An Error Diffusion Method for Color Reproduction in Ink Jet Printing

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Abstract

This paper describes a method of color rendition based on the extension of bilevel error diffusion technique from one component per pixel (originally gray image), to an arbitrary set of colors, with an arbitrary number of color components per pixel.

For each color pixel in the original image, the method selects that color from the output set, that minimizes the error of color rendition in a local array around the current investigated pixel. A decision function was introduced in order to investigate the error between the original and the error diffusion represented picture, for all color components.

For each pixel, the error of color rendition results as the sum over all pixel errors in the local array, weighted according to the geometrical distance to the current investigated point.

The paper describes also the influence of the shape and size of local array as well as the weight mask used to compute the color error. Different weight masks are used for different color components of the pixel in order to reduce the moiré effect on the printed colors. The optimal local array parameters (size, shape and weight mask) are derived experimentally and results are compared in terms of color accuracy and computational performance. Additionally, few color spaces are investigated in order to find perceptually the better color distance for error computation.

Introduction

In the conventional error diffusion techniques,[1, 2] only two levels are used to represent the gray level of the input image, corresponding to presence or absence of the dot in the final image. Due to the vision mechanism of human eye, by modifying the density of the dots in the local array, a gray level is perceived when the local array is observed from a certain distance. Based on this, a large number of error diffusion techniques were developed, as are discussed in [1].

Based on trichromatic color vision of the human eye, the error diffusion technique can be extended for color images. The CIE chromaticity diagram[3,4] was introduced in order to specify the color gamut perceived by the human eye, in comparison with the color gamut that can be reproduced using different other devices. In principle, only three color components are required in order to render any color inside the region determined by the points corresponding to the three colors. Starting from this observation, an error diffusion method can be designed in order to render any color of an input image by a certain arrangement of dots of three primary colors, in order to create the illusion of the input color.

In case of ink jet printing, the region of the CIE chromaticity diagram that depicts the color gamut of reproducible color by the method is determined by all color combinations of the three primary components. In general case, when an arbitrary set of colors is used, the printed color gamut is contained inside the convex hull of the region determined by representation of the particular set of used colors.

This paper describes a method of color rendition based on the extension of bilevel error diffusion technique from one component per pixel (originally gray image), to an arbitrary set of colors, with an arbitrary number of color components per pixel. The case of bilevel and multilevel output images are derived as a particular instances of the general proposed algorithm. The set of colors to be used in error diffusion method can be selected, in the general case by a method of color quantization (i.e. [5]), in case when only the number of elements in the color set represents the single constraint of the color set, or can be imposed by other method (or by user) in more specific cases.

The Method

The color set used to represent the picture by the error diffusion procedure is $\{color_m\}$, m = 1,2,..., N. Each color of the color set or of the input image is specified by a vector of components C_k, color = $(C_1, C_2, ..., C_S)$, where S describes the number of color components per pixel. For each color pixel in the original image, the method

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selects that color from the output set, that minimizes the error of color rendition in a local array, **A**, around the current investigated pixel. Figure 1 depicts an example of local array corresponding to the current pixel, when the processing direction of the image is from up to down and from left to right.

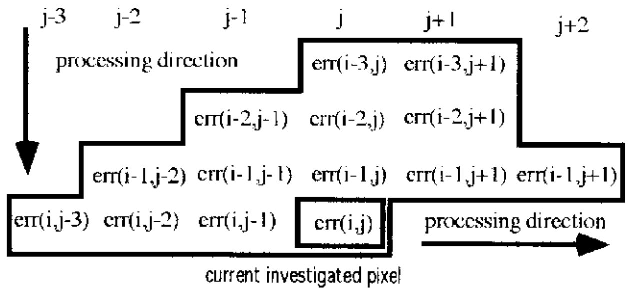

Figure 1. Shape and size of the local array around the investigated pixel

A decision function was introduced in order to investigate the error between the original and the picture represented by error diffusion method, including all color components of the pixel. Denoting by $C_{k,color}$ the component k of one color of the color set, and by $C_{k,pixel}$ the component k of the input pixel, the decision function has the following form:

$$\mathbf{E}(\text{color, pixel}) = \sum_{\text{k components}} (T_k + \sum_{(i,j) \text{ in A}} \text{mask}_k(i,j).\text{err}_k(i,j))^2 ,$$

where T_k represents a threshold factor for each color component k. The term mask_k (i,j) represents the weight mask of the error terms inside the local array, **A**, for the component k. The term $\text{err}_{k,}$ (i,j) represents the error on each color component, with respect to the color space where the error is investigated, and it has the form:

$$\text{err}_k(i,j) = \left\| C_{k,\text{color}}(i,j) - C_{k,\text{pixel}}(i,j) \right\| ,$$

for all the elements (i, j) inside the local array, **A**, and || || represents the color distance according to the color space. The exterior sum is computed with respect to the k index, describing the color components (i.e. k = 0, 1, 2 for red, green, blue components) and (i, j) in the interior sum refers to the position of counted error in the local array, **A**, around the current pixel.

For RGB color space, the error terms are:

$$\text{err}_r(i,j) = r_{\text{color}}(i,j) - r_{\text{pixel}}(i,j) ,$$
$$\text{err}_g(i,j) = g_{\text{color}}(i,j) - g_{\text{pixel}}(i,j) ,$$
$$\text{err}_b(i,j) = b_{\text{color}}(i,j) - b_{\text{pixel}}(i,j) ,$$

and for Lab and Luv color space, the r, g, b components are replaced by L,a,b and L,u,v components respectively.

