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Publication Date
1992

Peer reviewed

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Space Scale Analysis for Image Sampling and Interpolation

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Abstract

In image processing operations involving changes in the sampling grid, including increases or decreases in resolution, care must be taken to preserve image structure. Structure includes regions of high contrast, such as edges, streaks, or corners, all indicated by large gradients. In this paper, we consider the use of local spatial analysis for both sampling and interpolation. Anisotropic diffusion is considered as a directional smoothing technique that preserves structure. This is used in conjunction with a method of directional interpolation, which is also based on structure analysis.

1 Introduction

In a previous ICASSP paper [1], we reported on new methods for the directional interpolation of images, based on image analysis. We note that anisotropic smoothing has been proposed by several researchers in recent years. In this work, local properties of the image are used to determine the direction and extent of smoothing. Notably, in anisotropic diffusion, a function of the gradient of the image is used to determine the smoothing filter. Since the gradient is also an indicator of structure used in interpolation, we now consider the use of analysis for both sampling and interpolation. In this paper, we limit our work to a specific directional smoothing scheme, anisotropic diffusion, and consider its advantages in the sampling and interpolation of images.

2 Anisotropic Diffusion

Anisotropic diffusion [4] is a scale-space analysis technique to smooth an image while preserving image discontinuities, such as edges. Isotropic scale-space smoothing involves the generation of coarser images by convolving the original image with a family of Gaussian kernels [5], which can be implemented by successive convolution with small averaging masks. This process has been shown to be equivalent to the solution of the heat diffusion equation with a constant conduction coefficient [3]. However, this isotropic smoothing blurs image structure. In anisotropic diffusion, the conduction coefficient is space-varying and is chosen to be large in homogeneous regions to encourage smoothing and small at the region boundaries to preserve this image structure. The properties of immediate localization and piecewise smoothing defined by Perona and Malik [4] are relevant criteria for our scale-space analysis applications. At each resolution or scale, image structures must remain sharp and smoothing must not occur across structures or across a structure and its background.

Anisotropic smoothing as defined in [4] involves the convolution of the image with the kernel

0	λC_N	0
λC_W	$1 - \lambda(C_N + C_S + C_E + C_W)$	λC_E
0	λC_S	0

where $0 \leq \lambda \leq 1/4$ for stability and C_N, C_S, C_E and C_W are the conduction coefficients for the north, south, east and west directions respectively, chosen to be nonlinear functions of estimates of the image gradients in these directions. A rough estimate can be taken to be the absolute value of the first difference in the appropriate direction. One appropriate nonlinear function is

$$g(\nabla I) = e^{-(||\nabla I||/K)^2},$$

which bounds the conduction coefficients between 0 and 1, being 1 in regions with zero gradient and approaching 0 at major discontinuities.

Anisotropic diffusion can be interpreted as an directional filtering process. For example, at a vertical symmetric edge, $C_N = C_S = 1$, $C_W = C_E = C$, and the filter kernel becomes

0	λ	0
λC	$1 - \lambda(2 + 2C)$	λC
0	λ	0

The frequency response in both directions is a raised cosine and is strongly low pass in the N-S direction

$$H(0, \omega_2) = 1 - 2\lambda + 2\lambda \cos \omega_2,$$

with a minimum gain of $1 - 4\lambda$. The response is more nearly all pass in the E-W direction

$$H(\omega_1, 0) = 1 - 2\lambda C + 2\lambda C \cos \omega_1,$$

with a minimum gain of $1 - 4\lambda C$, with C approaching zero for a strong edge discontinuity.

Thus, anisotropic diffusion is a directional filter based only on the gradient magnitude. An example of anisotropic diffusion is shown in the Lenna image of figure 1.

3 Directional Interpolation

Directional interpolation is a directional filtering approach to interpolation that is driven by a local analysis of image structure, which involves more than the determination of image gradient [1]. This problem has been investigated previously and with similar goals recently [2]. The presence of possible structures in a local window is first tested, and if present, the structure type is determined. The structure types considered include image streaks, corners, edges and planar transitions. Interpolation is then based on the structure detected and is performed in the direction of slow change or low spatial frequencies.

