Error Diffusion for CMYK Color Images

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Abstract

Error Diffusion is an important halftoning method that has been used in many color printers. A four color (CMYK) printing process is generally more desirable than a three color (CMY) one in terms of image sharpness, color gamut, neutral color reproduction and ink consumption. However, the treatment of black ink is a challenging problem for error diffusion. A straightforward approach is to process K component and CMY ones independently. Whether a black dot is placed on top of CMY dots or printed on white paper is a random event. This results in poor image quality and waste of ink.

In this paper, we present a new color error diffusion algorithm for CMYK images. It correlates the K component with CMY ones in such a way that overlapping of K dots and CMY dots is discouraged. Compared to the conventional error diffusion, it has the similar computational complexity, but provides much better image quality and consumes less ink.

1. Introduction

Error diffusion is an important technique for digital halftoning.[1,2] It has been applied in many black & white, as well as color printers. Roughly speaking, error diffusion can be considered as a 2-D extension of sigma-delta modulation. The output of error diffusion is produced by quantizing the modified input, which is defined to be the input signal plus the sum of the weighted past quantization errors. For color images, the input, modified input, output, and error signals are all vectors. According to the underlying quantization methods, color error diffusion can be classified into two types, namely, vector error diffusion and scalar error diffusion.

Color images can be produced using a three color (CMY) process, or a four color (CMYK) one.[3] The additional black ink introduced in the four color printing is desirable for several reasons. First, the process consumes less ink. This not only reduces ink cost, but also alleviates paper wet problems in inkjet printing. Secondly, black ink usually provides better image quality for black and white images, in particular, for black text. Thirdly, the addition of black ink expands the printer color gamut. It improves detail rendition and shadow contrast. The process of converting CMY to CMYK is usually called under color removal and gray component replacement (UCR/GCR).

The treatment of the black ink is a challenging problem for error diffusion. A straightforward approach is to process black component and CMY ones independently. Whether a K dot is placed on top of a CMY dot (K-dot-on-CMY-dot, or simply dot-on-dot) or printed on white paper (K-dot-off-CMY-dot, or simply dot-off-dot) is a random event. It introduces noise and artifacts in the image and requires extra ink.

In this paper, we present a new color error diffusion algorithm for CMYK images. It correlates the black component with CMY components in such a way that dot-on-dot is minimized. It provides much better image quality and consumes less ink.

This paper is organized as follows. In Section 2, an introduction is presented on color error diffusion. Section 3 describes the new algorithm. A summary is given in Section 4.

2. Color Error Diffusion

Let **i**(m,n) and **b**(m,n) denote the input and output vectors in CMYK space for error diffusion at pixel (m,n), respectively. It is assumed that $b_d(m,n)$ has a binary value of 0 or 1, and $i_d(m,n)$ has a value in the range of [0,1], where $b_d(m,n)$ and $i_d(m,n)$ are the components of **i**(m,n) and **b**(m,n), respectively. The color error diffusion algorithm can be characterized by the following steps:

$$\mathbf{i}^*(m,n) = \mathbf{i}(m,n) + \Sigma_{k,r}\, \mathbf{e}(m\text{-}s,n\text{-}t) \times a(s,t) \qquad (1)$$

$$\mathbf{b}(m,n) = Q[\mathbf{i}^*(m,n)] \qquad (2)$$

$$\mathbf{e}(m,n) = \mathbf{i}^*(m,n) - \mathbf{b}(m,n), \qquad (3)$$

where $\mathbf{i}^*$(m,n) is the modified input, Q[.] is the quantization operation, **e**(m,n) is the quantization error, and a(s, t) is the weight for error propagation in the (s, t) direction. A combination of steps (1) and (3) yields

$$\mathbf{e}(m,n) = \mathbf{i}(m,n) - \mathbf{b}(m,n) + \Sigma_{k,r}\, \mathbf{e}(m\text{-}s,n\text{-}t) \times a(s,t). \qquad (4)$$

The frequency representation of (4) is given by

$$[\mathbf{I}(z_1, z_2) - \mathbf{B}(z_1, z_2)] = \mathbf{E}(z_1, z_2)\, F(z_1, z_2), \qquad (5)$$

which shows the system error [$\mathbf{i}(m, n) - \mathbf{b}(m, n)$] is a filtered version of the quantization error. The linear filter $F(z_1, z_2)$ is a high-pass filter typically with a zero at the DC. As a result, the average value of the image is usually maintained during the error diffusion process and the additional noise is "blue" in nature.[2] The quantization operation in (2) is defined as

$$Q[\mathbf{i}^*] = \arg\min_{\mathbf{b}} \text{distance}\,[\mathbf{b}, \mathbf{i}^*]. \tag{6}$$

The optimization in (6) is subject to the constraints that the components of **b** are binary. In the case that an Euclidean distance measure is applied, the minimization can be simply performed independently for each separation. This results in scalar quantization given as follows:

$$b_d = \begin{cases} 1, & \text{if } i^*_d > 0.5; \\ 0, & \text{otherwise.} \end{cases} \tag{7}$$

For better image quality, it is usually beneficial to consider all (or several) image components together to perform vector quantization.[4-7] The distance measure for a three color CMY process typically correlates to the human visual systems. However, the extension to four color CMYK error diffusion is non-trivial. A straightforward approach is to process black ink and CMY ones independently. K component is scalar-quantized, while CMY components are error diffused either using scalar quantization, or vector quantization. Specifically,

$$b_K = \begin{cases} 1, & \text{if } i^*_K > 0.5; \\ 0, & \text{otherwise.} \end{cases} \tag{8}$$

and

$$\underline{\mathbf{b}} = \arg\min_{\underline{\mathbf{b}}} \text{distance}\,[\underline{\mathbf{b}}, \underline{\mathbf{i}}^*], \tag{9}$$

where vectors $\underline{\mathbf{b}}$ and $\underline{\mathbf{i}}^*$ contain the CMY components of **b** and $\mathbf{i}^*$, respectively.

