Halftoning via Error Diffusion using Circular Dot-overlap Model

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Abstract

Circular dot-overlap model is one of the simplest printer models, which is used to predict the actual gray levels of printed images. Model-based halftoning can produce print outputs which can render the gray levels of original input image more correctly and keep more detail in the outputs. Cluster-dot halftoning is a classical method used to minimize dot gain. In this paper, the model-based halftoning is executed via Error Diffusion using the hard circular dot-overlap printer model, and the cluster-dot halftoning is achieved through feed-back error diffusion. The main contributions of this paper are: first, we modify the model-based error diffusion by way of changing the computing method of equivalent gray values and incorporating edge enhancement information (in the following text, this modified model-based error diffusion is entitled Our Edge-enhanced Bias-reduction Error Diffusion); second, we combine the modified model-based error diffusion with the feed-back error diffusion to give Our Edge-enhance Bias-reduction Cluster-dot Error Diffusion. Using our new model-based error diffusion, we can obtain resulting images which reproduce the gray levels of the original input gray scale images accurately.

Keywords: *Image Processing, Halftoning, Error Diffusion, Cluster-dot Halftoning, Model-based halftonging, Feed-back Error Diffusion, Printer model, Edge enhancement*

1. Introduction

Digital gray scale halftoning is the process of transforming continuous-tone gray scale images (e.g., 8 bits per pixel) into bi-level images (e.g., 1 bit per pixel) with the same size. This process is necessary for printing or displaying with bi-level devices. There are three main classes of monochrome halftoning methods: iterative optimization methods[3][4][5], ordered dither[1] and error diffusion[2]. Iterative optimization methods consist of iterative approaches where several passes over the whole pixels of the intermediate halftone image are made to minimize the perceived error between the output halftone image and the input continuous-tone image. The perceived error is computed based on the human visual model (HVS) such as Gaussian filter. Direct binary search (DBS)[3] is one example of iterative methods. Ordered dither is a simple halftoning algorithm where an ordered dither is defined by a matrix of threshold values. To binarize a continuous-tone image, the ordered dither is periodically tiled over the image, and each pixel is compared with the corresponding threshold value. If the pixel is greater than the threshold, the binary value is set to 1; otherwise, it is set to 0. Error diffusion is the class of halftoning methods which needs to get information of neighboring pixels to determine the halftone state of a given pixel. In error diffusion, the halftoning errors of the neighboring determined pixels should be diffused to the given pixel according to some coefficients.

Model-based halftoning is a halftoning algorithm which is combined with some printer model. The purpose of printer model is to accurately predict the actual gray levels produced by a printer. Printers produce more or less circular dots that overlap adjacent spaces which are referred to as dot overlap, causing the perceived gray level to be darker than fraction of black dots. There are several kinds of printer models proposed in papers: circular dot-overlap model[8][10], tabular model[13][14], offset-centered model[9], and electrophotographic printer model[15], ink-jet printer model[11]. Circular dot-overlap printer model, which is one of the simplest printer models, assumes that the printer produces circularly shaped black dots, and assumes that the ink dots are saturated so that the overlapping areas do not get any darker (logical OR). Most printers produce black dots larger than the ideal print dot size, a phenomenon that is called dot gain, which distorts the gray levels of the printed output images. With the simplest circular dot-overlap printer model, these distortions are estimated by computing the gray level of each pixel of printed images as the covered area of the pixel by ink.

In U.S.Pat.No.5,463,472, the circular dot-overlap printer model was combined with error diffusion and a computing method of the equivalent gray level was proposed. Using the computing method of the equivalent gray level utilized in U.S.Pat.No.5,463,472, the equivalent gray value of the given pixel keeps getting updated before all its eight neighbours have been determined, which introduce some bias in the printed gray level and can't reproduce the gray levels of the original input image accurately. As the main contribution of this paper, we resolve this problem by modifying the computing method of the equivalent gray level. When there is no ink dot printing at the given pixel location, the equivalent gray value is computed as the percentage of the pixel area covered by the adjacent printed black dots; when there is a dot printing at the given pixel location, the equivalent gray value is not only computed as the given pixel size as in U.S.Pat.No.5,463,472, which is computed as the add-up areas of two parts: one part is the given pixel area, and another part is the area percentage of the neighbouring determined pixels covered by the ink dot printing at the given pixel.

In reference[16], a method of computing edge enhancement information is proposed. We alter this edge enhancement method a little to obtain the edge enhanced gray scale images before halftone the gray scale images using our modified model-based error diffusion. In the following part of this paper, we call our new halftoning method as Our Edge-enhanced Bias-reduction Error Diffusion.