An important issue in directional or structure-based interpolation is to ensure that we preserve or enhance all meaningful structures. Thus, we have generalized from the extensively studied high contrast edge to the more complete set of structures mentioned above. Because of this broader focus, the methods used to detect and analyze structure for interpolation purposes have to be reexamined. In particular, the gradient, Laplacian, and other local differential operators will work well only for high contrast edges. Our approach to this problem is to separate the detection of structure from its analysis.

Detection and analysis of structure is based on a local analysis window centered on the pixel to be interpolated [1]. The window is a 4×4, 3×4, or 4×3 low resolution neighborhood, depending on how the pixel to be interpolated is oriented with respect to the original grid. From this window, a 3×3 directional averages matrix (DAM) of intensities is computed.

The assumption that relevant structure is bimodal suggests that a bimodal segmentation of the DAMs would be a good indicator of structure. Therefore, each DAM is segmented into high and low values using a simple nearest neighbor clustering algorithm about its 2^{nd} highest and 2^{nd} lowest values. The exclusion of the extreme values is based on the assumption that any structure we wish to detect will have at least 2 high and 2 low values. Structure is then indicated by the strength of the bimodality, which is the difference between the cluster means mentioned above. If this difference is larger than a specified threshold, we proceed to classify and analyze the structure.

The method used to classify structure proceeds as follows. Determine the number of high and low regions by locating the transitions (from high to low and vice-versa) in the 8 pixel periphery of the DAM. Two transitions indicate 2 regions which implies an edge, corner, or plane. Four transitions indicates 3 regions which implies a streak, ridge, or valley. For edges and streaks, the goal is to determine the angle of the structure. For edges this is simple; it is just the line between the transitions. For streaks the problem is more complex: given 4 transitions, there are two possible ways of connecting them to create a streak. By considering only streaks which include the center pixel, this discrepancy can be resolved. Finally, if the difference between the lines on either side of the streak is less than $45°$, the angle is determined as an average of them, otherwise no streak is detected.

If no structures are detected with the above methods, a test for the detection of planar transitions is made on the analysis window. A ratio of the Laplacian over the gradient is used to determine planar fit. Detected planar transitions are then analyzed to determine the orientation of the plane, as described in [1].

For the most part, the detection of structure reduces to the detection of a low frequency direction or iso-intensity contour about each high resolution pixel. Of the major structures considered above (corners, edges, streaks, and planes), only corners are not adequately described by an angle. For the structures that are well described, the directional interpolate is determined as was done in [1]. Currently, corners are interpolated by averaging them with the other members of their bimodal class.

If no structure is detected, then the interpolation defaults to a bilinear interpolator.

The fact that relevant structures can be described by low frequency directions suggests an alternate strategy based solely on the prediction of iso–intensity contours, or angles which can be considered to be local estimates of the contours. Current work to this end suggests that this is a valid strategy.

4 Combining Anisotropic Diffusion and Directional Interpolation

If a method is available to remove the artifacts due to aliasing in the most important areas, then the filter/sampling process should also be based on local structure analysis. Anisotropic diffusion will provide low pass filtering in sub-areas without structure, but will not smooth out edges. As discussed in the previous section, directional interpolation removes aliasing effects when they occur in structured regions. Thus, anisotropic filtering and directional interpolation provide complementary strategies.

Since some amount of noise will always be present in an image, we need to consider as well the effects of the filter on the perceptible noise. Even in flat portions of an image, the noise will be accentuated if the image is sampled and interpolated without filtering. The subsampling process does not modify the noise pixels, but the interpolation produces visible distortion. For example, with additive white noise, the noise remains white after subsampling, but the interpolation process shifts the frequency spectrum of the noise to the frequency band of the interpolation filter. Thus the noise is now low pass, correlated, and much more objectionable perceptually. However, low pass filtering in an unstructured region is quite useful to remove noise effects even if the image contains no other high frequencies.

