Novel Bilateral Filter Approach: Image Noise Reduction with Sharpening

Milivoje Aleksic, Maxim Smirnov, Sergio Goma
ATI Technologies, 75 Tiverton Court, Markham, ON, Canada, L4A4Y8

ABSTRACT

The classical bilateral filter smoothes images and preserves edges using a nonlinear combination of surrounding pixels. Our modified bilateral filter advances this approach by sharpening edges as well. This method uses geometrical and photometric distance to select pixels for combined low and high pass filtering. It also uses a simple window filter to reduce computational complexity.

Keywords: image processing, bilateral filter, CMOS sensor

INTRODUCTION

Cell phone cameras are gaining consumer acceptance, and at the same time introducing new challenges to the design of the image pipeline related to CMOS sensors with small pixel size, and small optical lens. Those limitations are increasing noise levels and degrading overall image appearance. There are a lot of different approaches and methods to improving the overall visual quality with the bilateral filter being one of the very successful. The original bilateral filter combines two kernels: spatial, which processes the pixels based on their geometrical distance, and photometric, which takes into account the perceptual similarity between the currently processed pixel and the pixels in its vicinity[1,2]. The bilateral filter relies on the brilliant idea that it makes sense to combine only pixel which are close and similar in color. It is in essence a nonlinear low pass filter for noise reduction, which preserves the edge structure.

To improve image appearance it is desirable to emphases edges, especially in images blurred due to long exposure time with low light conditions. The modified bilateral filter presented in this paper introduces additional sharpening effects similar to the traditional unsharpening mask by adding a high pass filter.

PROPOSED MODIFIED BILATERAL FILTER

Traditional bilateral filter uses two spatial kernels – a low-pass, and a high-pass. The spacious kernel, if used alone, processes the input pixel sequence $\vec{x}_{ij}$ to produce the output pixel sequence $\vec{y}_{ij}$ in the following manner:

$$\vec{y}[i,j] = \frac{\sum_{n=\frac{-N+1}{2}}^{\frac{N-1}{2}} \sum_{m=\frac{M+1}{2}}^{\frac{M-1}{2}} W_S[n,m] \times \vec{x}[i-n, j-m]}{\sum_{n=\frac{-N+1}{2}}^{\frac{N-1}{2}} \sum_{m=\frac{M+1}{2}}^{\frac{M-1}{2}} W_S[n,m]}$$

Here N and M - vertical and horizontal sizes of the special kernel correspondingly - are assumed to be odd numbers. Note that $\vec{x}_{ij}$ and $\vec{y}_{ij}$ are scalars for grey-scale images and multi-component (usually three-component) vectors for color images. The scaling denominator in the equation reflects the requirement for the filter to preserve the DC

Digital Photography II, edited by Nitin Sampat, Jeffrey M. DiCarlo, Russel A. Martin,
Proc. of SPIE-IS&T Electronic Imaging, SPIE Vol. 6069, 60690F, © 2006 SPIE-IS&T · 0277-786X/06/$15

component of the input signal. The DC component transfer function of the spatial filter is a property of the filter kernel and does not depend upon the input signal.

The output of the photometric filtering can be written in a similar way:

$$\vec{y}[i,j] = \frac{\sum_{n=\frac{-N+1}{2}}^{\frac{N-1}{2}} \sum_{m=\frac{M+1}{2}}^{\frac{M-1}{2}} W_P[n,m] \times \vec{x}[i-n, j-m]}{\sum_{n=\frac{-N+1}{2}}^{\frac{N-1}{2}} \sum_{m=\frac{M+1}{2}}^{\frac{M-1}{2}} W_P[n,m]}$$

Here WP [n, m] is a photometric kernel calculated adaptively as a function of Euclidian distance D^2 between the current pixel $\vec{x}_{ij}$ and its neighbors:

$$W_P[n,m] = f(D^2(\vec{x}[i,j], \vec{x}[i-n, j-m]))$$

Bilateral filtering combines the special and photometric kernels in one:

$$\vec{y}[i,j] = \frac{\sum_{n=\frac{-N+1}{2}}^{\frac{N-1}{2}} \sum_{m=\frac{M+1}{2}}^{\frac{M-1}{2}} W_P[n,m] \times W_S[n,m] \times \vec{x}[i-n, j-m]}{\sum_{n=\frac{-N+1}{2}}^{\frac{N-1}{2}} \sum_{m=\frac{M+1}{2}}^{\frac{M-1}{2}} W_P[n,m] \times W_S[n,m]}$$

Please note that the scaling denominator in this equation is now a function of the input signal and, therefore, must be calculated for each pixel of the input image.