A classical approach to decrease the phenomenon of dot gain is to cluster black dots so that the effect percentage of dot gain on perceived gray level is reduced. Feed-back error diffusion[6][7] is a halftoning method to generate cluster-dot halftone image by feeding back the neighboring determined halftone pixel values according to some weights. Feeding back the previous neighboring pixel values encourages the output at the current location to be the same as the determined outputs at the previous neighboring locations, which is the way to generate cluster dots.

Feed-back error diffusion generates output image which are much darker than original images. In this paper, we combine Our Edge-enhanced Bias-reduction error diffusion and the Feed-back error diffusion to encourage the advantages of them to reduce the dot gain and make the perceived output print images render the input continuous-tone images accurately in gray levels. In halftoning, the perceived gray levels of halftone images are estimated to be proportional to the fraction of black dots in the pattern. For an input gray scale image with constant gray level, we compute the perceived gray level of its corresponding output halftone image as the value of dividing the covered area of black dots by the image size.

The remainder of this paper is organized as follows. Section 2 reviews the traditional error diffusion method. In Section 3, we introduce the hard circular dot-overlap printer model and how to compute the equivalent gray levels, and introduce the model-based error diffusion. In Section 4, we introduce our edge-enhanced bias-reduction error diffusion and show some simulation results. In Section 5, we discuss the combined halftoning method of our edge-enhanced bias-reduction error diffusion and the feed-back error diffusion and show experimental results. Finally, we give our conclusion.

2. Error Diffusion

In this section, we will review the traditional error diffusion method[2] for the reader's benefit. Suppose that an original gray-scale image $A=(a_{i,j})$ of size $N\times N$ (for simplicity, we assume the image is square) is given, where $a_{i,j}$ denotes the intensity level at position $(i, j)(0\leq i,j\leq N-1)$ taking a real number in the range [0, 1]. The goal of halftoning is to find a binary image $A'=(a'_{i,j})$ of the same size that reproduces the tone and the details of the original image A, where each $a'_{i,j}$ is either 1(black) or 0(white).

Error diffusion[2] is one of the well known halftoning methods, which propagates the quantization errors to unprocessed neighboring pixels according to some fixed ratios. Pixels in the image are processed in a raster order, i.e., from left to right and top to bottom. The binary value of $a'_{i,j}$ is determined as follows:

$$a'_{i,j} = \begin{cases} 1, & \text{if } a_{i,j} > 0.5 \\ 0, & \text{otherwise} \end{cases}, \qquad e = a_{i,j} - a'_{i,j}$$

where $a_{i,j}$ is updated when any of its related neighbors has been processed, and e is the rounding error. Note that the threshold value 0.5 is selected such that the absolute value of the rounding error $|a_{i,j}-a'_{i,j}|$ is minimized. This point is used in our model-based error diffusion later.

The key idea of error diffusion is to compensate the rounding error to diffuse it over the unprocessed pixels around it with fixed ratios. Floyd and Steinberg[2] proposed a ratios matrix as follows:

$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 7/16 \\ 3/16 & 5/16 & 1/16 \end{pmatrix}$$

Using this matrix, the intensity levels of the neighboring unprocessed pixels of given pixel $a_{i,j}$ are updated by the diffusing error such that $a_{i,j+1} \leftarrow a_{i,j+1}+e\times 7/16$, $a_{i+1,j+1} \leftarrow a_{i+1,j+1}+e\times 1/16$, $a_{i+1,j} \leftarrow a_{i+1,j}+e\times 5/16$, $a_{i+1,j-1} \leftarrow a_{i+1,j-1}+e\times 3/16$. Since the sum of elements in the matrix is 1, the rounding error is diffused to the neighboring four pixels.

3. Model-based error diffusion

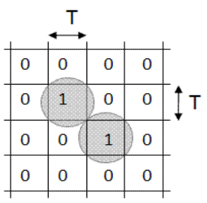
In this section, we introduce the error diffusion combined with the circular dot-overlap printer model. Circular dot-overlap model is one of the simplest printer models and assumes that printer produces circularly shaped black dots and the darkness of the printed ink dots are saturated so that the overlapping areas do not get any darker.

We suppose that an original gray scale image $B=(b_{i,j})$ and its corresponding halftone image $B'=(b'_{i,j})$ of size $N\times N$, where $0\le b_{i,j}\le 1$ and $b'_{i,j}=1$ (black) or $b'_{i,j}=0$ (white) at location (i, j) $(0\le i,j\le N-1)$. We also suppose that the equivalent gray scale image $P=(p_{i,j})$ of B', the value of $p_{i,j}$ is computed by the dot covered areas of $b'_{i,j}$.

