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A Novel Edge Enhanced Error Diffusion*

Tae-Ha Kang[1], Tae-Seung Lee[2 **], Syng-Yup Ohn[2], and Byong-Won Hwang[2]

[1] Agency for Defense Development, Korea
thkang@add.re.kr
[2] School of Electronics, Telecommunication and Computer Engineering, Hankuk Aviation University, Korea
thestaff@hitel.net, {syohn, bwhwang}@mail.hangkong.ac.kr

Abstract. The error diffusion method is good for reconstructing continuous tones of an image to bilevel tones. However, the reconstruction of edge information by the error diffusion is represented as weak when the power spectrum is analyzed for display error. In this paper, we present an edge enhanced error diffusion method to preprocess original images to achieve an enhancement for the edge information. The preprocessing algorithm consists of two processes. First, the value of difference between the current pixel and the local average of surrounding pixels in the original image is obtained. Second, weighting function is composed by the magnitude and the sign of the local average. To confirm the effect of proposed method, the method is compared with the standard error diffusion and conventional edge enhanced error diffusion methods by measuring various objective measuring criteria including the radially averaged power spectrum density (RAPSD) for display error. The results of comparison demonstrate the superiority of the proposed method over the conventional ones.

Keywords: error diffusion, edge enhancing, radially averaged power spectrum density, edge correlation, local average accordance

1 Introduction

Image output devices, including printers and faxes, usually have only the two levels of tones or colors in technical and economical reasons. However the devices must output images sawn as natural as possible even if such limitations are imposed. Halftoning is introduced to content with the requirement.

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** The corresponding author would reply to any questions or problems from this paper. Postal: Department of Avionics, Hankuk Aviation University, 200-1, Hwajon-dong, Deokyang-gu, Koyang-city, Kyonggi-do, 412-791, Republic of Korea. Fax: +82-2-3159-9257. Email: thestaff@hitel.net or tslee@mail.hangkong.ac.kr.

Halftoning is the process to convert continuous-toned image into bilevel-toned one and let see the latter as the former when looked at from a distance. Of many halftoning algorithms studied before, the error diffusion is remarkable for its superior blue-noise property [1]. The error diffusion was proposed by Floyd et al. It distributes the error made at a pixel over the surrounding pixels by quantizing the pixel into bilevel tones and using an error diffusion filter that makes the average error for the entire image be zero.

However, the error diffusion filter is designed to retain the average tone of original image, i.e. direct current element frequency, so the degradation of original image for high frequency edge information has to be made [2]. The bilevel-toned image faces contradictory necessities. That is, it has to make the direct current element of display error power spectrum be zero to retain the same average tone to original image, while it has to minimize the error power of high frequency to preserve the original edge information.

The studies conducted to achieve the error diffusion include the methods to modify the error diffusion filter, adaptively adjust filter coefficients to minimize local errors, introduce the property of human visual system (HVS), utilize the characteristics of printers, and so on [3], [5], [6]. Most of all, the edge enhanced error diffusion proposed by Eschbach et al. is remarkable. This method adds multiples of pixel tones to original image in the process of error diffusion to emphasize the edge of original image and get clearer bilevel-toned image. However, the bilevel-toned image converted by the method of Eschbach et al. has some errors at low frequency areas because it uniformly applies the transformation to original image without considering local area characteristics.

This paper studies an improved error diffusion method to maintain edge information with keeping up the enhancement for general information. The heart of the method is a preprocessing filter to reduce the distortions of original image for low and high frequency information. The proposed filter consists of difference value and weighting function. The former is made between a pixel and the local average for the surrounding area in the original image, and the latter use the difference.

The paper hereafter is organized as follows. Section 2 describes the preprocessing filter algorithm proposed by this paper. The performance of the proposed filter is compared with that of the existing edge enhanced methods for various objective measuring criteria including the radial averaged power spectrum density (RAPSD) in Section 3 and is discussed in Section 4. Section 5 finally concludes this paper.

2 Preprocessing Filter Added Edge Enhanced Error Diffusion

The proposed preprocessing filter is designed to maintain general information with keeping up the improvement of edge enhanced error diffusion proposed by Eschbach et al. [7]. The overall error diffusion system is depicted in Fig. 1. The proposed filter is designated by the dotted box and the rest modules are the same to the proposal of Floyd et al. [1]. In the figure, $i(m,n)$ and $b(m,n)$ are the input image and the bilevel-toned image of $M \times N$ samples, respectively. It is assumed that $b(m,n)$ has

0 or 1 and $i(m,n)$ is belong to the range $[0,1]$. $e(m,n)$ is the error generated during quantizing the original tone into 0 or 1.

