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Adaptive bilateral filtering of image signals using local phase characteristics

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Abstract

This paper presents a novel perceptually based method for noise reduction of image signals characterized by low signal to noise ratios. The proposed method exploits the local phase characteristics of an image signal to perform bilateral filtering in an adaptive manner. The proposed method takes advantage of the human perception system to preserve perceptually significant signal detail while suppressing perceptually significant noise in the image signal. Experimental results show that the proposed method is effective at removing signal noise while enhancing perceptual quality both quantitatively and qualitatively.

Keywords: Denoising; Local phase; Adaptive; Bilateral filtering

One of the most fundamental problems encountered when dealing with signal acquisition and processing is the presence of signal noise. Signal noise may be caused by various intrinsic and extrinsic conditions that are difficult to avoid. As such, the first step to processing a signal is often to suppress noise and extract the desired signal from the noisy signal. Of particular interest over recent years is the denoising of image signals, due largely to the incredible rise in popularity of digital images and movies. A large number of different image signal denoising methods have been proposed and can be generalized into two main groups: (i) spatial domain filtering and (ii) transform domain filtering.

Spatial domain filtering methods have long been the mainstay of signal denoising and manipulate the noisy signal in a direct fashion. Traditional linear spatial filters such as Gaussian filters attempt to suppress noise by smoothing the signal. While this works well in situations where signal variation is low, such spatial filters result in undesirable blurring of the signal in situations where signal variation is high. To alleviate this problem, a number of newer spatial filtering methods have been proposed to suppress noise while preserving signal characteristics in regions of high signal variation. These techniques include anisotropic filtering techniques [1], total variation techniques [2], and bilateral filtering techniques [3,4]. Bilateral filtering is a non-iterative and non-linear filtering technique which utilizing both spatial and amplitudinal distances to better preserve signal detail. In contrast to spatial filtering methods, frequency domain filtering methods transform the noisy signal into the frequency domain and manipulate the frequency

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coefficients to suppress signal noise before transforming the signal back into the spatial domain. These techniques include Wiener filtering [5] and wavelet-based techniques [6,7].

While effort has been made in the design of image signal denoising techniques to better preserve signal detail, little consideration has been given to the characteristics of the human perception system in such techniques. This is particularly important in the context of image signals, where the goal of signal denoising is often to improve the perceptual quality of the image signal. Furthermore, many of the aforementioned denoising techniques, including bilateral filtering, utilize fixed parameters that may not be well suited for noise suppression and detail preservation for all regions within an image signal. Therefore, a method for adapting the denoising process based on the human perception system is desired.

In this paper, we propose a novel approach to image signal denoising that performs perceptually adaptive bilateral filtering based on local phase characteristics. The proposed method is robust in situations where the image signal is characterized by low signal to noise ratios and provides improved noise suppression and signal detail preservation. This paper is organized as follows. The mathematical background behind the proposed method is presented in Section 1. Experimental results are presented and discussed in Section 2. Finally, conclusions are drawn in Section 3.

1. Mathematical background

Consider a 2-D signal f that has been degraded by a white Gaussian noise n. The contaminated signal g can be expressed as follows:

$$g(\underline{x}) = f(\underline{x}) + n(\underline{x}), \tag{1}$$

where $\underline{x} = (x, y)$. The goal of signal denoising is to suppress n and extract f from g. In spatial filtering techniques, an estimate of f is obtained by applying a local filter h to g:

$$f(\underline{x}) = h(\underline{x}, \varsigma) \times g(\underline{x}). \tag{2}$$

In a traditional linear spatial filtering technique, the local filter is defined based on spatial distances between a particular point in the signal at (x, y) and its neighboring points. In the case of Gaussian filtering, the local filter is defined as follows:

$$h(\underline{x}, \varsigma) = \mathrm{e}^{-(1/2)(\| \underline{x} - \varsigma \| / \sigma)^2}, \tag{3}$$

where ς represents a neighboring point. Such filters operate under the assumption that the amplitudinal variation within a neighborhood is small and that the noise signal consists of large amplitudinal variations. By smoothing the signal over a local neighborhood, the noise signal should be suppressed under this assumption. The problem with this assumption is that significant signal detail is also characterized by large amplitudinal variations. Therefore, such filters result in undesirable blurring of signal detail. A simple and effective solution to this problem is the use of bilateral filtering, first introduced by Tomasi et al. [3] and shown to emerge from the Bayesian approach by Elad [4].

In bilateral filtering, a local filter is defined based on a combination of the spatial distances and the amplitudinal distances between a point in the signal at (x, y) and its neighboring points. This can be formulated as a product of two local filters, one enforcing spatial locality and the other enforcing amplitudinal locality. In the Gaussian case, a bilateral filter can be defined as follows:

$$f(\underline{x}) = \frac{(h_{\mathrm{a}}(\underline{x}, \varsigma) h_{\mathrm{s}}(\underline{x}, \varsigma)) \times g(\underline{x})}{h_{\mathrm{a}}(\underline{x}, \varsigma) h_{\mathrm{s}}(\underline{x}, \varsigma)}, \tag{4}$$

where

$$h_{\mathrm{s}}(\underline{x}, \varsigma) = \mathrm{e}^{-(1/2)(\| \underline{x} - \varsigma \| / \sigma_{\mathrm{s}})^2}, \tag{5}$$

$$h_{\mathrm{a}}(\underline{x}, \varsigma) = \mathrm{e}^{-(1/2)(\| g(\underline{x}) - g(\varsigma) \| / \sigma_{\mathrm{a}})^2}. \tag{6}$$

The main advantage of defining the filter in this manner is that it allows for non-linear filtering that enforces both spatial and amplitudinal locality at the same time. The estimated amplitude at a particular point is influenced by neighboring points with similar amplitudes more than by those with distant different amplitudes. This results in reduced smoothing across signal regions characterized by large but consistent amplitudinal variations, thus better preserving such signal detail. Furthermore, the normalization term in the above formulation allows the bilateral filter to smooth away small amplitudinal differences associated with noise in smooth regions.

The main issue with bilateral filtering is that while the shape of the filter can change depending on the underlying signal, the way in which the shape can change is constrained by a fixed set of parameters for the entire image signal. While constraining the shape variations of the bilateral filter using a fixed set of parameters is sufficient for contaminated signals characterized by high signal to noise ratios,