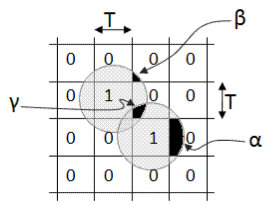
3.1. Circular dot-overlap model

The main purpose of this section is to review the circular dot-overlap printer model described in U.S.Pat.No.5,463,472.

Suppose the image pixels are squares and have size $T\times T$. Printers should print the minimal (ideal) dot of radius $T/\sqrt{2}$ to cover the whole pixel area which is shown in FIG.1 (a). Since the print dots overlap, the equivalent gray levels of halftone patterns at any pixel is dependent on the given pixel itself and its neighbors. It is reasonable to compute the equivalent gray level of a given halftone pixel in the 3×3 window, in which case there are $2^9=512$ kinds of halftone patterns. The equivalent gray value can be determined by three parameters α, β, and γ. These parameters are the ratios of the areas of the black shaded regions shown in FIG.1 (b) to the pixel area (T^2), where α denotes the covered areas generated by vertical or horizontal adjacent black dots, β denotes the covered areas generated by black dots which are not adjacent to any horizontal and vertical neighboring black dots, and γ denotes pairs of neighboring black dots in which one is a horizontal neighbor and another one is a vertical neighbor.



(a) Ideal print dots



(b) Circular dot-overlap model

Figure 1. Halftone pattern(denoted by the squares) and the print dots(denoted by the circular)

Let $\rho T/\sqrt{2}$ be the radius of the actual black dots. We assume that $1\le\rho\le\sqrt{2}$, because the black dots are large enough to cover a pixel square, but not so large that the black dots do not expand over the centers of the pixel's neighbors horizontally or vertically. Using the ratio ρ of the actual dot radius to the ideal dot radius $T/\sqrt{2}$, we can compute parameters α, β, and γ using the following formulas:

$$\alpha = \frac{1}{4}\sqrt{2\rho^2 - 1} + \frac{\rho^2}{2}\sin^{-1}(\frac{1}{\sqrt{2}\rho}) - \frac{1}{2}$$

$$\beta = \frac{\pi\rho^2}{8} - \frac{\rho^2}{2}\sin^{-1}(\frac{1}{\sqrt{2}\rho}) - \frac{1}{4}\sqrt{2\rho^2 - 1} + \frac{1}{4}$$

$$\gamma = \frac{\rho^2}{2}\sin^{-1}(\frac{\sqrt{\rho^2 - 1}}{\rho^2}) - \frac{1}{2}\sqrt{\rho^2 - 1} - \beta$$

For a typical printer $\rho \approx 1.25$, and this value results in $\alpha \approx 0.33$, $\beta \approx 0.03$ and $\gamma \approx 0.1$. The experimental results given in this paper are based on these values.

The equivalent gray value $p_{i,j}$ corresponding to $b'_{i,j}$ can be determined in a 3×3 window ($W_{i,j}$ denotes a 3×3 window where $b'_{i,j}$ is at the center) as follows:

$$p_{i,j} = F(W_{i,j}) = \begin{cases} 1, & \text{if } b'_{i,j} = 1 \\ n_1\alpha + n_2\beta - n_3\gamma, & \text{if } b'_{i,j} = 0 \end{cases}$$

where n_1 is the number of horizontal and vertical adjacent black dots, n_2 is the number of diagonally adjacent black dots and they are not adjacent to any horizontal and vertical neighboring black dots, n_3 is the number of pairs of neighboring black dots in which one is a horizontal neighbor and the other is a vertical neighbor.

3.2. Model-based error diffusion

In this subsection, we will review the model-based error diffusion proposed in the United States Patent No.5,463,472.

Model-based error diffusion proposed in the U.S.Pat.No.5,463,472 computed the equivalent gray level in the way as we introduced in Sec.3.1. As the characteristics of error diffusion, pixels are determined one by one. However, the equivalent gray level was computed based on the assumption that all the pixels had been determined. So, the unprocessed pixels are assumed to be zero and the equivalent gray values are modified as the neighbors pixels are determined, which introduce a bias in the gray levels of printed images and can't reproduce the original gray levels accurately.