The proposed filter adds to the quantizer the tone difference of the current pixel to the local area, while the filter of Eschbach et al. multiplies a weighting value directly to original image and adds the multiplications to the quantizer [7]. The proposed filter is represented by the formulations such as:

$$D_{mn} = G_C - \frac{1}{25}\sum_{k=-2}^{2}\sum_{l=-2}^{2} i(m+k, n+l)\,. \tag{1}$$

$$G_{mn} = \frac{a_{mn}}{1 + b_{mn} \times |D_{mn}|} \times sign(D_{mn})\,. \tag{2}$$

where, D_{mn} is the difference between the current pixel tone G_C and the local average which is averaged for the 5×5 pixels surrounding to the pixel in the original image. G_{mn} is the weighting function and defined with the magnitude and the sign of D_{mn}. D_{mn} outputs 0 for the even tone distribution of the averaging pixel area, positive values for tones changing like peak, and negative values for valley. When D_{mn} is zero, this means the area is flat in tone distribution and the average tone of the bilevel-toned image will have the similar characteristic to that of the Floyd et al. The coefficient a_{mn} of the weighting function G_{mn} controls the emphasizing level of edge reconstruction and b_{mn} protects edge emphasis from being excessive by steep tones change.

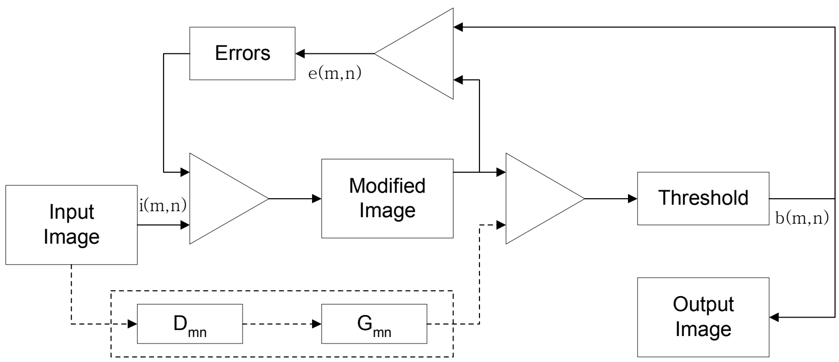

Fig. 1. The edge enhanced error diffusion to which the preprocessing filter is added

3 Evaluation

To evaluate the effect of the proposed edge enhanced preprocessing filter described in Section 2, the two filters of Floyd et al. and Eschbach et al. are compared with the proposed filter for Lena image. This paper adopts three measurement criteria for the objective comparison of them: RAPSD, edge correlation, and local average accordance. In this section, the three measurement criteria are first described, and then the results of comparison for Lena are presented.

3.1 Radially Averaged Power Spectrum Density for Display Error

The RAPSD is a measurement to determine how similar the original image and the bilevel-toned image are to each other [8]. The preferable bilevel-toned image should not have directive biases in pixel pattern and be radially symmetric. This criterion is tested for power spectrum. The power spectrum is defined as $\hat{P}(f)$ which conducts two-dimensional Fourier transform on bilevel-toned image, squaring of the result, and dividing it by the number of samples. Although $\hat{P}(f)$ is represented in three-dimension, one-dimensional figure can be presented for effective observation of characteristics by the frequency. The one-dimensional figure is made by partitioning power spectrum into circular rings of width Δ as shown in Fig. 2.

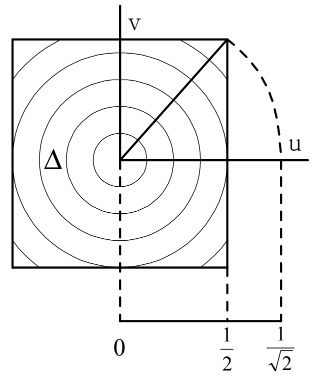

Fig. 2. Partitioning of power spectrum into unit circular rings

This paper constructs the preprocessing filter by utilizing the difference between a pixel and the local average to the surrounding area in the original image. Therefore, for the flat area in tones distribution, the effect of the preprocessing filter is generated little. In this paper, the display error is defined as the difference between the original image and the error diffused bilevel-toned image, and the RAPSD for the display error will be presented in the evaluation.