Two problems arise in this simple naive approach. First, noise and artifacts are introduced. Second, extra ink is required. This can be best explained by the following simple example, in which the contone input is a uniform dark cyan image with

$$i_C = 0.5;\ i_M = 0;\ i_Y = 0;\ \text{and } i_K = 0.5, \tag{10}$$

for all pixels. The output halftone has half of the pixels "on" and half of the pixels "off" for C and K color separations. The appearance of the image is then determined by the relative positions of the "on" and "off" pixels. Let's consider two extreme configurations. The first is the dot-off-dot case, where all the black pixels and cyan pixels are printed next to each other. There is no white space. This is the ideal situation as the average output color matches the input. The second is the dot-on-dot case, in which each black dot overlaps a cyan dot. This leaves half of the pixels white. Since a black dot on a cyan dot looks largely black, the output image has an appearance of 50% gray instead of dark cyan. If K and C components are halftoned independently, there is no control which case will happen. Quite often, we have something in between. The output switches from one pattern to another in different image regions. This results in alternation in color. Depending on the scale and the distribution of the color variation, it may appear as noise, or as color patches. Another consequence of the naïve approach is the requirement of excess ink. Since dot-on-dot reduces the number of effective cyan dots, the output image looks less saturated than it should be. As compensation, the cyan input value has to be raised during color calibration. This increases ink consumption.

3. Proposed Algorithm

CMYK contone images sometimes satisfy the following relationship.

$$i_K(m,n) + \text{Max}\,[i_C(m,n), i_M(m,n), i_Y(m,n)] > 1 \tag{11}$$

This happens typically when the introduction of black ink is mainly to produce richer black and greater gamut. We call it "rich black". Apparently, dot-on-dot halftone is desirable and inevitable for rich black inputs.

We argue, unless for rich black, dot-on-dot should be generally avoided. First, it wastes ink. The CMY ink drops covered by black dots are simply sacrificed, usually for almost nothing positive. Secondly, it causes a mismatch between the theoretical and the actual output colors. Dot-on-dot and dot-off-dot have totally different perceptual effects, yet they are typically not distinguished in the conventional error diffusion calculation.

Based on the above observation, we propose a simple method that creates high quality CMYK error diffused images. The algorithm generally eliminates dot-on-dot, except for rich black inputs.

The algorithm quantizes each pixel in three steps. First, a scalar quantization is performed to determine the output for the black component. The input values of the CMY component is then adjusted according to the black output. Finally, CMY components are quantized. It may use either vector or scalar quantization. The procedure is specified as follows:

$$b_K = \begin{cases} 1, & \text{if } i^*_K > 0.5; \\ 0, & \text{otherwise}; \end{cases} \tag{12}$$

$$i^{**}_d = i^*_d + (i_K - b_K) \text{ for } d = C, M, \text{ and } Y; \tag{13}$$

and

$$\underline{\mathbf{b}} = \arg\min_{\underline{\mathbf{b}}} \text{distance}\,[\underline{\mathbf{b}}, \underline{\mathbf{i}}^{**}]. \tag{14}$$

Compared to the naïve procedure illustrated in (8)-(9), the only difference is the addition of step (13). As shown in equation (5), [i_K - b_K] is a high-pass noise sequence that does not modify the average of the CMY input values. However, it has a great impact on the configuration of the dots, and provides significant improvement on the output image quality.

Whenever a black dot is printed, the term (i_K - b_K) is always non-positive and CMY values are adjusted downwards. As a result, the placement of a CMY dot at this pixel is discouraged. In fact, dot-on-dot is only permitted for rich black case. This can be shown as follows for the case that (14) is performed using scalar quantization:

In scalar quantization, CMY output b_d is only turned on when $i^{*'}_d > 0.5$, or $i^*_d + (i_K - b_K) > 0.5$. For the case where b_K is 1, the condition becomes $i^*_d + i_K > 1.5$. As the contribution of the diffused error to the pixel is limited between –0.5 and 0.5, this requires $i_d + i_K > 1$. In other words, the input is rich black. The above conclusion can also be extended to the cases where vector quantization is applied in (14). However, the proof will depend on the specific distance measure used.

4. Summary

In this paper, a new color error diffusion method for CMYK images was presented. Dot-on-dot is avoid by introducing a simple adjustment term to the CMY inputs. Compared to the conventional error diffusion, where K and CMY colors are processed independently, it saves ink and achieves much higher image quality. This was verified by extensive experiments.

References

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