Model-based error diffusion is the error diffusion (we introduced in Sec.2) combined with the circular dot-overlap printer model. We need to modify how we compute the quantization error. We assume $u_{i,j}$ is the value after the rounding error has been added to the original gray scale pixel value $b_{i,j}$, and we modify the equations given in Sec.2 as follows:

$$u_{i,j} = b_{i,j} + \sum_{m,n} c_{m,n}\ e^{i,j}_{i+m,j+n}$$

$$b'_{i,j} = \begin{cases} 1, & \text{if } u_{i,j} > 0.5 \\ 0, & \text{otherwise} \end{cases}$$

$$e^{i,j}_{m,n} = u_{m,n} - p^{i,j}_{m,n} \quad \text{for } (m,n) < (i,j)$$

where $c_{m,n}$ is the diffusing ratio of the rounding error, as the elements in the ratios matrix proposed by Floyd and Steinberg[2] (raster order):

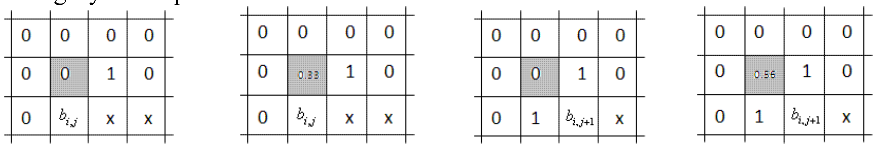
$$\begin{pmatrix} c_{-1,-1} & c_{-1,0} & c_{-1,1} \\ c_{0,-1} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} = \begin{pmatrix} 1/16 & 5/16 & 3/16 \\ 7/16 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

where $(m, n)<(i, j)$ means that (m, n) precedes (i, j) in the scanning order, and

$$p^{i,j}_{m,n} = F(W^{i,j}_{m,n}) \quad \text{for } (m,n) < (i,j)$$

where $W^{i,j}_{m,n}$ consists of $b'_{m,n}$ and its eight neighbors, but here the neighbors $b'_{k,l}$ have been determined only for $(k, l)<(i, j)$; they are assumed to be zero for $(k, l)\geq(i, j)$. Since only the dot-overlap contributions of the previous pixels can be used for computing the equivalent gray value, the previous rounding errors keep getting updated as more binary values are computed (the equivalent gray values of the past pixels keep getting updated before all their eight neighbors have been halftoned, and the rounding error is computed from the equivalent gray value, hence the rounding errors continue updating). Let us take an example to understand it more clearly. In

FIG.2 (a), suppose we are computing $b_{i,j}$. Let's only focus on the pixel which is emphasized with gray color for simplicity. We know this pixel should diffuse its rounding error multiplied by the ratio 5/16 to $b_{i,j}$. In order to get the rounding error, we need to compute the equivalent gray value at this pixel. We use symbol "x" to denote undetermined pixels. These undetermined pixels and $b_{i,j}$ are assumed to be 0 when we compute the equivalent gray value at the gray color pixel. In FIG.2 (b) we can see before $b_{i,j}$ is computed, the equivalent gray value is 0.33. FIG.2 (c) shows the bitmap after $b_{i,j}$ is determined. In FIG.2 (d) we in turn to compute $b_{i,j+1}$. Since more pixels are determined in the eight neighbors of the gray color pixel, the equivalent gray value at the gray color pixel has become 0.56.



(a) (b) (c) (d)

Figure 2. (a)Halftone pattern before $b_{i,j}$ is computed, (b)Equivalent gray value of the gray color pixel, (c)Halftone pattern after $b_{i,j}$ is computed, (d)Equivalent gray value of the gray color pixel.

4. Our edge-enhanced bias-reduction error diffusion

The main purpose of this section is to present our new halftoning method of edge-enhanced bias-reduction error diffusion.

As we discussed above in Sec.3.2 about the model-based error diffusion, the rounding error and printer model output depend on the pixel location (i, j). The assumption that the undetermined pixels are white leads to some bias in the gray levels of the printed image. In this section, we will propose our computing method of the equivalent gray value. We assume $B=(b_{i,j})$ $(0\leq i,j\leq N-1)$ is the original gray scale image, $EB=(Eb_{i,j})$ $(0\leq i,j\leq N-1)$ is the edge enhanced gray scale image, $B'=(b'_{i,j})$ $(0\leq i,j\leq N-1)$ is the halftone image from EB, and $P=(p_{i,j})$ $(0\leq i,j\leq N-1)$ is the equivalent gray scale image of B'.

The target of our edge-enhanced bias-reduction error diffusion is to eliminate the bias and enhance the edges. Our new halftoning method consists of two steps as follows:

Step 1 Generate the edge enhanced image EB from the original gray scale image B.

Step 2 Using our bias-reduction error diffusion, generate the halftone image B' from the edge enhanced gray scale image EB.