When the two-dimensional Fourier transform is designated by $\tau[\cdot]$, the power spectrum density is expressed like this:

$$\hat{P}(u,v) = \frac{1}{M \times N}\left|\tau\left[i(m,n) - b(m,n)\right]\right|^2 . \quad (3)$$

The power spectrum is partitioned into circular rings of the uniform width Δ on the basis of center of power spectrum as seen in Fig. 2. In the figure, it is noted that the circular frequency f_r is distant from the center of circular rings by $\Delta_r / \sqrt{2}$. The RAPSD $P_r(f_r)$ is obtained by integrating the power spectrum within the r -th circular ring area and dividing by the number of samples included in the area as follows:

$$P_r(f_r) = \frac{1}{N_r(f_f)} \sum_{i=1}^{N_r(f_f)} \hat{P}(u,v). \tag{4}$$

where, $N_r(f_r)$ is the number of samples within the r-th circular ring area.

3.2 Edge Correlation

The most important information is in edge area. Therefore, it has objectiveness in quality assessment to measure the correlation for edge area between bilevel-toned and original images. The measuring function C for edge correlation is designed as below:

$$D_I(i,j) = I_h(m,n) - I_h(m-i,n-j). \tag{5}$$

$$D_B(i,j) = B_h(m,n) - B_h(m-i,n-j). \tag{6}$$

$$C = \sum_{n=0}^{N-1}\sum_{m=0}^{M-1}\left(\sum_{i=-1}^{1}\sum_{j=-1}^{1} W_{ij} D_I(i,j) D_B(i,j)\right). \tag{7}$$

where, $I_h(m,n)$ is the original image and $B_h(m,n)$ the 7×7 low pass filter to filter out the bilevel-toned image and reconstruct the continuous-toned image [9]. W_{ij} is the weighting matrix for the directions of horizontal, vertical and diagonal. The rate of the diagonal values for the horizontal and vertical values is made by $1:\sqrt{2}$ and is normalized such that 0.1465 is made for the directions of horizontal and vertical, and 0.1035 for diagonal. The finally generated function C evaluates the representing performance for edge area of the bilevel-toned image to the original image. Large C means that the edge area of bilevel-toned image is consistent with the one of original image.

3.3 Local Average Accordance

The performance to preserve the average of local area in original image is important as well along with the one to maintain edge information. This performance is evaluated by the function to measure local average accordance between bilevel-toned and original images. The original image is divided into rectangles of a specific size and the local average of a rectangle is designated as L_{mI}. The bilevel-toned image is reconstructed by using the 7×7 low pass filter mentioned in Section 3.2 and the local average of it is denoted as L_{mB}. The L_{mI} and L_{mB} are formulated like these:

$$L_{mI} = \frac{1}{M^2}\sum_{i=0}^{M-1}\sum_{j=0}^{M-1} I_h(i,j). \tag{8}$$

$$L_{mB} = \frac{1}{M^2}\sum_{i=0}^{M-1}\sum_{j=0}^{M-1} B_h(i,j). \tag{9}$$

where, M^2 is the area to get the local averages. The accordance for local average is defined as follows:

$$A_{Lm} = \frac{1}{\frac{1}{N^2}\sum_{k=0}^{N-1}\sum_{l=0}^{N-1}\left(L_{mI}(k,l) - L_{mB}(k,l)\right)^2}. \quad (10)$$

where, N^2 is the number of local areas. The large A_{Lm} means that the local average of bilevel-toned image is consistent with that of original image.

3.4 Experimental Results

The bilevel-toned images generated by the filters of Floyd et al. and Eschbach et al. and the proposed filter are depicted in figures (a), (b) and (c) of Fig. 3, respectively. The figures are cut down from the Lena of original size to consider better resolution of the printed image.

(a) (b) (c)

Fig. 3. Bilevel-toned images generated by the filters of (a) Floyd et al. and (b) Eschbach et al. and (c) the proposed filter

The RAPSDs ($\Delta = 0.004$) for the display errors made between the original images and the bilevel-toned images for Lena are displayed in Fig. 4. In the figure (a) of Fig. 4, the low frequency range of f_r from 0 to 0.3 generates rare RAPSD and the high frequency range from 0.5 to 0.7 high RAPSD. Figure (b) of Fig. 4 reports the RAPSD for the display error by the filter of Eschbach et al. As seen in the figure, the RAPSD for the high frequency range from 0.5 to 0.7 has lower level than that of figure (a). Figure (c) of Fig. 4 shows the RAPSD for the display error by the proposed filter. To obtain the result, $a_{mn} = 2.5$ and $b_{mn} = 0.02$ are used for calculating G_{mn}. The RAPSD for the low frequency range from 0 to 0.2 is low as with figure (a), but over the upper frequency the RAPSD increases until 0.4. In the high frequency range from 0.5 to 0.7, the similar RAPSD to figure (b) is generated.

