

A Fast Implementation of Bilateral Filter Based on Edge Protection

Li Ying Jiang^{*}, Yan Li and Yang Bo

School of engineering institute, HongHe University, HongHe, Yunnan, 661100, P.R. China

Abstract: To improve the arithmetic speed of bilateral filter, an improved ascending dimension bilateral filtering algorithm was proposed. The algorithm based on linearization the bilateral filter and the mapping image matrix to improve the operation speed, inverse mapping the calculation to restore the image matrix after the total area filtering of the mapping image. In the process of filtering, in order to preserve the edge of image while denoising, According to the information extracted from image phase consistency, self-adaptive to adjust the Spatial proximity factor and gray similarity factor. Through the experiment results from subjectivity and objectivity, this algorithm of the bilateral filtering can not only improve the speed, but also retained more of the image edge information during the denoising.

Keywords: Ascending dimension, bilateral filter, denoising, phase consistency.

1. INTRODUCTION

Image acquisition process will inevitably introduce noise, before the image compression coding and transmission, a very important problem must be solved, that is how to quickly and efficiently filter the noise and maintain image edge details at the same time. To solve this problem is especially urgent for video surveillance applications. Image quality reduction, some detail features always submerged in the noise, it gives image processing brought great difficulties, such as image observation, characteristic information extraction and analysis. So, image enhancement and recovery has been an important research topic in the field of image processing.

This is a very contradictory things, Image denoising is a filtering process, and the image edge and texture is easy to be smooth out as a noise in the filtering process, Until now, there was no algorithm can completely solve this contradiction. As early as 1998, Tomasi and Manduchi proposed a bilateral filtering algorithm, it could reduce the image noise effectively, and kept the edge details [1]. Compared with classic Gaussian filtering, bilateral filter not only consider the space of proximity, but also the gray similarity, the effect of protect the edges of the image is better than Gaussian filtering in the process of filtering.

At present, the bilateral filtering algorithm [2, 3] will smooth the edge and texture of image during the filtering procedure, And bilateral filtering is nonlinear filtering, image linear convolution operation cannot be achieved, filtering process is very time-consuming, Weiss's Iterated Box theory [4] is minor adjust the masking in the process of point by point filter. It is an approximate Gaussian bilateral filter

ing, has a fast calculation speed, and mask size does not much affect the computational complexity. The ascending dimension filtering [5], make the bilateral filter express as linear convolution in the higher dimensions, down sampling in spatial domain and gray domain, accelerate the algorithm by linear filtering method. The filtering precision of this method is closer to the traditional bilateral filter, and the speed is fast, but the defect is can not keep image edge effectively.

The paper work is to improve the operation speed of bilateral filtering and at the same time reduce the smooth operation to image edge and texture. Using the improved ascending dimension bilateral filtering, on the premise of ensure the filtering precision to improves the filtering speed. At the same time using phase consistency principle [6, 7] to extract image information to adaptive select the important parameters and that influence the filtering. Make sure the bilateral filtering process can better retain the image edge information.

2. THE BASIC PRINCIPLE OF ASCENDING DIMENSION BILATERAL FILTERING

The weighted coefficient of the bilateral filter consists of two parts, One part determined by the difference between the space distance of pixels, can call it a spatial proximity factor; Another part is determined by the difference between the gray value of pixels, called gray similarity factor.

Assuming that the image I in coordinates $p(x, y)$, it's gray value is $I(p)$, after filter, get the images BI , in the coordinates point p , it's gray value is defined as $BI(p)$, bilateral filtering formula is given in formula (1), (2).

$$BI(p) = \frac{1}{W(p)} \sum_{q \in S} G_s(p, q) G_r(p, q) I(q) \quad (1)$$

$$W(p) = \sum_{q \in S} G_s(p, q) G_r(p, q) \quad (2)$$

In the above formula, $q(u, v)$ is the neighborhood pixels of center pixel p , S is the neighborhood pixels set, $W(p)$ is the normalization factor, G_s is spatial proximity factor, G_r is gray similarity factor. Their expressions are given in the following formula.

$$G_s(p, q) = e^{-[(x-u)^2 + (y-v)^2] / 2\sigma_s^2} \quad (3)$$

$$G_r(p, q) = e^{-|I(p) - I(q)|^2 / 2\sigma_r^2} \quad (4)$$

σ_s is the distance standard deviation based on the Gaussian function, σ_r is the gray level standard deviation based on it.