Generate edge enhanced gray scale image

In reference[16], a method of computing edge enhancement information is proposed. In this part, we modify this method and give our edge enhanced gray scale images. Suppose $(2s+1)\times(2s+1)$ is the local area in the original gray scale image B and $V=(v_{i,j})$ $(0\leq i,j\leq N-1)$ is the visual error image which is computed as follows:

$$\overline{b}_{i,j}=\frac{1}{(2s+1)^2}\sum_{k=-s}^{s}\sum_{l=-s}^{s}b_{i+k,j+l}\quad,\qquad v_{i,j}=b_{i,j}-\overline{b}_{i,j}$$

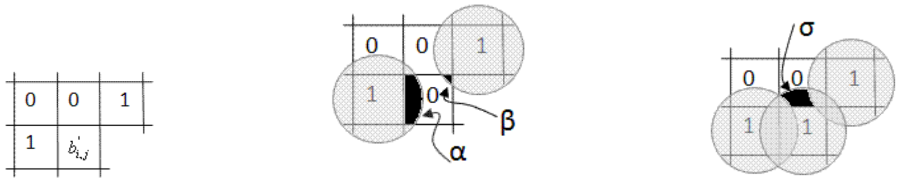
After we get the visual error image V, we can obtain the edge enhanced gray scale image as follows:

$$Eb_{i,j}=b_{i,j}+w\times v_{i,j}$$

where w is the weight used to control the edge enhancement. All the experimental results given in this paper using $w=3$ and $s=1$. If an original gray scale image has constant gray value, its edge enhanced gray scale image equals its original gray scale image.

Using our bias-reduction error diffusion for edge enhanced gray scale image

Our bias-reduction error diffusion still bases on the circular dot-overlap model. In this part, we modify the computing way of the equivalent gray level of a given halftone pixel in a window consisting of five pixels, four of which are the neighboring determined pixels and the other one is the given pixel which we are computing, as shown in FIG.3(a). When there is no dot printing at the given pixel location, the equivalent gray level is computed as the covered area of the given pixel by its four neighboring determined pixels, as shown in FIG.3(b); when there is dot printing at the given pixel location, the equivalent gray level is computed by two parts: one part is the pixel area, and another part is the covered areas of its four neighboring determined pixels only generated by the black dot printed at the given pixel location as shown in FIG.3(c).



(a)computing window (b)covered area when $b'_{i,j}=0$ (c)covered area when $b'_{i,j}=1$

Figure 3. Computing window and the covered areas

The equivalent gray value of $p_{i,j}$ corresponding to $b'_{i,j}$ is computed as follows:

$$p_{i,j} = \begin{cases} 1+\sigma, & \text{if } b'_{i,j} = 1 \\ n_1\alpha + n_2\beta - n_3\gamma, & \text{if } b'_{i,j} = 0 \end{cases}$$

As before, where n_1 is the number of horizontal and vertical adjacent black dots, n_2 is the number of diagonally adjacent black dots and they are not adjacent to any horizontal and vertical neighboring black dots, n_3 is the number of pairs of neighboring black dots in which one is a horizontal neighbor and the other is a vertical neighbor. Also, σ denotes the covered ratio of areas of neighboring four determined pixels which is only generated by the dot printing at the given pixel location and σ can be computed by α, β and γ. The covered area σ cannot be compensated in the future, which means the gray level error generated by σ cannot be propagated to the unprocessed pixels. Hence it should be considered currently when we are computing the given pixel. By this way, the printed image of the halftone image generated by our bias-reduction error diffusion can keep the gray levels of the original input image accurately.

A computing window of five pixels has $2^5=32$ kinds of halftone patterns. We compute all the equivalent gray values of these 32 patterns, and store them in a Look-Up-Table (LUT). Thus the halftone image $B'=(b'_{i,j})$ is determined as follows:

$$b'_{i,j} = \begin{cases} 1, & \text{if } Eb_{i,j} > T \\ 0, & \text{otherwise} \end{cases}, \qquad T = \frac{p^{on}_{i,j} + p^{off}_{i,j}}{2}$$

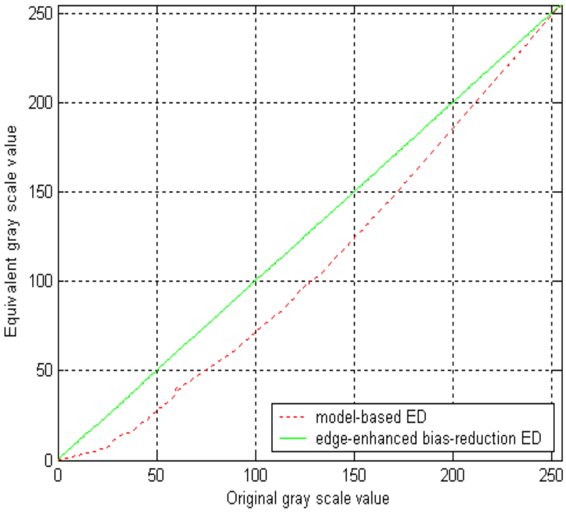
where $p^{on}_{i,j}$ denotes the equivalent gray value if $b'_{i,j}=1$ and $p^{off}_{i,j}$ denotes the equivalent gray value if $b'_{i,j}=0$. Hence it means if the updated value $Eb_{i,j}$ is more close to $p^{on}_{i,j}$, a dot is printed; otherwise no dot is printed at the given pixel location. The value of $p^{on}_{i,j}$ and $p^{off}_{i,j}$ are got from the LUT, where we have stored all the possible value of $p_{i,j}$.

