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A design framework for hybrid approaches of image noise estimation and its application to noise reduction

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ABSTRACT

Noise estimation is an important process in digital imaging systems. Many noise reduction algorithms require their parameters to be adjusted based on the noise level. Filter-based approaches of image noise estimation usually were more efficient but had difficulty on separating noise from images. Block-based approaches could provide more accurate results but usually required higher computation complexity. In this work, a design framework for combining the strengths of filter-based and block-based approaches is presented. Different homogeneity analyzers for identifying the homogeneous blocks are discussed and their performances are compared. Then, two well-known filters, the bilateral and the non-local mean, are reviewed and their parameter settings are investigated. A new bilateral filter with edge enhancement is proposed. A modified non-local mean filter with much less complexity is also present. Compared to the original non-local mean filter, the complexity is dramatically reduced by 75% and yet the image quality is maintained.

1. Introduction

Noise can be introduced into digital images during the acquisition and transmission processes. Estimation of the noise level is very important for a variety of digital image and video processing algorithms, such as denoising [1–8], super-resolution [9], feature extraction [10], and motion estimation [11]. The estimated results are usually used to adapt the algorithm parameters to the amount of noise instead of fixed values. The noise model which was often assumed is the additive white Gaussian noise (AWGN) process given by:

$$I(x,y) = f(x,y) + \eta(x,y), \tag{1}$$

where x and y are the vertical and horizontal coordinates of a pixel, $I(x, y)$, $f(x, y)$ and $\eta(x, y)$ are the observed noisy image, the original ideal image and the additive Gaussian noise respectively. The image has width W and height H, and each pixel has an intensity value between 0 and 255. The goal of image noise estimation is to estimate the standard deviation σ_n of the Gaussian noise while the only information available is the noisy image $I(x, y)$. The deviation σ_n is referred to as the noise level.

Many algorithms for estimating the AWGN deviation in images have been proposed. They can be classified into wavelet-based [13,14], fuzzy-based [15], filter-based [16–18], block-based [12,19,20], or hybrid [21,22]. The challenge is to separate noise from image features or details.

In filter-based approaches, the noisy image is first filtered by a low-pass filter to remove the noise. Then the noise variance is computed from the difference between the noisy image and the filtered image. The main difficulty of filter-based approach is that the difference image is assumed to be the noise but this assumption is not always true, especially for images with fine structures or details.

In blocked-based approaches, the noisy image is tessellated into a number of blocks. The noise variance is then computed based on a set of homogeneous blocks. The main issue of block-based approaches is how to identify the homogeneous blocks.

A new hybrid approach was proposed in [22]. The noisy image is first tessellated into blocks. To identify the homogeneous blocks and exclude structures or details from contributing to the estimation of noise variance, a Sobel edge detection operator with a self-determined threshold is applied to each block. Then a filter operation, followed by an averaging of the convolutions over the selected blocks, provides a very accurate estimation of noise variance. It has been shown that the new hybrid approach achieves better performance in terms of accuracy, reliability and stability compared to other recently published methods.

The goal of image noise estimation is to provide the estimated noise variance for the image processes that follow. Besides the noise variance, some side information generated during the estimation process could be valuable, too. For example, the Sobel edge detection operator can provide the edge information. But, not all image processes require the same side information. Therefore, it is of

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interest to know the possibility of using homogeneity analyzers other than the Sobel operator in the noise estimation process.

The main contributions of this work are the follows. First, a design framework for hybrid approaches of image noise estimation is proposed. Then, the performances of four homogeneity analyzers in terms of estimation accuracy and reliability are evaluated. Finally and most importantly, information provided by noise estimation is successfully integrated with two well-known non-linear noise reduction filters, the bilateral filter and the non-local mean filter. A new bilateral filter equipped with edge enhancement is proposed. A modified non-local mean filter with less complexity is also present. All of these improvements are made possible by the side information provided by noise estimation process.

The remaining of this paper is organized as follows: Section 2 presents the proposed design framework. Section 3 introduces four homogeneity analyzers and Section 4 compares their performances in terms of estimation accuracy and reliability. Section 5 reviews the bilateral filter and investigates its parameter settings. A modified bilateral filter with edge enhancement is also proposed there. Section 6 reviews the non-local mean filter and investigates its parameter settings. A modified version of the non-local mean filter with much less complexity is presented there, too. Section 7 concludes the paper.

2. A design framework for hybrid approaches of image noise estimation

Based on our previous work [22], a design framework for combining the hybrid approach of image noise estimation and noise reduction is presented in Fig. 1. The intention is to identify the homogeneous blocks first. Then, it will become much easier to separate noise from image itself on these blocks.