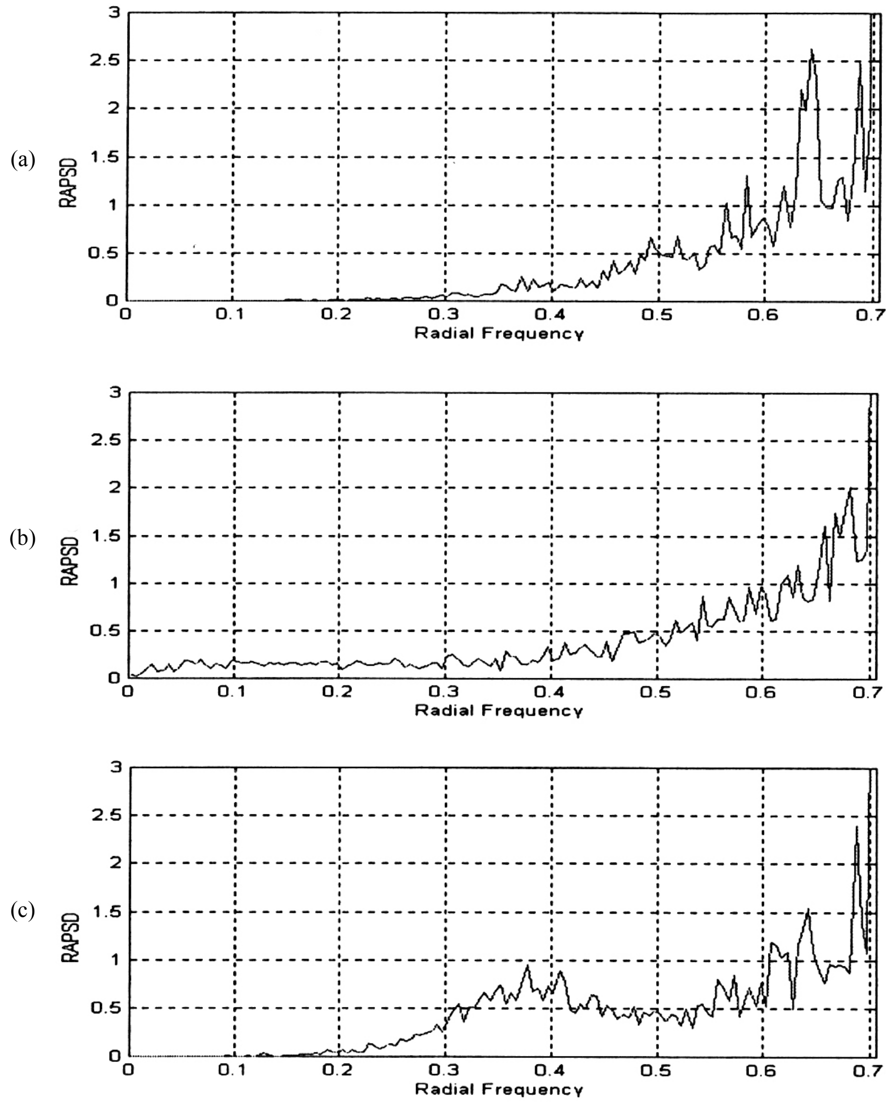

Fig. 4. RAPSD characteristics for the display errors by (a) the filter of Floyd et al.; (b) the filter of Eschbach et al.; (c) the proposed filter

The edge correlation and local average accordance for the bilevel-toned Lena image are recorded in Fig. 5 and Fig. 6, respectively. Fig. 5 presents the edge correlation values as to increasing observation distances for the three filters. In this figure, the values for the filters of Eschbach et al. and the proposed filter are greater than that of Floyd et al. The difference between the two groups decreases with increasing observation distance, but is recognizable when the bilevel-toned image is observed from 10 inches distance. Fig. 6 displays the local average accordance values as to increasing observation distances for all three filters. In this figure, the values for the filters of Floyd et al. and the proposed filter are better than those of Eschbach et al.