The quantization error is computed as:

$$e = \begin{cases} Eb_{i,j} - p^{on}_{i,j}, & \text{if } b'_{i,j} = 1 \\ Eb_{i,j} - p^{off}_{i,j}, & \text{if } b'_{i,j} = 0 \end{cases}$$

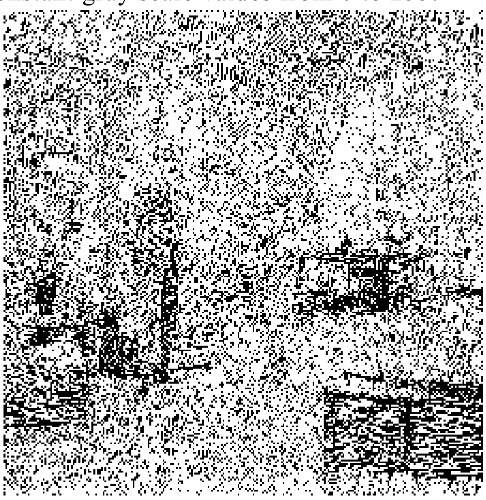
This error is propagated to the neighboring unprocessed pixels according to a matrix of ratios. The experimental results given in this section are obtained using the ratio matrix given in Sec.2, and the neighboring unprocessed pixels are updated such that $Eb_{i,j+1} \leftarrow Eb_{i,j+1}+e\times 7/16$, $Eb_{i+1,j+1} \leftarrow Eb_{i+1,j+1}+e\times 1/16$, $Eb_{i+1,j} \leftarrow Eb_{i+1,j}+e\times 5/16$, and $Eb_{i+1,j-1} \leftarrow Eb_{i+1,j-1}+e\times 3/16$.

In FIG.4 we show the equivalent gray scale values and halftone images generated by model-based error diffusion introduced in Sec.3.2 and our edge-enhanced bias-reduction error diffusion. FIG.4(a) shows the equivalent gray scale values for halftone images generated by model-based error diffusion and our edge-enhanced bias-reduction error diffusion from gray scale images with constant gray scale values from 0 to 255. In order to get the equivalent gray scale values, we prepare gray scale images of size 256×256 with constant values from 0 to 255, and halftone these images using model-based error diffusion and our edge-enhances bias-reduction error diffusion. For the generated halftone image of each gray scale value, we compute the total covered area of black dots using the circular dot-overlap model introduced in Sec.3.1, and divide this total covered area by the image size to get the corresponding equivalent gray scale value. In FIG.4(a), we can see the equivalent gray scale values of halftone images generated by our edge-enhanced bias-reduction error diffusion and the original gray scale values almost make a straight line (the green line), which means our halftoning method can reproduce the original gray scale values accurately. FIG.4(c) and FIG.4(d) show the halftone images obtained by model-based error diffusion and our edge-enhanced bias-reduction error diffusion from the original gray scale image shown in FIG.4(b) of size 512×512. Comparing FIG.4(c) and FIG.4(d), we can see the halftone image of FIG.4(d) has more details than that of FIG.4(c). For example, the man's eyes, the carved side of the table behind the man, the picture on the wall, and so on look clearer in FIG.4(d) than that in FIG.4(c).

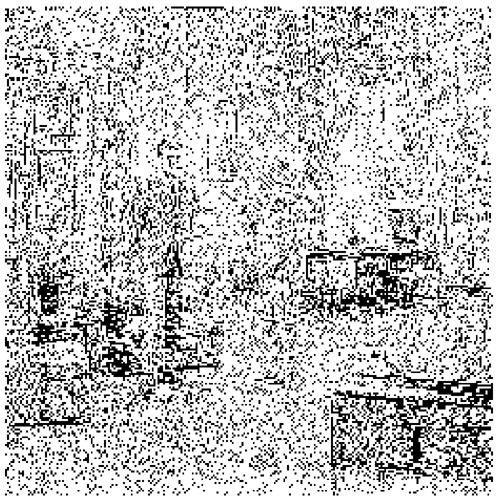


(a).Equivalent gray scale values for halftone images generated from gray scale images with constant gray scale values from 0 to 255.