The entire system begins with a block-based operation. The noisy image is tessellated into adjacent non-overlapping blocks with the block size equal to W_b. The choice of W_b has a great impact on the performance of the noise estimator. Considering performance and complexity, the best choice of W_b was shown to be 5 [22]. Let B_{xy} denote the block centered at (x, y) (2).

$$B_{xy} = \left\{ (m,n) \,\middle|\, |m-x| \leqslant \left\lfloor \frac{W_b}{2} \right\rfloor \text{and } |n-y| \leqslant \left\lfloor \frac{W_b}{2} \right\rfloor \right\}, \quad \lfloor\rfloor \text{ is the floor function.} \tag{2}$$

The homogeneity measure H_{xy} of each block is obtained by applying convolution with a homogeneity analyzer F^H which is consisted of N_f masks F_i^H. The homogeneity measure is then defined as:

$$\begin{aligned} H_{xy} &= \sum_{i=1}^{N_f} |F_i^H \otimes B_{xy}| \\ F_i^H \otimes B_{xy} &= \sum_{(m,n)\in B_{xy}} w(m,n) I(m,n), \end{aligned} \tag{3}$$

where $w(m,n)$'s are the coefficients of the masks. Four different operators are proposed to be the homogeneity analyzer and will be discussed in the next section. Depending on the choice of the operator, N_f could be 1, 2, 4, or 8.

The main challenge of block-based approaches is to decide a threshold value for the homogeneity measures and identify the homogeneous blocks. Since the only information available is the homogeneity measure H_{xy} of each block, a self-determined threshold can be obtained based on the statistics of these measures. The histogram of H_{xy} is computed first. Then, the threshold value H_{th} is selected to be the H_{xy} value when the accumulated histogram reaches P% of the whole image. An image block is claimed to be homogeneous if the homogeneity measure H_{xy} is less than the threshold value of H_{th}. Considering the complexity and the estimation performance, the best choice of P was shown to be 10 [22].

After identifying the homogeneous blocks, each block is filtered by the Laplacian filter (4), which is the difference between two second-order masks, to reduce the interference of noise and exclude the image structures from contributing to the estimation [16].

$$L_A = \begin{bmatrix} 1 & 0 & 1 \\ 0 & -4 & 0 \\ 1 & 0 & 1 \end{bmatrix} - 2 \times \begin{bmatrix} 0 & 1 & 0 \\ 1 & -4 & 1 \\ 0 & 1 & 0 \end{bmatrix} = \begin{bmatrix} 1 & -2 & 1 \\ -2 & 4 & -2 \\ 1 & -2 & 1 \end{bmatrix} \tag{4}$$

Let B_H^* denote the set of homogeneous blocks and B_H^* denote the total number of pixels in B_H^*. The estimated noise deviation is shown [16] to be given by (5)

$$\begin{aligned} \sigma_{est} &= \left(\frac{\pi}{2}\right)^{1/2} \frac{1}{6N_H^*} \sum_{B_H^*} |L_A \otimes B_{xy}| \\ B_H^* &= \{B_{xy} | H_{xy} < H_{th}\} \end{aligned} \tag{5}$$

Finally, the estimated noise variance and the side information generated by the homogeneity analyzer are integrated into the noise reduction process.

There are only two parameters in our estimation algorithm, the block width (W_b) and the percentage (P). P controls how many

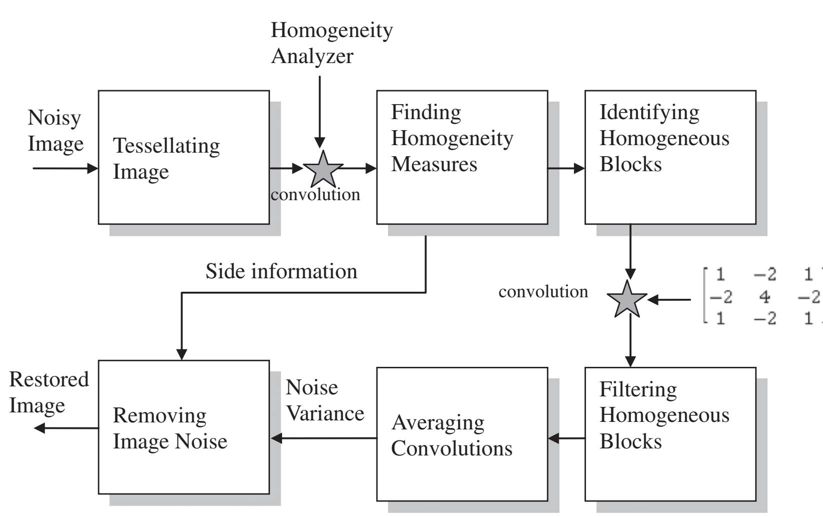

Fig. 1. Design framework for image noise estimation and reduction.