Providing a combined method for denoising using a bilateral filter and wavelet transform

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Abstract
In this paper, we provide an optimal and new method for denoising using a bilateral filter which in this method, first using wavelet transform, we perform a preprocessing and then use a bilateral filter for denoising. In the bilateral filter, after filtering, the edges of the image are lost and that is due to the use of neighboring pixels in this filter and also this filter has a better performance in low variance noises. To eliminate this flaw, a combination of this filter and wavelet transform was used to get better results. At the end, we compare the results with similar methods and discuss how to get optimal parameters in this filter.
Keywords
Denoising, bilateral filter, wavelet transform, image quality, Gaussian filter

1. Introduction

Today, due to the extensive use of the science of image processing, processing speed and accuracy are very important. Due to the existence of noise generation sources such as camera quality, stage lighting quality, heat generation sources and image receptor, most images become noisy. For this problem, denoising methods have become very special.
The most important criteria for the performance evaluation of these methods, are the visual and quantitative criteria such as the mean square error or signal to noise ratio. In this method, a bilateral filter has been used for denoising because this filter uses both the information of image brightness level as well as neighboring pixels for noise estimation in the image and the denoising it and has a good performance for denoising. But since this filter will not perform well alone when noise variance is high, we used wavelet transform as preprocessing. In wavelet transform, an image is divided into four frequency bands, low frequency including image general information and high frequency includes image details and noise. By filtering high frequency in wavelet transform, a big part of noise is removed but the low frequency noises will still be present which can be denoised using a bilateral filter. Therefore, image noise in all the frequencies is easily eliminated in all frequencies.
There are many methods for image denoising. For example, Wiener filter [1], wavelet thresholding, dissimilar filter [2], bilateral filter [3], surface alteration method [4], nonlinear method [5]. In the following, we will continue to describe the bilateral filter and its former denoising methods in section 2. In section 3, we discuss about various values of image noise variance and the relation of bilateral filter parameters with it and in section 4 we will propose a method, and in section 5, we will discuss the results of the experiments and will compare the proposed method with Bayesian drop [9] and fast filtering [8] and main bilateral filter [3]. The results show that the proposed method in this paper, is better than said methods and in section 6, we will provide the conclusion.

2. Introducing the bilateral filter and its former denoising methods

Of the methods mentioned in section 1, the wavelet thresholding method is considered as an appropriate method. In wavelet transform, an image is divided into four frequency bands, part 1 has information about the low frequency which consists of image general information and part 4, has information about the high frequency which consists of image details and noise where thresholding can be used for denoising.
The bilateral filter can be a better alternative for wavelet thresholding. This filter uses the weighted average of neighboring pixels and image brightness level information and has a good performance when image edges do not matter. The bilateral filter uses a combination of two Gaussian filters, one of which has location data and the other has image brightness level data. Equation 1, shows the output energy of a bilateral filter, where x represents one pixel.

$$I(\widetilde{x}) = \frac{1}{c} \sum_{y \in N(x)} e^{\frac{-\|y-x\|^2}{2\sigma_d^2}} e^{\frac{-|I(y)-I(x)|^2}{2\sigma_r^2}} I(y) \qquad (1)$$

Here, σ_r and σ_d are the control parameters of the Gaussian filter of brightness level and location. N(x) is a neighborhood of the x pixel and C is its constant number which is obtained from equation 2.

$$C = \sum_{y \in N(x)} e^{\frac{-\|y-x\|^2}{2\sigma_d^2}} e^{\frac{-|I(y)-I(x)|^2}{2\sigma_r^2}} \qquad (2)$$

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Image denoising using a bilateral filter is used in applications such as transmission of light texture [10], mapping [11], volumetric noise reduction [12] and many other places. Iliad [13] showed that the bilateral filter is a special case of Jacobins algorithm. Doran et al. [8], introduced a version of the bilateral filter which tangibly increased its speed. They optimized the bilateral filter using FFT. Paris et al. [4] later proposed a better plan compared to [11]. They showed that if the filter is measured in upper space, the signal intensity for the background pixels increases.

A big problem with the bilateral filter is that it does not have a good performance for salt pepper denoising and the more the noise variance increases, the worse the performance of this filter gets. Another problem with the bilateral filter, is its analysis quality which does not have an optimal performance in high frequencies.

3. The relationship between noise variance and the parameters of the bilateral filter

In the bilateral filter, according to equation (1), there are the two control parameters of σ_r and σ_d that show the locational characteristics and brightness level. In this paper, we provide an empirical analysis of the various values of these parameters and at the end, with the criterion of mean square error, we will evaluate each one.

In figure 1, various values of noise variance and the parameters of the bilateral filter with mean square error are shown.

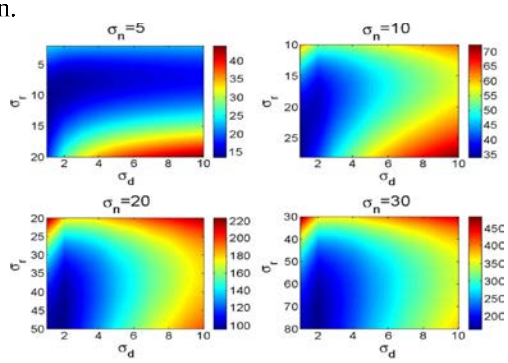

Figure 1 – mean square error for various noises

According to figure 1, the changes of σ_r in proportion to σ_d are intangible. To see the relationship between σ_r and σ_d, we consider the noise variance of σ_n as being constant and adjust the optimal value of σ_r as the main factor of σ_d. In figure 2, some designs for 3 standard images are shown. Based on these designs, σ_r and σ_n have a linear relationship, σ_r almost equals 1.76 * σ_n.

