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| 20. ABSTRACT (Continue on reverse side if necessary and identify by block number)<br><br>The main goal of this program is the development of efficient methods for the two-dimensional (2-D), recursive filtering of images corrupted by noise. This goal is to be achieved by the use of our extension of Kalman recursive estimation techniques to two-dimensions, which permits order-of-magnitude savings in computer time and storage over previously developed techniques for optimal recursive estimation of noisy images. Such images could arise for example in a communications context by an image transmission system which is noise limited because of power constraints. |                                                                                               |                                             |  |

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Two Dimensional Recursive Estimation With  
Application to Real-Time Filtering of Images  
for period 7/1/77-7/31/78

The main goal of this program is the development of efficient methods for the two-dimensional (2-D), recursive filtering of images corrupted by noise. This goal is to be achieved by the use of our extension of Kalman recursive estimation techniques to two-dimensions, which permits order-of-magnitude savings in computer time and storage over previously developed techniques for optimal recursive estimation of noisy images. Such images could arise for example in a communications context by an image transmission system which is noise limited because of power constraints.

In the first year of this grant, the 2-D recursive estimation method has been improved by substantially increasing the efficiency of the existing algorithm both with regard to run time and random-access memory requirements. We have achieved a better understanding of the 2-D boundary condition problem. We have extended the recursive estimation algorithm to image restoration and have obtained experimental results to confirm the theory. Also we have experimented with 2-D linear predictive models as well as spectrally designed models. We find the linear predictive models, derived by least squares methods, to be well suited to 2-D Kalman filtering.

With regard to program efficiency, we have reduced the execution time by a factor of two and the memory page-minutes by a factor of four. Also we have decoupled covariance processing from picture processing, so that a picture may be filtered with a (2x2)th order model in 45 sec. CPU time.

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The time is on the IBM 360/67. For the new IBM 3033, the time is approximately 4 seconds.

The 2-D boundary condition problem has been studied from the point of view of causal (in the raster scanning sense) recursive estimation. This work has resulted in an extension of the 2-D Kalman filter to the reduced update filter in the realistic case of random boundary conditions. This essentially involves augmenting the 2-D state vector to include 'future' boundary values. These results are included in [5]. However the main topic of [5] is the extension of the reduced update filter to image restoration. These deconvolution type problems fit into the reduced update formulation if the distortion or blurring matrix is FIR and of small size. This assumption is appropriate for several deconvolution problems, including blurring caused by motion and finite aperture width.

We have compared various modeling procedures with regard to both subjective and mean square error when used with the 2-D reduced update filter. The three methods consisted of a spectral design using windows, a linear prediction design using the 2-D Fourier transform, and a recursive least squares design in the spatial domain. Comparison of the results showed a 20% MSE advantage to the recursive least squares. Subjectively the results slightly favored the recursive-least squares model. A paper on the spectral design method and reduced update filtering will appear this October [3].

A problem with the optimality of dynamical prediction when doing reduced updating has been noted. This necessitated a correction item [4] pointing out weak but not strong optimality of the reduced update filter. However experimental results are presented to indicate approximate strong optimality.

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The 2-D recursive theory allows spatially varying recursive data models that would permit better matching of the image statistics. We have begun to experimentally investigate this using two different approaches: first, a multi-mode recursive model which matches varying image statistics; and second, a 2-D adaptive recursive model which uses the concepts of the well developed theory of system identification. Papers on the later approach were presented this past summer [1] and [2]. In [2] an adaptive estimation algorithm combines least squares parameter identification with 2-D reduced update filtering. A comparison of infinite memory recursive least squares, block processing, and fixed memory identification procedures was conducted using a (1x1)th order 2-D Kalman filter structure. Factors of 2 reduction in mse, with respect to spatially constant processing, with improved subjective picture quality were noted using block processing on a (5x5) non-symmetric half-plane type data history consisting of 41 points which were used to estimate the 5 coefficients in the (1x1)th order Kalman model. Under study are methods to remove observation noise induced bias in the parameter estimates.

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2. A. Radpour, V. Ingle, H. Kaufman and J. Woods, "Adaptive Kalman Type Estimation Applied to Image Processing", Proc. Twenty-First Midwest Symposium on Circuits and Systems, Ames, IO , August 1978.
3. J. W. Woods, "Markov Image Modeling", IEEE Transactions on Automatic Control, to appear October 1978.
4. J. W. Woods, "Correction to 'Kalman Filtering in Two-Dimensions'", submitted to IEEE Transactions on Information Theory.
5. J. W. Woods and V. K. Ingle, "Kalman Filtering for Image Restoration", in preparation.