(b).Original gray scale image (512×512).



(c).Halftone image by Model-based Error Diffusion introduced in Sec.3.2 (512×512).



(d).Halftone image by Our Edge-enhanced Bias-reduction Error Diffusion (512×512).

Figure 4. Equivalent gray scale values and halftone images generated by Model-based Error Diffusion and Our Edge-enhanced Bias-reduction Error Diffusion.

5. Our edge-enhanced bias-reduction cluster-dot error diffusion

In this section, we will introduce our edge-enhanced bias-reduction cluster-dot error diffusion which combines our edge-enhanced bias-reduction error diffusion and the feed-back error diffusion.

Feed-back error diffusion is used to generate cluster-dot halftone outputs that decrease the dot gain by clustering the black dots, but the print outputs are still perceived much darker than the original input gray scale images. Our edge-enhanced bias-reduction error diffusion can generate print outputs which reproduce the original gray scale levels accurately, and our edge-enhanced bias-reduction error diffusion is very easy to be combined with other error diffusion method.

We combine our edge-enhanced bias-reduction error diffusion discussed in Sec.4 with the Feed-back error diffusion[6]. By feeding back the neighboring determined pixel values, the given pixel has the trend to be the same as its past neighbors, in which way our edge-enhanced bias-reduction cluster-dot error diffusion can generate cluster dots. The feeding back values are controlled by some weights.

We continue to assume $EB=(Eb_{i,j})$ is the edge enhanced gray scale image, $B'=(b'_{i,j})$ is the halftone outputs of image EB and $P=(p_{i,j})$ is used to save the equivalent gray scale value of the halftone output patterns, where $0\leq i,j\leq N-1$. Here gray scale value $Eb_{i,j}$ keeps getting updated when there is rounding error diffusing to the gray scale pixel at location (i, j). The halftone pixel value $b'_{i,j}$ is determined by our edge-enhanced bias-reduction cluster-dot error diffusion as follows:

$$b'_{i,j} = \begin{cases} 1, & \text{if } Eb_{i,j} + H > T \\ 0, & \text{otherwise} \end{cases}$$

$$T = \frac{p^{on}_{i,j} + p^{off}_{i,j}}{2}$$

$$H = \sum_{m,n} h_{m,n} b'_{i+m,j+n}$$

where T is the threshold value, $p^{on}_{i,j}$ is the equivalent gray scale value if a black dot is printed at the current location and $p^{off}_{i,j}$ is the equivalent gray scale value when there is no black dot printing at the current pixel. H is the feeding back value from the neighboring determined halftone pixels, and $h_{m,n}$ is the feeding back weight, for example the element given in the following weights matrix[6]:

$$\begin{pmatrix} 0 & h_{-1,0} \\ h_{0,-1} & 0 \end{pmatrix} = \begin{pmatrix} 0 & 1/2 \\ 1/2 & 0 \end{pmatrix}$$

The feeding back value H is computed as $H=b'_{i-1,j}\times 1/2+b'_{i,j-1}\times 1/2$. The feeding back value just affects the determining condition, and it doesn't affect the halftoning error. The halftoning error is still computed as:

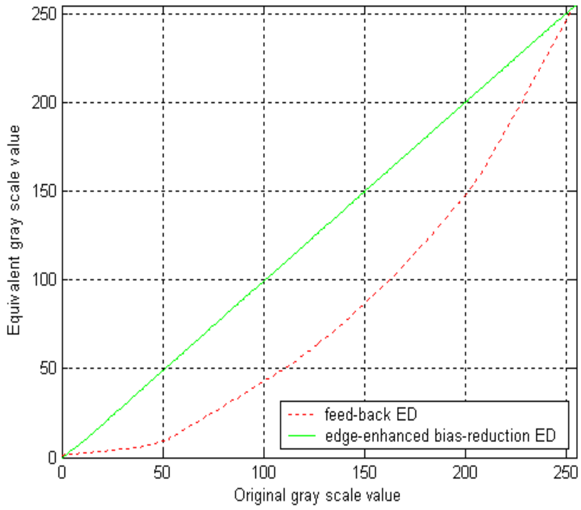
$$e = \begin{cases} Eb_{i,j} - p^{on}_{i,j}, & \text{if } b'_{i,j} = 1 \\ Eb_{i,j} - p^{off}_{i,j}, & \text{if } b'_{i,j} = 0 \end{cases}$$