Traditional bilateral filter implementation assumes that both spatial and photometric kernels have Gaussian shape[1] and, the Euclidean distances between pixel values are calculated in CIE-lab perceptual color space although different kernel shapes and different methods of calculating the Euclidean distances are not precluded.

To enhance image edges we added high pass filter which combines pixels geometrically further away and also less similar. This way filter can recover real edge from smeared edge. The adaptive noise removal/sharpening kernel is calculated as sum of low-pass (noise reduction) and high-pass (sharpening) components as:

$$W[n,m] = \left\{K_{sharp} \times W_P^{HP}[n,m] \times W_S^{HP}[n,m]) - b_{HP} \times U\right\} + \left\{K_{LP} \times W_P^{LP}[n,m] \times W_S^{LP}[n,m]\right\}$$

Here, $W_P^{HP}[n,m]$ and $W_P^{HP}[n,m]$ are low-pass and high-pass photometric kernels; b_{HP} and K_{LP} are filter normalizing coefficients; U is kernel of a pass-through 2D filter:

$$U = \begin{bmatrix} 0 & 0 & \dots & 0 & 0 \\ \dots & \dots & \dots & \dots & \dots \\ 0 & \dots & 1 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & 0 & 0 \end{bmatrix}$$

Both photometric kernels use the following definition of Euclidean distance in YCrCb colour space (this is a simplification of the classical bilateral filter approach, which uses CIE-lab perceptual color space):

$$D^2(\vec{x}[i,j],\vec{x}[i-n,j-m]) = \left(Y[i,j]-Y[i-n,j-m]\right)^2 + \left(Cb[i,j]-Cb[i-n,j-m]\right)^2 + \left(Cr[i,j]-Cr[i-n,j-m]\right)^2$$

The standard procedure with Gaussian filter requires significant computational power, and one of the methods to simplify it is described in Tuan paper[3]. The computational simplification is based on approximating the bilateral filter by a separable filter, which can be implemented as two one dimensional filters – one operates in the horizontal and the second one in the vertical direction. In our modified filter the low-pass photometric kernel is also calculated in a simplified way (flat window with threshold parameter instead of the regularly used Gaussian function):

$$W_P^{LP}[n,m] = \begin{cases} 1, if\ D^2[n,m] \le LpThreshold^2 \\ 0, otherwwise \end{cases}$$

Normalizing low-pass coefficient ensures that the low-pass part of the resulting kernel passes the DC component unchanged and it is consistent with the classical bilateral filtering equation:

$$K_{LP} = \frac{1}{\sum_n \sum_m W_P^{LP}[n,m] \times W_S^{LP}[n,m]}$$

The high-pass photometric kernel exploits an equation similar to its low-pass counterpart:

$$W_P^{HP}[n,m] = \begin{cases} 1, if\ D^2[n,m]\ > HpThreshold^2 \\ 0, otherwwise \end{cases}$$

The coefficient normalization procedure, however, is different, i.e. the middle element of the high-pass kernel is shifted so that the kernel's frequency response would be zero for the DC signal components:

$$b_{HP} = \sum_n \sum_m K_{sharp} \times W_P^{HP}[n,m] \times W_S^{HP}[n,m])$$

The modified bilateral filter in order to remove noise from the image adapts two fixed spatial kernels, one high-pass and one low-pass, for each pixel based upon analysis of pixel surrounding area. The adaptation process uses three parameters:

LpThreshold - noise removal threshold, which is used to classify variations in input image as noise or as an edge

HpThreshold - sharpening threshold, which determines variation levels qualifying for edge sharpening

Ksharp - sharpening coefficient, which sets the desired amount of sharpening.

The Figure 1 presents original signal, Figure 2 signal with additive noise and signal after applying the low pass filter. The Figure 3 demonstrates the sharpening combined with noise removal. In this example the ringing effect is visible around sharp change of the slope of the signal.

