enhancement approaches, and an extensive bibliography are presented.

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MISCELLANEOUS

Itten, K., and Fasler, F., 1979, Thematic adaptive spatial filtering of Landsat landuse classification results: Proceedings, 13th Symposium on Remote Sensing of Environment, Ann Arbor, Michigan, April 23-27, 1979, p. 1035-1042.

With simple low-cost thematic adaptive filtering in the space domain, systematic as well as non-systematic errors showing up in digital landuse classifications can be corrected. Concurrently, scale-dependent generalization can be performed. The method implemented in the University of Zurich "IBIS" image processing system is based on the use of individually formed classwise filters, consisting of two-dimensional specifically weighted arrays. The results of an application in northeast Switzerland are presented and discussed.

Strickland, Robin N., 1983, Transforming images into block stationary behavior: Applied Optics, v. 22, no. 10, May 15, 1983, p. 1462-1473.

The statistical behavior of images is inherently nonstationary. Unfortunately, most image processing algorithms assume stationary image models. Spatially adaptive algorithms have been developed which take into account local image statistics. Radiometric and geometric transforms are derived that generate nearly stationary (block stationary) images in the first and second moments. True stationarity is impossible to realize. The aim of these transformations is to enhance the performance of nonadaptive processing techniques, in particular data compression.

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