The advantages of combined anisotropic diffusion and directional interpolation are most obvious in processing a noisy image with high contrast edges, such as that shown in figure 2. This image after being filtered using anisotropic diffusion, subsampled 2:1, then directionally interpolated back to the original resolution, is shown in figure 3. This can be compared to the traditional approach of isotropic filtering, subsampling, and bilinear interpolation, shown in figure 4. The degree of filtering in both cases was chosen to provide similar noise suppression and it can be seen that with anisotropic diffusion and directional interpolation, the resulting image is much sharper.

Therefore the general approach is as follows:

a) Apply anisotropic diffusion to filter noise in flat regions and avoid aliasing due to noise. The anisotropic diffusion will not smooth out the high contrast edges.

b) Subsample the image. The high contrast transitions will be preserved or accentuated, and the subsampled image will retain the major features of the image.

c) Interpolate the image using directional filtering. As discussed earlier, in smooth portions of the image, bilinear filtering is satisfactory. Because of the prior anisotropic diffusion, the noise will have been suppressed and will not objectionable in interpolation. For structured areas, such as high contrast transitions, directional interpolation greatly reduces the aliasing artifacts.

5 Applications

5.1 Generation of Icons and Sketches

Image resolution must be reduced substantially to produce an icon, for use, for example, in an interactive image database system. A considerable amount of filtering is required to produce a recognizable icon. To preserve structure, this can be done by anisotropic diffusion, followed by subsampling, as shown in figure 5a, where 8:1 subsampling has been applied. For comparison purposes, figure 5b shows the same image subsampled 8:1, but without anisotropic diffusion.

An image sketch is a binary rendition of the image, consisting of the major transitions in the image. Heavy anisotropic filtering is required to smooth out minor transitions, eliminating extraneous detail in the resulting sketch.

5.2 Image Interpolation

The use of anisotropic diffusion for any image interpolation problem will maintain transitions, but reduce the noise that interpolation filters will produce. For these applications, a limited amount of filtering is required, as opposed to the heavy filtering for icon generation.

5.3 Pyramidal Decomposition of Images

In the pyramidal decomposition of images for the purpose of scale-space analysis, we again perform successively anisotropic diffusion and subsampling to generate a set of subimages.

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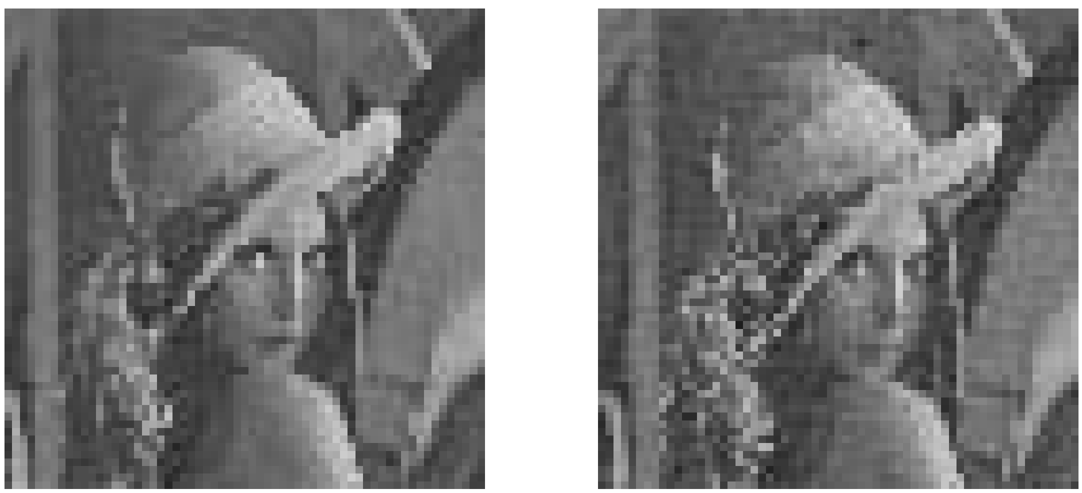
Figure 1: Anisotropic diffusion example.

Figure 2: Noisy image with high contrast edges.

Figure 3: Image processed by anisotropic diffusion, subsampling, and directional interpolation.

Figure 4: Image processed by isotropic filtering, subsampling, and bilinear interpolation.



(a) (b)

Figure 5: Icon produced (a) with anisotropic diffusion, (b) without anisotropic diffusion.