The idea of ascending dimension bilateral filtering is use the 2D image coordinates and the coordinates on the gray levels of pixels to build three-dimensional space. To form the linear convolution by three-dimensional image function and three dimensional Gaussian kernel function. The multiplication corresponding to the frequency domain, here we use the inverse Fourier transform, it converts the complicated point by point calculation to fast Fourier transform, improve the computation efficiency.

Set the 3D image matrix IX and three weighting matrix EX is the input image I ascended, their expression is shown in (5), (6).

$$IX(x, y, z) = \begin{cases} z, z = I(x, y) \\ 0, z \neq I(x, y) \end{cases} \quad (5)$$

$$EX(x, y, z) = \begin{cases} 1, z = I(x, y) \\ 0, z \neq I(x, y) \end{cases} \quad (6)$$

For the 3-d matrix of the above perform "average Downsampling", spatial domain sampling rate is S_s and gray domain sampling rate is S_r , it divides the 3-d matrix into several pixels, each pixel block size is $S_s \times S_s \times S_r$. Each pixel block corresponds to a 3-d sampling interval, every sampling interval needs a amplitude. The amplitude is sum of all the pixel gray value of the area.

In the literature [8], sampling and interpolation is the key step in the bilateral filter, directly affects the filtering precision and computing speed. With the sampling rate improve continually, interpolation operation time will far outweigh the sampling and convolution. In order to overcome this problem, this paper improve the way of sampling instead of interpolation algorithm.

The mapping relationship of 2-d matrix and 3-d matrix after sampling the is shown as formula (7), (8), (9).

$$IX(x, y, z) = \sum_{(u,v) \in M(x,y,z)} I(u, v) \quad (7)$$

$$EX(x, y, z) = \sum_{(u,v) \in M(x,y,z)} 1 \quad (8)$$

$$M(x, y, z): \left\{ (u, v) \left| \begin{array}{l} x - 0.5 \leq \frac{u}{S_s} \leq x + 0.5 \\ y - 0.5 \leq \frac{v}{S_s} \leq y + 0.5 \\ z - 0.5 - n \leq \frac{I(u,v)}{S_r} \leq z + 0.5 \end{array} \right. \right\} \quad (9)$$

This is equivalent to there have overlap in 3 d sampling interval of gray domain. The overlapping area element

classified to two sampling interval, they sampled twice in the process of Average Downsampling. At the same time, we need transform the standard deviation σ_s and σ_r : $\sigma_s = \sigma_s / S_s$, $\sigma_r = \sigma_r / S_r$.

Three dimensional Gaussian filtering to the three dimensional matrix IX and the EX , now we do not need interpolation algorithm, but direct point divide the two filter results. The result three dimensional matrix BIX is shown in formula(10).

$$BIX = \frac{G \otimes IX}{G \otimes EX} \quad (10)$$

3. PHASE CONSISTENCY PRINCIPLE

A signal can be expansion by the Fourier transform:

$$f(x) = A_0 + \sum_{n=1}^{\infty} A_n \cos(n\omega x + \phi_n) \quad (11)$$

As the formula (11) shows, the $f(x)$ is made up of a number of sine signals superposition in different frequency, unfold the square wave signal, can be found in the step up and step down of the square wave signal, each phase of harmonic component is fit, but the other component of the signal, the phase is different. Find out those biggest position which is the phase consistency of original signal, such as rising edge and falling edge of the square wave, the edges are strongly change edges of a signal. The largest phase consistency of the signal Fourier decomposition is corresponds to the change huge edges of the signal intensity [9].