The errors of color rendition in the local array are weighted, by the factor mask_k (i, j), dependent of the geometrical distance to the current investigated point. In order to reduce the moiré effect in the final printed image and the alignment of pixels in rendition of constant color regions, the pixels to be processed are scanned in different direction from line to line (some authors recommend a diagonal scanning direction for better results) and consequently the mask is reverted and rotated accordingly.

In the following paragraphs, the influence of the shape and size of local array as well as the weight mask used to compute the color error are discussed.

Shape and Size of Local Array

Experimentally, it was observed that as the number of terms in the error decision function increases, the characteristic of the transfer function of the error diffusion technique is more linear and, consequently, the rendition of the color gradation is more accurate. More than this, a correspondence between the number of terms in the decision function and the number of steps in the transfer function was established. Due to this observation, the size of the local array where the error is counted was increase. Figure 2 depicts the transfer function that experimentally was derived for the error diffusion algorithm, as result of rendition of uniform gradation of color (linear ramp). The transfer function was derived in case of RGB color space was used for color distance between color components, but a similar result can be obtained also for other color spaces.

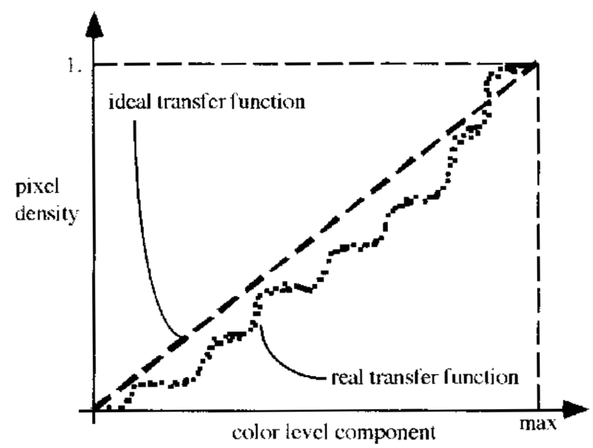

Figure 2. The ideal and real transfer function with number of discontinuities corresponding to the number of terms in the decision function and with the number of elements in the local array.

Over a certain limit in increasing of the local array size, the steps in the transfer function are enough small such that the increasing of the size of local array does not conduct to an improvement of color accuracy.

Weight Mask

The error produced in a single pixel representation has an influence in color perception for neighbors pixels, and the perturbation depends on the geometrical distance to the observed pixel. The weight values in the weight mask quantize this influence decreasing according to the distance to the position of the investigated pixel. Additionally, the decreasing of the weights in the weight mask around the current investigated pixel must be enough irregular in order to avoid the appearance of certain patterns in rendition of constant color regions. Different weight masks were investigated subject to minimize the effect of specific patterns ("worms" or "right angles lines") that currently appears in error diffusion techniques. Figure 3 shows two cases of the weight masks that conduct to acceptable results.

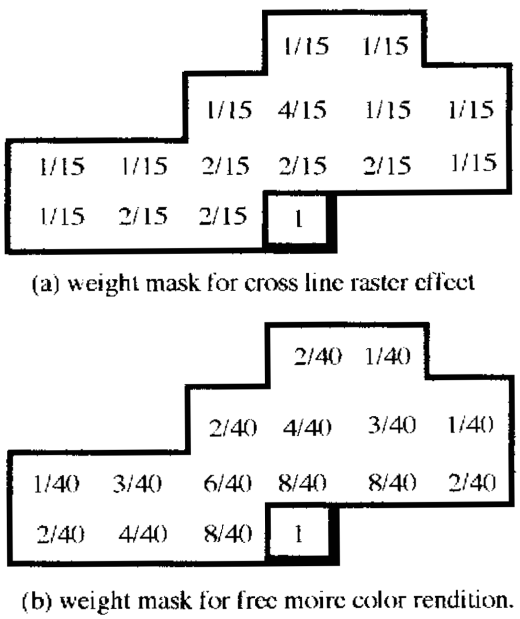

Figure 3. Two examples of weight mask used in decision function

The Color Space

Additionally, few color spaces are investigated in order to find perceptually the better distance for color error representation. It is natural that the color errors to be computed in more perceptual color spaces that enable a correspondence between the value of decision function and the perceived color error by the observer. The **Lab** and **Luv** color spaces[3,4] were investigated. The **Lab** color space was found to give best visual color accuracy performance if the quality of color reproduction is investigated for the printed colors, and the **Luv** color space was found better if the color accuracy is observed for CRT displayed colors.

Results

Generally, the error diffusion techniques are intensive computational. As result the time performance of the algorithms are modest with respect industrial requirements. The computation time increases about 3 times for color images compared to B&W images and increases linearly with the number of non-zero terms in the weight mask.

Enlarged arrays conducts to accurate rendition of color gradation but the computation time increases more. The optimal local array parameters (size, shape and weight mask) are derived experimentally and results are compared in terms of color accuracy and computational performance.

A compromise between the color rendition accuracy and the computation time was accepted. Figure 3 shows two examples of the local array size and shape and the weight mask that experimentally were considered acceptable in terms of color accuracy and processing time.

Conclusions

This paper proposed a method of error diffusion for color images. The method was successfully applied for ink jet printers (Canon 660 and IRIS 3050) that enables a direct control of the printer dot. The paper was oriented in describing a method more than in comparing the method with the large number of error diffusion techniques proposed in literature. The efforts were concentrated in discovering a suitable size and shape of the local array, together with an adequate weight mask.

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