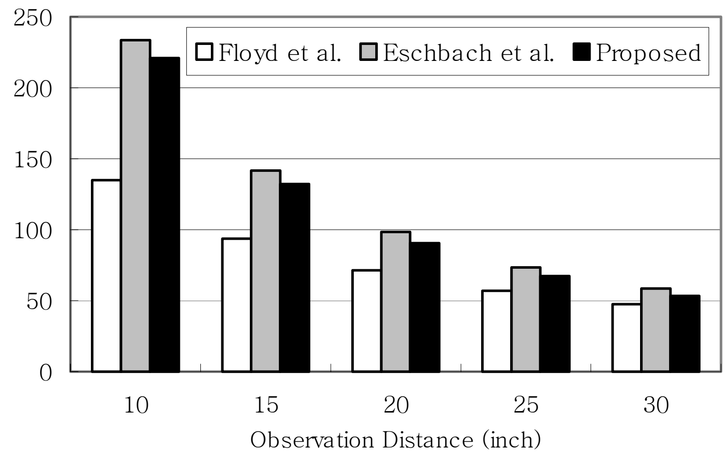

Fig. 5. Comparison of edge correlation values for all the filters

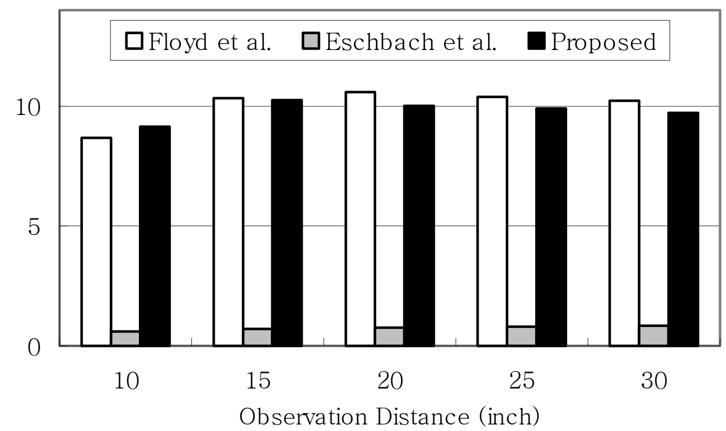

Fig. 6. Comparison of local average accordance values for all the filters

4 Discussion

The results in the aspects of visual, RAPSD for display error, edge correlation and local average accordance confirm an efficient improvement of the proposed filter compared with the filters of Floyd et al. and Eschbach et al. The filter of Eschbach et al. makes bilevel-toned image sharper than that of Floyd et al. does. However, the filter of Eschbach et al. considers little that the negative effect of the edge-enhancing method might cause to damage general information of original image. Compared with the method of Eschbach et al., the proposed filter can sustain general information as well as enhance edge information.

It is hard to be identified visually how much the filter of Eschbach et al. blurs the general information of Lena, although the visual investigation on Fig. 3 suggests both the filters of Eschbach et al. and the proposed filter improve the edge information of Lena over the bilevel-toned image by the filter of Floyd et al. Such a negative can be found out to compare the RAPSD in the low frequency rage from 0 to 0.2 of figure (b) of Fig. 4 with that of figure (c). It becomes clear when the local average accordance values made by the filters of Eschbach et al. and proposal are examined. As seen in Fig. 6, the distortion of the bilevel-toned image in general information was made seriously for the bilevel-toned Lena image by the filter of Eschbach et al.

The investigation for RAPSD and edge correlation convinces that the proposed filter generates more fine edge information than the filter of Floyd et al. does without losing general information. Figure (c) of Fig. 4 shows that in the high frequency rage from 0.5 to 0.7 the RAPSD of the proposed filter achieves the similar level to that of the filter of Eschbach et al. It is supported by Fig. 5, in which the edge correlation value of proposal at the distance of 10 inches does not show much difference from that of the filter of Eschbach et al., because edge correlation value presents an objective criterion about how much the edge information of original image is preserved into the bilevel-toned image. From the experimental evidences it can be argued that the proposed filter conducts more efficiently edge enhanced error diffusion than the filter of Eschbach et al. do.

5 Conclusion

So far this paper has studied the preprocessing filter emphasizing the edge information of original image based on the standard error diffusion by Floyd et al. with retaining general information. Applying the filter to Lena image and analyzing the bilevel-toned image specified that the sharper bilevel-toned image can be acquired over the error diffusion by Floyd et al. and the more general image over the error diffusion by Eschbach et al. From the experimental results, it can be finally concluded that the proposed filter presents superior properties than the filter of Floyd et al. for the high frequency range that includes most edge information in the original image and that of Eschbach et al. for the low frequency range that includes general information.

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