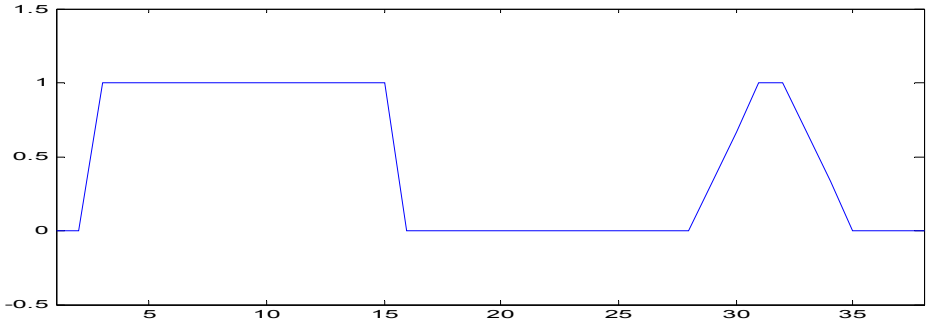


Figure 1 Original signal before noise insertion

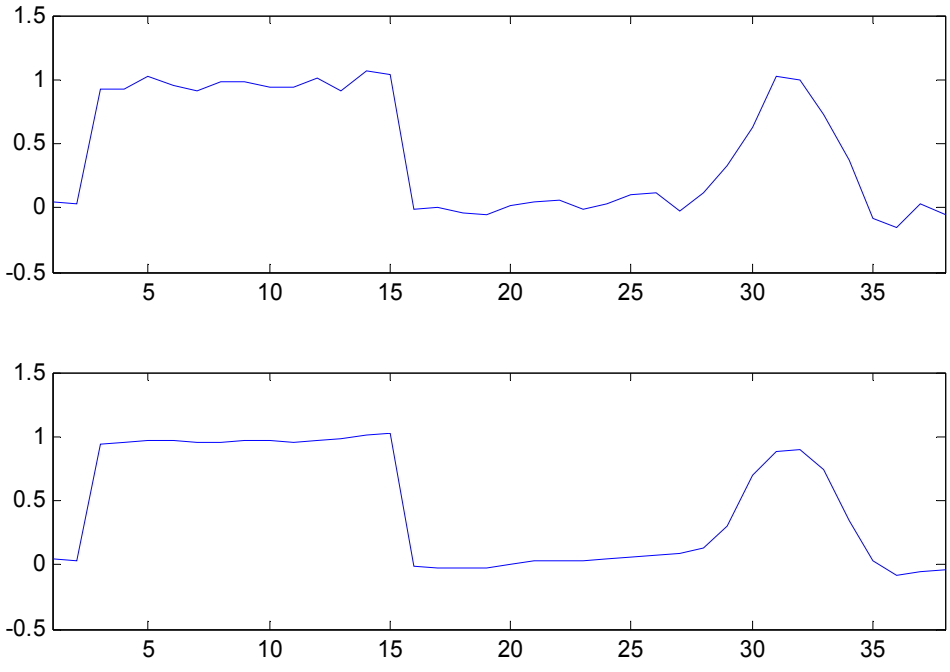


Figure 2 Noise reduction (Thresh = 0.25)

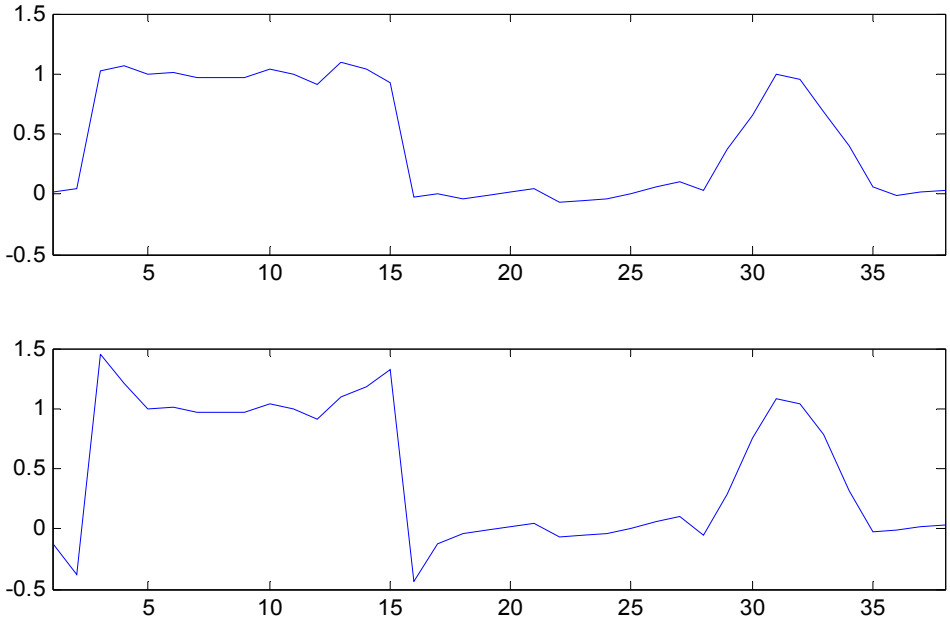


Figure 3 Sharpening (Ksharp = 1.3, Thresh = 0.25)

Figure 4 is an example of an ISO400 image before and after sharpening. Figure 5,7 are example of applying the modified bilateral filter for typical 2Mpixel cell phone CMOS sensor images.