According to this principle, Morrone was put forward a theory, that is: signal at position x , its phase consistency function of Fourier series expansion [7] is shown in formula (12).

$$PC(x) = \max_{\bar{\phi}(x) \in [0, 2\pi]} \frac{\sum_n A_n \cos(\phi_n(x) - \bar{\phi}(x))}{\sum_n A_n} \quad (12)$$

In the formula, A_n is the amplitude of n times ic, $\phi_n(x)$ is phase values of x , and $\bar{\phi}(x)$ is the weighted average of the signal Fourier transform's local phase when $PC(x)$ in x place to obtain the maximum value. According the formula, the more close between $\phi_n(x)$ and $\bar{\phi}(x)$, the bigger we got the $PC(x)$ value. Obviously, we detect the signal change information here.

4. THE BILATERAL FILTER DESIGN BASED ON PHASE CONSISTENCY AND ASCENDING DIMENSION

The filtering effect of bilateral filter depends on the selection of parameter σ_s and σ_r . In the operation, each part of the image property is different. Phase consistency represent the detail information of image, this paper, in order to get the better filter effect, we tend to use the phase consistency to self-adapt the spatial proximity factor and gray similarity factor of bilateral filter [4].

Through formula (12) to calculate the phase consistency of the image information, but the calculation process is very complex to calculate the frequency of the signal decomposition. Local energy model study shows, Maximum phase



(a) Add the Gaussian Noise



(b) Phase Consistency Information

Fig. (1). Capture the image phase consistency information.

consistency can be converted into calculate the peak point of local energy.

$$|E(x)| = \sqrt{F^2(x) + H^2(x)} \quad (13)$$

According to the literature [6, 7, 9] energy research conclusion, the formula (12) can be translate into formula (14).

$$PC(x) = \frac{\sqrt{F^2(x)+H^2(x)}}{\sum_n A_n + \epsilon} = \frac{\sqrt{(\sum_n e_n(x))^2 + (\sum_n o_n(x))^2}}{\sum_n \sqrt{e_n(x)^2 + o_n(x)^2} + \epsilon} \quad (14)$$

ϵ is stable factor in the formula, given the value 0.01 commonly, Fig. (1a) is the Lena image after add the Gaussian noise, Fig. (1b) is the image phase consistency information captured by formula (14) and use the log Gabor wavelet, from the Fig. (1b), we can be seen the edge and texture information of the image were captured.

Using Hysteresis Threshold method to mark these special processing area. This paper combines the local image variance information to self-adapt the factor of the Bilateral filter, calculate the variance of each point to the whole image window, get the maximum variance G_{max} . Later in the process of filtering, if we found that the center point we handled is the chosen special processing area of the mark point, then transform the spatial correlation factor G_s and G_r of the formula (3) and (4) to formula (15) and (16):

$$G_s(p, q) = e^{-[(x-u)^2 + (y-v)^2]/2} \left[\sigma_s \left(1 - \frac{G}{G_{max}} \right)^2 + \xi_1 \right]^2 \quad (15)$$

$$G_r(p, q) = e^{-|I(p)-I(q)|^2/2} \left[\sigma_r \left(1 - \frac{G}{G_{max}} \right)^2 + \xi_2 \right]^2 \quad (16)$$

In the formula (15) and (16), G is a variance value of the processing window. And ξ_1 and ξ_2 is used to increase the stability of calculation, in the experiment value is 0.001.

