Color halftoning by indexing the visual-optimized dot profiles

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ABSTRACT

A new halftoning method for color image is proposed. The proposed algorithm is very simple to implement the halftoning in hardware and software, which indexes the image pixel values to a binary database as proposed by Sullivan et al. The database is a set of dot profiles representing the corresponding gray levels. The dot profiles are sequentially generated from a visual-optimized seed pattern which is well-distributed by contrast sensitivity function (CSF), in order that the dot profiles have the visual-optimality as well as correlation between dot profiles of all gray levels. Circular convolution technique is used for generating the dot profiles so that the periodic blocking artifacts can be reduced. The proposed color halftoning method uses one database which is shared for all color components and can be directly used for monochrome halftoning, but each color component has different indexing scheme with a circularly shifted indexing to reduce the correlation between dot profiles of color components. The simple structure and small memory requirement of the proposed halftoning method make the processing time fast. The halftone image quality of the proposed method is better than that of ordered dither.

Keywords: color halftoning, contrast sensitivity function (CSF), halftoning database, dot profiles, visual optimization, circular convolution, circularly shifted indexing

1. INTRODUCTION

Digital halftoning is a gray level rendition in the printing devices that have the limited capabilities of the gray representation. The most noticeable algorithms are ordered dither[1] and error diffusion algorithms[2]. The ordered dithering is a good halftoning method for real-time processing, but its image quality is relatively poor. Whereas the error diffusion algorithm shows good image quality but requires large computation time. For an alternative of these algorithms, Mitsa proposed a blue noise mask method[3], which took advantages of both ordered dither and error diffusion algorithms. Despite pleasing image quality, the blue noise mask is just the dither matrix of the ordered dithering so that the algorithm still requires thresholding process. A recent approach is the human-visual-model based halftoning. Sullivan et al.[4] produces the visual-optimized halftone pattern (dot profile) using the contrast sensitivity function. The binary database is a set of the dot profiles, and the halftoning process is just indexing the binary database to the pixel value at the location of a current processing pixel.

The proposed algorithm doesn't require a thresholding process as proposed by Sullivan et al. The proposed process to generate the dot profiles consists of two parts: The first is a seed pattern generation, and the second is the generation of dot profiles. The generation process for the seed pattern uses the iterative exchanging method using the Daly's CSF. The other dot profiles are sequentially generated from the seed pattern to give the correlation property between dot profiles of all gray levels as well as to preserve the visual-optimality of the dot profiles. In this process, one clustered dot is found in one sub-block. The dot profiles, which are generated by the proposed method, can improve the quality of the halftone image.

In conventional color halftoning, each color component has its own database[4]. However, in the proposed algorithm, all color components share one binary database using a circularly shifted indexing method, as if there are different databases for each color component. Therefore, the required memory size for color halftoning database is apparently reduced. Additionally, the database can be directly applicable to the monochrome halftoning.

The color halftone-image from the proposed algorithm has good image quality rather than that from the ordered dither. This result is confirmed from objective evaluation using a mean square error (MSE) of some monochrome halftone-images.

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The proposed algorithm has the fastest processing time without any thresholding and multiplication operations, so that it can be easily implemented with simple hardware.

In this paper, section 2 describes the proposed procedure to generate the dot profiles. The procedure of monochrome half-toning and the objective evaluation method of halftone image quality are introduced in section 3. In section 4, the color half-toning scheme including the circularly shifted indexing is explained. Finally, experimental results and conclusions are also described in sections 5 and 6, respectively.

2. DOT PROFILES

2.1. Generation of seed pattern

Two sequential procedures are applied to generate an optimum binary seed pattern, which are the random pattern generation and the pattern distribution. The binary seed pattern should represent the gray level of $\frac{g_{\max}-1}{2}$ when $g_{\max}$ is the maximum gray level because the correlated dot profiles can be easily generated from the seed pattern by decreasing the number of black dots or white dots. The random pattern generator generates the 2-D coordinates of the black dots to be placed in the seed pattern. The number of black dots for the gray level of $\frac{g_{\max}-1}{2}$ is

$$N = \frac{N_i \times N_j}{g_{\max}} \times \frac{g_{\max}-1}{2} \tag{1}$$

where N is the number of black dots, N_i and N_j are the horizontal and the vertical lengths of the binary pattern, respectively, and $g_{\max}$ is the maximum gray level of the continuous-tone image $g(i,j)$. The value of $g_{\max}$ is 255 for 8 bit-per-pixel images. In this paper, $g_{\max}$ is 255, and N_i and N_j have a value of 32 for monochrome halftoning (64 for color halftoning).