CONCLUSION

In this paper we presented the modified bilateral filter by adding sharpening effect to the classical one. The proposed method has a similar effect as unsharp masking but with a unified filter for noise removal and edge preservation.

The classical filter uses complex coefficients calculated based on Gaussian distribution. Our modified bilateral filter applies a simple window filter based on geometric and photometric Euclidian distance. Despite this simplification our filter has significant number of arithmetic operations. This number of operations per pixel is still one of the key road blocks to widespread implementation of this method in real time systems although there are recent efforts to reduce it[3] . One of the options is to simplify photometric Euclidian distance with sum of absolute values, and/or reduce division complexity.

ACKNOWLEDMENTS

The authors would like to thank Steven Turner, VP of engineering in ATI, for his substantial help in forming this paper and his overall support.

REFERENCES

1. C. Tomasi, R. Manduchi, Bilateral Filtering for Gray and Color Images, Proceedings of the 1998 IEEE International, Conference on Computer Vision, Bombay, India
2. Michael Elad, On the Origin of the Bilateral Filter and Ways to Improve It, IEEE Transactions on Image Processing, VOL. 11, NO. 10, October 2002
3. Tuan Q. Phan, Lucas J.vanVliet , Separable Bilateral Filtering for Fast Video Preprocessing, Proc. IEEE Int. Conf. on Multimedia & Expo (Amsterdam, Jul.6-8), 2005



Figure 4 ISO400 detail, before and after filtering

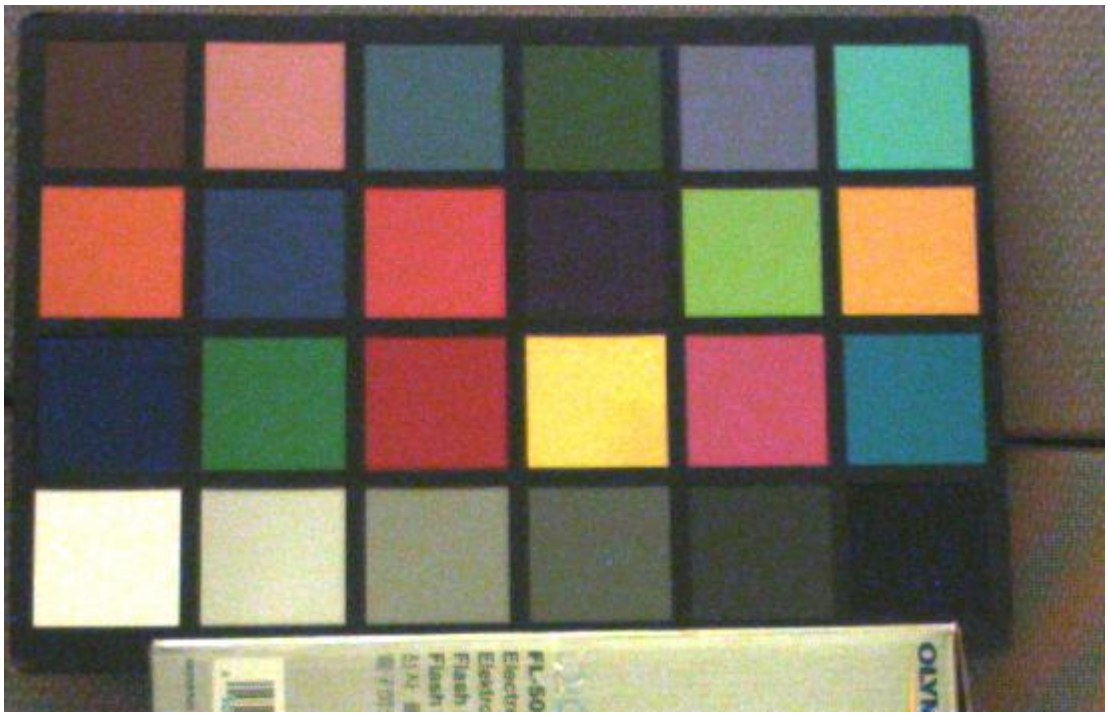


Figure 5 2Mpixel CMOS sensor with visible noise



Figure 6 Image from Figure 5 after filtering