Use the matrix inverse mapping operations to replace the linear interpolation, on the basis of the two coordinates and grey value of the original image to valuation or evaluation. as shown in formula (17), the similar gray value pixel before filter will become into same value after filter. This is amount to average and filter for the similar gray value pixel.

$$BIS(x, y) = BIX \left(\left[\frac{x}{S_s} \right], \left[\frac{y}{S_s} \right], \left[\frac{I(x,y)}{S_r} \right] \right) \quad (17)$$

The expression of recovery of bilateral filter output image BI is shown in formula (18).

$$BI(x, y) = BIS(x, y) + w_x + w_y + w_z \quad (18)$$

Among them, w_x, w_y, w_z is the compensation factor, specific parameters can view the literature [5]. For the ascending 3-d image matrix, Bilateral filtering algorithm is based

Table 1. PSNR of bilateral filter and this paper algorithm with different σ_s and σ_r .

σ_s	σ_r	Fruits		Camera	
		Bilateral Filter	This Paper Method	Bilateral Filter	This Paper Method
1	10	24.854	24.884	25.191	25.231
1	50	28.568	28.723	29.638	29.705
1	100	27.067	28.951	27.938	29.495
3	10	25.309	25.314	25.931	25.955
3	50	26.745	28.247	28.635	29.614
3	100	24.045	26.205	24.706	27.313
10	10	25.041	25.356	26.043	26.157
10	50	26.130	27.621	28.012	29.143
10	100	23.301	25.104	23.762	26.201

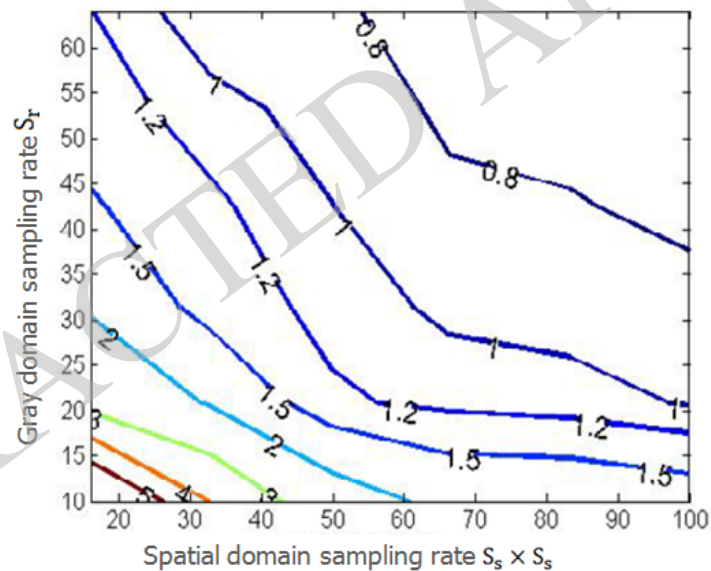


Fig. (2). Ascending bilateral filter operation time.

on space distance to define the weighted coefficient of neighborhood pixels. From the perspective of spatial domain, a bilateral filtering of two-dimensional image matrix is equivalent to a low-pass Gaussian filter of 3-d image matrix, only the dimension is different.

5. EXPERIMENTAL RESULTS AND ANALYSIS

Experiment mainly from two aspects to validate the filtering algorithm: operation time of the filtering and edge and texture details of image.

5.1. Operating Rate Verification

In order to test and verify the effect of the proposed approach, use a computer configuration is: CPU Intel(R) core i3-4000M CPU 2.4GHz, RAM 4GB, the OS is Windows 7.0, programming software is vs2010+opencv2.4.9.

Using two function: cvGetTickCount() and cvGetTickFrequency() to make a time statistic of using bilateral filtering algorithm to processing about 1 M pixels gray image. The algorithm use full kernel, as shown in Fig. (2), the horizontal axis is the sampling rate in the spatial domain, Is the product of sampling rate of the horizontal and vertical

Table 2. SSIM of bilateral filter and this paper algorithm.