The binary pattern, which is generated by the random pattern generator, may have some clustered and void black pixels. These undesirable clusters should be well-distributed visually using Daly's CSF[4]. The Daly's CSF is the low-pass filter, which has the angular dependency in the diagonal direction. By exchanging two dots of the maximum and the minimum values after the CSF filtering, the binary pattern becomes well-distributed visually as the iterations of the exchanging process are progressed. For automatic stopping of iterations, a visual cost is measured as follows,

$$\text{cost(n)} = \frac{1}{N_i \times N_j} \sum_{i=0}^{N_i-1} \sum_{j=0}^{N_j-1} \left(\frac{g_{\max}-1}{2} - \tilde{B}_g^{(n)}(i,j) \right)^2 \tag{2}$$

where $\tilde{B}_g^{(n)}(i,j)$ is the CSF filtered value of the n-th iterated binary seed pattern. When the derivative of the cost function is equal to zero, the iteration will be stopped. The first derivative of the cost function in terms of iteration is approximated as follows,

$$\frac{d\text{cost(n)}}{dn} = \text{cost}(n) - \text{cost}(n-1) \tag{3}$$

The CSF filter is applied with a wrap-around property, which is the circular convolution. When the span of such a filter extends beyond the bounds of the pattern, some dots located at wrap-around position of the other side are taken. It makes the seed pattern have an uncorrelation property between boundaries so that the blocking artifacts can be reduced.

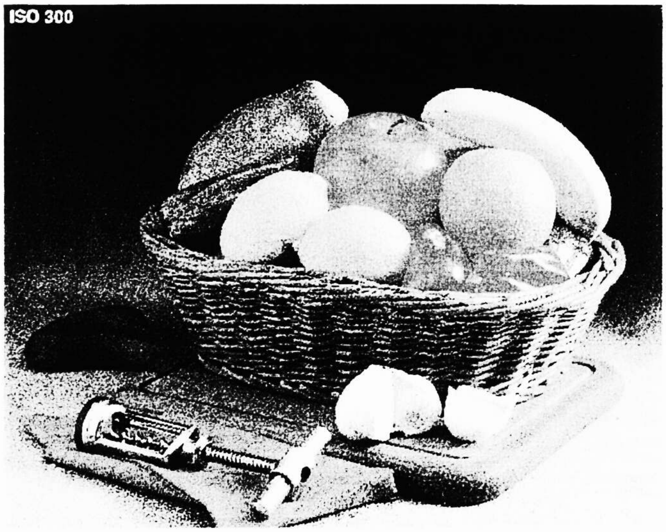

Fig. 3. Halftone color image generated by the proposed algorithm using 64x64 dot profiles.

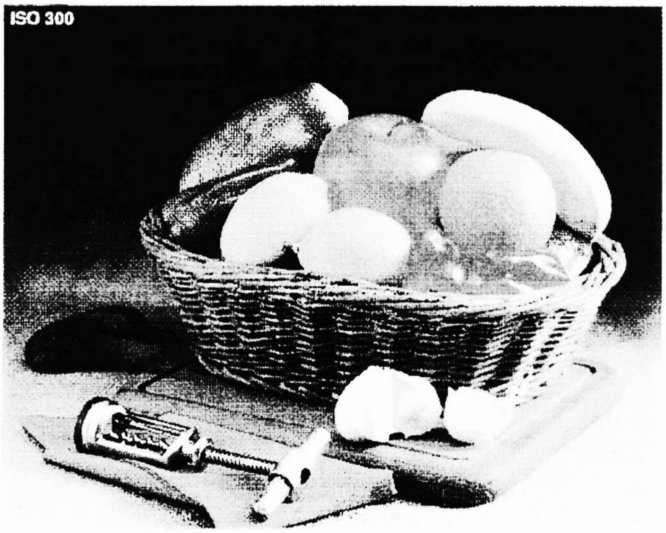

Fig. 4. Halftone color image generated by the dispersed-dot ordered dither using 16x16 matrix.