In figure 3, the proposed algorithm is shown where the image in high frequency is filtered and denoised using wavelet thresholding and in low frequency it is filtered and denoised using the bilateral filter.

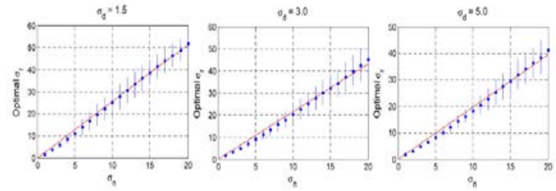

Figure 2 - the relationship between σ_r and σ_n for 3 standard images

4. Proposed algorithm

The algorithm given in this paper is shown in figure 3. First, the image is analyzed into high and low frequencies and its low frequency is denoised using wavelet thresholding. We analyze the high image frequencies into two low and high frequency parts and like before, we will denoise the high frequency with wavelet thresholding and denoise the low frequency using the bilateral filter and the result of this part is filtered using the bilateral filter and at the end, the final product is filtered once more with the bilateral filter and obtain the denoised image. Here, in fact, a multilevel bilateral filter was used to provide better performance. In the next part, we will discuss about the selection of threshold for wavelet thresholding and we used the Bayesian drop method [9] for it.

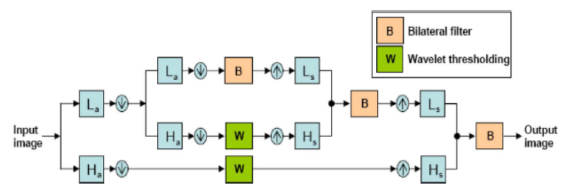

Figure 3 – proposed algorithm

5. Experiments

To evaluate the performance of the proposed method, we compared it with 3 other methods in visual and quantitative (mean square error) terms. The first method is Bayesian drop based wavelet thresholding algorithm [9]. The noise difference is estimated using strong median estimators [1]. The second method, is the bilateral filter [3]. Based on the experiments discussed in the previous section, we select the parameters below for the bilateral filter:

$$\sigma_d = 1.8 \text{ , } \sigma_r = 2 * \sigma_n$$

The window size is 11* 11 (this means that we placed a mask with these dimensions on the desired pixel and all the pixels that are located in this mask are considered as

neighboring pixels). The third method, is the consecutive applications [3,9].
In the proposed method, 8db filters in Matlab are used for one-level analysis. For the bilateral filter parts from the proposed method, the parameters are adjusted as below:

$\sigma_d = 7.8 \cdot \sigma_r = 1.5 * \sigma_n$

The window size is considered 11*11. We could consider $\sigma_r = 2 * \sigma_n$, but since we use a consecutive number of bilateral filters, this decreased the signal to noise ratio in the image and for the visual quality of the image to be high, it is necessary that the signal to noise ratio is also high. The results for the signal to noise ratio are given in table 1.

Table 1 – comparing signal to noise ratio of the bilateral Bayesian drop

Input image	σ_n	Bayesian drop	Bilateral filter	Consecutive applications [3,9]	Proposed method
Barbara 512*512	10	31.25	31.71	30.92	31.79
	20	27.32	27.02	27.16	27.74
	30	25.34	24.69	25.23	25.61
Ship 512*512	10	31.98	32.02	31.81	32.58
	20	28.55	28.40	28.43	29.25
	30	26.71	26.57	26.66	27.24
Goldhill 512*512	10	31.94	32.08	31.93	32.48
	20	28.69	28.90	28.80	29.50
	30	27.13	27.50	27.34	27.77

In the second experiment, one noise-less image taken with a digital camera in a low-light environment is investigated. We use thresholding algorithms for this image. Figure 4 shows the results for this image and the results for thresholding for the Bayesian drop of the bilateral filter and the proposed algorithm. Based on the results from these experiments, the proposed method produced very good visual results using real images.

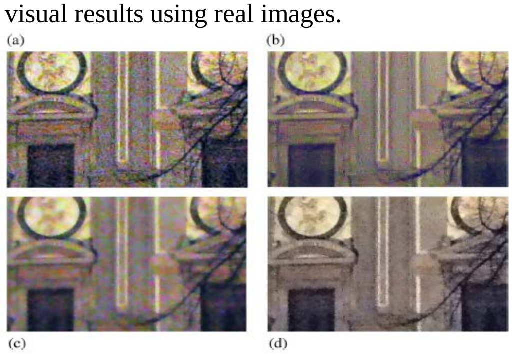

Figure 4 – a) input image, b) main bilateral filter, c) Bayesian drop, d) proposed method with three analysis levels

6. Conclusion

In this paper, we proposed a new method to obtain a noise-free image. We combined bilateral filter with wavelet thresholding. We analyzed the image in low and high frequencies and used the bilateral filter near the bands and used wavelet thresholding in the details of the bands. We concluded that the optimal value of σ_r of the bilateral filter, is linearly dependent on the standard deviation of the noise. The optimal value of σ_d is to some extent, independent from the power and force of the noise. Based on these results, we estimate the variability of the noise at each level of band analysis and use of the optimal value of σ_r for the bilateral filter. The main factor in this multilevel method is the use of the bilateral filter which can denoise rough noises in images. Also, use of wavelet thresholding, increases the capability of this method.

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