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# A gradient-based adaptive error diffusion method with edge enhancement

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ABSTRACT

This paper presents a gradient-based adaptive error diffusion method with edge enhancement effect while preserving the smoothness effect. The proposed method not only can modulate the threshold in halftoning dynamically but also can determine the weights of the error diffusion filter adaptively to diffuse the quantization error to neighboring pixels properly. Under six testing images, experimental results demonstrate that our proposed new error diffusion method has a good compromise between the edge enhancement effect in the halftone image and the image quality effect in the corresponding inverse halftone image when compared to the methods by Floyd–Steinberg, Eschbach and Knox, Hwang et al., Li, and Feng et al., but it has some execution-time degradation.



## 1. Introduction

Halftoning (Ulichney, 1987) is a process which transforms gray images into halftone images. It has been widely used in publishing applications, such as newspapers, books and magazines. Error diffusion (Floyd & Steinberg, 1976; Javis & Roberts, 1976; Stucki, 1981) is a popular approach in halftoning and has better tradeoff between the visual quality and the computational effort when compared to the other approaches like the dithering (Bayer, 1973) and the dot diffusion (Meşe & Vaidyanathan, 2000). In 1976, Floyd and Steinberg (1976) presented the first error diffusion method. Their method produces halftone images by diffusing the quantization error of the current pixel to neighboring pixels and usually the quantizer is played as a threshold specified by the mid-gray value. In the same year, Javis and Roberts (1976) presented another error diffusion method independently. Afterwards, several variants of error diffusion methods (Chang & Allebach, 2005; Damera-Venkata & Evans, 2001; Eschbach & Knox, 1991; Feng, Lin, & Chu, 2007; Huang, Su, & Kuo, 2008; Hwang, Kang, & Lee, 2004; Kolpatzik & Bouman, 1992; Li, 2006; Li & Allebach, 2004; Wong, 1996) have been developed.

Among these developed error diffusion methods, some error diffusion methods (Eschbach and Knox, 1991; Feng et al., 2007; Hwang et al., 2004; Li, 2006) emphasize the edge enhancement effect. Eschbach and Knox (1991) presented a threshold-modulation approach by using a fixed multiplicative parameter. Hwang et al. (2004) adopted a weighting function to modulate the threshold. Recently, Feng et al. (2007) proposed an interesting method that the received error of each pixel can be dynamically adjusted according to the gradient magnitude. Li (2006) proposed a hard-decision approach for adjusting filer coefficients to achieve edge enhancement effect. In the first variant of his method, the quantization error of the current pixel is not diffused to the neighboring pixels when the neighboring pixels contain edge pixels. Since the diffusion process is stopped at the edge boundary, it can alleviate the edge blurring effect caused by the error diffusion. In the second variant of his method, it considers an adaptive way to diffuse the quantization error. For each pixel, if the neighboring pixels contain no edge pixels, the conventional error diffusion process is applied; otherwise, only edge pixels are considered in the diffusion process. The motivation of this research is to present a error diffusion method with better compromise between the image quality effect and the edge enhancement effect when compared to five previous methods.

In this paper, a gradient-based adaptive error diffusion (GAED) method is presented. The proposed new GAED method not only can modulate the threshold in halftoning dynamically but also can determine weights of the error diffusion filter adaptively based on the gradient and orientation information extracted from the subimage covered by the filter. The threshold-modulation process is realized by a function whose arguments are concerned with the

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gradient magnitude and orientation of the current pixel and the neighboring pixels of the current pixel. After the current pixel is quantized to a halftone pixel by using the determined threshold, an adaptive error diffusion filter whose weights are determined adaptively is used to diffuse the quantization error to neighboring pixels properly. In order to evaluate the edge enhancement and image quality performance of the concerned error diffusion methods, the Gaussian lowpass filter (Gonzalez and Woods, 2002) is used to reconstruct the gray image from the resultant halftone one. Based on the reconstructed gray image, the edge correlation and the peak signal-to-noise ratio (PSNR) are used to measure the edge enhancement effect and image quality effect, respectively. Based on six typical testing images, experimental results demonstrate that our proposed GAED method has better edge enhancement performance while preserving the smoothness effect when compared to Floyd–Steinberg error diffusion method, the method by Eschbach and Knox, the method by Hwang et al., the method by Feng et al., and the second variant by Li. Furthermore, experimental results also show that the PSNR performance of the proposed GAED method is better than that of the method by Eschbach and Knox, the method by Hwang et al., the method by Li, and the method by Feng et al., but only has some degradation when compared to Floyd–Steinberg error diffusion method.

The remainder of this paper is organized as follows. In Section 2, we review the Floyd–Steinberg error diffusion method. In Section 3, our proposed GAED method is presented. In Section 4, some experimental results are carried out to demonstrate the compromised advantage of our proposed GAED method between the image quality and the edge enhancement effect. In Section 5, some concluding remarks are addressed.