After that, the quantization error is diffused to the neighboring unprocessed pixels. Here we show another example of error diffusing ratios matrix[6]:

$$\begin{pmatrix} 0 & 1/2 \\ 1/2 & 0 \end{pmatrix}$$

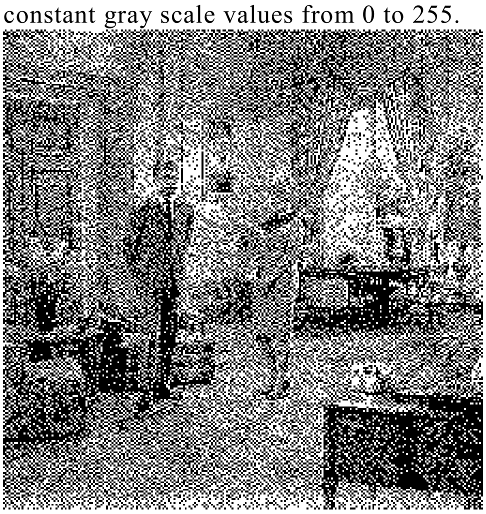
The unprocessed pixels are updated as $Eb_{i,j+1} \leftarrow Eb_{i,j+1}+e\times 1/2$ and $Eb_{i+1,j} \leftarrow Eb_{i+1,j}+e\times 1/2$. Here we can see the value $Eb_{i,j}$ is updated whenever there is error diffusing to it.

In FIG.5 we show the equivalent gray scale values and halftone images generated by Feed-back error diffusion and our edge-enhanced bias-reduction cluster-dot error diffusion. FIG.5(a) shows the equivalent gray scale values for halftone images generated by Feed-back error diffusion and our edge-enhanced bias-reduction cluster-dot error diffusion from gray scale images with constant gray scale values from 0to 255. In order to get the equivalent gray scale values, we prepare gray scale images of size 256×256 with constant values from 0 to 255, and halftone these images using Feed-back error diffusion and our edge-enhances bias-reduction cluster-dot error diffusion. For the generated halftone image of each gray scale value, we compute the total covered area of black dots using the circular dot-overlap model introduced in Sec.3.1, and divide this total covered area by the image size to get the corresponding equivalent gray scale value. In FIG.5(a), we can see the equivalent gray scale values of halftone images generated by our edge-enhanced bias-reduction error diffusion and the original gray scale values almost make a straight line (the green line), which means our halftoning method can reproduce the original gray scale values accurately. FIG.5(c) and FIG.5(d) show the halftone images obtained by Feed-back error diffusion and our edge-enhanced bias-reduction cluster-dot error diffusion from the original gray scale image shown in FIG.5(b) of size 512×512. Comparing FIG.5(c) and FIG.5(d), we can see the halftone image of FIG.5(d) has more details than that of FIG.5(c). For example, the woman's face, the eye-shape pattern on the top of the curtain, the carved side of the table behind the man, the picture on the wall, and so on look clearer in FIG.5(d) than that in FIG.5(c).

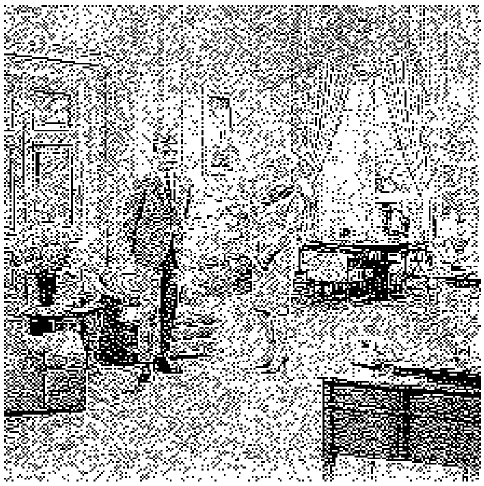


(a).Equivalent gray scale values for halftone images generated from gray scale images with constant gray scale values from 0 to 255.

(b).Original gray scale image (512×512).



(c).Halftone image by Feed-back Error Diffusion (512×512).



(d).Halftone image by Our Edge-enhanced Bias-reduction Cluster-dot Error Diffusion (512×512).

Figure 5. Equivalent gray scale values and halftone images generated by Feed-back Error Diffusion and Our Edge-enhanced Bias-reduction Cluster-dot Error Diffusion.

6. Conclusion

In this paper, we have presented our edge-enhanced bias-reduction error diffusion and our edge-enhanced bias-reduction cluster-dot error diffusion. Our new halftoning methods compensated the quantization error correctly to control the halftone image not to be printed darker than the original input gray scale image. From the equivalent gray scale values of our halftoning method, comparing with other dot-gain-suppress halftoning methods, we can see our halftoning methods can render the original gray scale values accurately.

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