σ_s	σ_r	Fruits		Camera	
		Bilateral Filter	This Paper Method	Bilateral Filter	This Paper Method
1	10	0.593	0.594	0.522	0.522
1	50	0.809	0.817	0.789	0.791
1	100	0.790	0.826	0.788	0.802
3	10	0.614	0.614	0.553	0.557
3	50	0.787	0.823	0.831	0.841
3	100	0.684	0.758	0.761	0.801
10	10	0.615	0.616	0.557	0.561
10	50	0.673	0.812	0.818	0.830
10	100	0.640	0.713	0.729	0.772

direction $S_s \times S_s$. The vertical axis represents the gray domain sampling rate S_r . Among them, 5×5 , 11×11 standard bilateral filtering algorithm running time is 22 seconds and 31 seconds. Can be seen from the data graph, with the increase of spatial domain and gray domain sampling rate, the algorithm of computing efficiency are improved greatly. The fastest operation time is about 0.6 to 0.6 seconds, the fastest operation time is related to the total number of pixels in the image. So, increase the sampling rate blindly will only reduce the filtering precision.

5.2. Filtering Precision

Evaluate this paper's algorithm use two aspects: subjective evaluation and objective evaluation, Objective evaluation use the peak signal to noise ratio(PSNR) index, and new image evaluation index: structure similarity(SSIM) [11, 12].

5.2.1. Reservation Image Details After FILTERING

Add the same noise to initial image, using different parameter σ_s and σ_r , used Bilateral Filter and this paper proposed method to process the image. In Fig. (3), the first line (Figs. a1, a2, a3, a4) is used the Bilateral Filter, the second line (Figs. b1, b2, b3, b4) is use this paper proposed method, the figure shows that with the parameter σ_s and σ_r values increase, The first line image gradually blur, image detail information degenerate severity. Comparative method in this paper, obviously more contour and edge details are reserved.

5.2.2. PSNR of Image

Add noise to the images Barbara and Camera, and then use the bilateral filter and this paper method to filter the two image. Table 1 is the PSNR index.

It is observed from the table, when the parameter σ_s and σ_r is very small, the PSNR value of two Filter algorithm are very close, when the parameter σ_s and σ_r enlarge, the PSNR of this paper method is high then the bilateral filter, it is reflect that this algorithm improve the denoising accuracy meanwhile still retain image edge well.

5.2.3. SSIM of Image

SSIM index is used to test the similarity of two images, can be used to evaluate the effect of filter denoising. Calculation the SSIM value by original image and the image after denoising process is closer to 1, it means the filter effect is better. SSIM of bilateral filter and this paper algorithm with different σ_s and σ_r is shown in Table 2.

Through the SSIM tests, the result is similar to the conclusion of PSNR, especially when the noise pollution is serious, this paper proposed method have more obvious advantage.

CONCLUSION

In this paper, in order to improve the running speed of bilateral filtering algorithm, put forward some improvement based on original bilateral filtering algorithm. From the perspective of signal system linearization, change the algorithm into image matrix and kernel function of the convolution operation through matrix transformation, then process after FFT transform to the frequency domain. Finally inverse transform the three-dimensional matrix to obtained the filter image, the method reduce the computational complexity. At the same time, this paper use the method of phase consistency to extract the image edge information. Then in the image filter processing adaptive calculate the spatial correlation and gray correlation factor of bilateral filter, under the condition



(a1) Original Image



(a2) $\sigma_s = 1, \sigma_r = 50$



(a3) $\sigma_s = 1, \sigma_r = 100$

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(a4) $\sigma_s = 10, \sigma_r = 100$



(b1) Original Image



(b2) $\sigma_s = 1, \sigma_r = 50$

(b3) $\sigma_s = 1, \sigma_r = 100$ (b4) $\sigma_s = 10, \sigma_r = 100$ **Fig. (3).** Bilateral Filter and this paper proposed method filter effect in different σ_s and σ_r .

of the strong noise interference, filter algorithm can effectively filter out noise, at the same time also retain the image edge and details.

The experimental results show that the improved algorithm enhance the operation efficiency an order of magnitude, compared to the Filter algorithm, in subjective and objective this algorithm filtering effect and the image edge retention are better than the former, especially under high noise conditions, the effect of filter is better.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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