## 2. Survey of Floyd–Steinberg error diffusion method

Before introducing Floyd–Steinberg error diffusion model, some notations are defined. Let the input gray image and output halftone image be denoted by $G$ and $H$, respectively, where the pixel located at $(x, y)$ in $G$ is denoted by $G(x, y)$; the pixel located at $(x, y)$ in $H$ is denoted by $H(x, y)$. For convenience, the gray value of $G(x, y)$ is normalized to [0, 1] and the value of $H(x, y)$ is quantized to 0 or 1. In addition, $W(x, y)$ denotes the weights of the error diffusion filter.

Fig. 1 shows the block diagram of Floyd–Steinberg error diffusion method. The fixed weights of the error diffusion filter in Floyd–Steinberg model are shown in Fig. 2 where the pixel located at $(x, y)$ denotes the current pixel and the neighboring weights are $W(x, y+1) = \frac{7}{16}$, $W(x+1, y-1) = \frac{3}{16}$, $W(x+1, y) = \frac{5}{16}$, and $W(x+1, y+1) = \frac{1}{16}$. Based on the row-major scanning order, Floyd–Steinberg error diffusion method consists of the following three steps:

**Step 1** : According to the threshold $T$, the halftone pixel $H(x, y)$ can be determined by

$$H(x,y) = \begin{cases} 0, & \text{if } G(x,y) < T \\ 1, & \text{if } G(x,y) \geqslant T \end{cases}$$

**Step 2** : Calculate the quantization error $e(x, y)$ by

$$e(x,y) = G(x,y) - H(x,y)$$

**Step 3** : Diffuse the quantization error $e(x, y)$ to neighboring pixels based on the following equation:

$$G(x+k, y+l) = G(x+k, y+l) + e(x,y) \times W(x+k, y+l)$$

where $(k, l) \in \{(0, 1), (1, -1), (1, 0), (1, 1)\}$. If the current pixel is the last pixel in the scanned image then stop the algorithm; otherwise, go to Step 1.

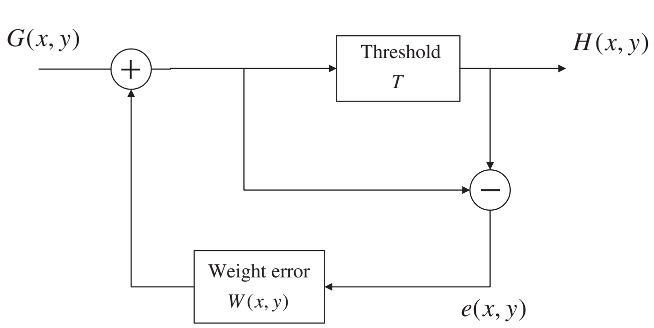


**Fig. 1.** The block diagram of Floyd–Steinberg error diffusion.

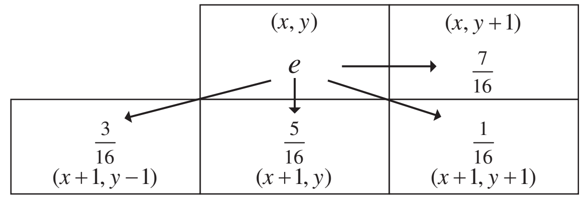


**Fig. 2.** The fixed weights of the error diffusion filter in Floyd–Steinberg model.

## 3. Proposed gradient-based adaptive error diffusion (GAED) method

After introducing Floyd–Steinberg error diffusion method, this section presents the proposed GAED method with a good compromise between the image quality and the edge enhancement effect. We first introduce how to apply Sobel edge detector (Gonzalez and Woods, 2002) to the input gray image to extract the gradient and the orientation information. The two $3 \times 3$ masks of Sobel operator are shown in Fig. 3a and b, respectively, for obtaining the vertical gradient and the horizontal gradient. Based on the two obtained gradients $\nabla_x G(x, y)$ and $\nabla_y G(x, y)$ for $G(x, y)$, the gradient magnitude $MG(x, y)$ and the gradient orientation $OG(x,y)$ can be computed by

$$MG(x,y) = \sqrt{(\nabla_x G(x,y))^2 + (\nabla_y G(x,y))^2}$$

and

$$OG(x,y) = \tan^{-1} \frac{\nabla_x G(x,y)}{\nabla_y G(x,y)}.$$

In the proposed GAED method, all the gradient magnitudes of the current pixel and the neighboring pixels are used to determine the modulated threshold of the current pixel. After the current pixel is quantized to a halftone pixel by using the determined modulated threshold, an adaptive error diffusion filter, whose weights are determined by using the gradient magnitudes and gradient

| | | |
|---|---|---|
| -1 | -2 | -1 |
| 0 | 0 | 0 |
| 1 | 2 | 1 |

(a)

| | | |
|---|---|---|
| -1 | 0 | 1 |
| -2 | 0 | 2 |
| -1 | 0 | 1 |

(b)

**Fig. 3.** Two $3 \times 3$ Sobel masks. (a) The mask $G_x$ for obtaining vertical gradient. (b) The mask $G_y$ for obtaining horizontal gradient.