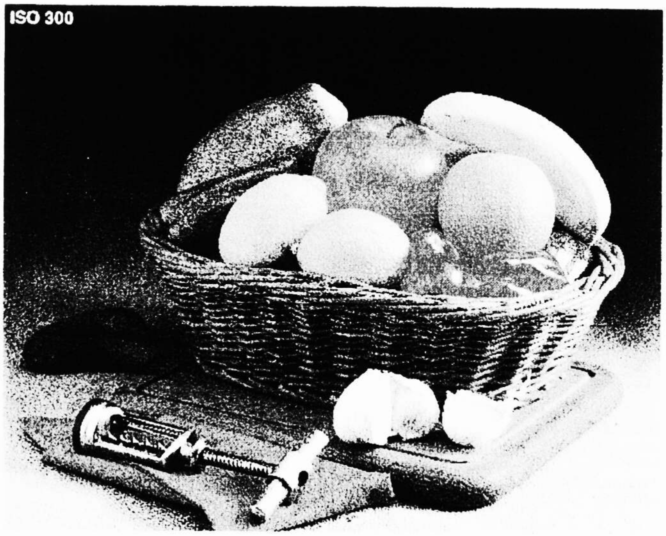

Fig. 5. Halftone color image generated by the error diffusion using Stucki's error filter.

For the objective evaluation of the halftone image quality, the MSE and Daly's CSF are also used[5,6]. In this paper, the MSE between the original continuous-tone image and the filtered halftone image from Daly's CSF is experimentally measured to show the objective quality of the halftone image as follows.

$$MSE = \frac{1}{N_W \times N_H} \sum_{i=0}^{N_W-1} \sum_{j=0}^{N_H-1} (g(i,j) - \tilde{h}(i,j))^2 \quad (5)$$

where $g(i,j)$ is the original continuous-tone image which has $N_W \times N_H$ pixels, and $\tilde{h}(i,j)$ is the filtered halftone image from Daly's CSF.

Using this evaluation method, the optimal size of dot profile can be selected. A reference image is halftoned by the dot profiles with different sizes, and each halftone-image is evaluated by the MSE in eq.(5). From the evaluation results of MSE, the optimum dot profile size can be selected to achieve best image quality with the minimum memory size.

4. COLOR HALFTONING PROCESS

One segment (pixel) in color image consists of three or four color components so that one halftoned segment is produced by three or four indexings. In conventional color halftoning, each color component has its own database[4], which requires large memory. The proposed color halftoning algorithm requires only one halftoning database, which can be shared for the color components.

4.1. Circular-shift indexing

Any correlation between color components produces the undesirable overlap of color dots so that the resulting image becomes darker than original image[7,8]. This phenomenon can be avoided by a circularly shifted indexing as shown in Fig. 2. The column number to start the indexing is shifted for each color component, as if there are different databases for each color component. The shift distances between color components are all the same.

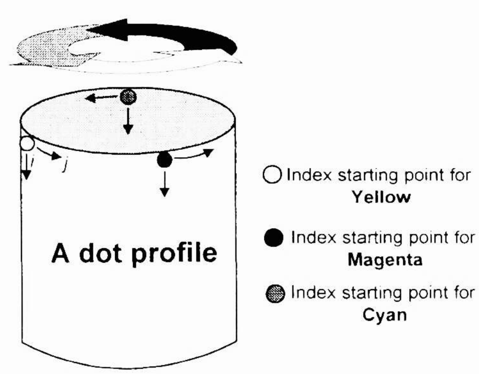

Fig. 2. Circularly shifted indexing scheme of dot profiles for color halftoning

4.2. Color halftoning procedure

The procedure of the proposed color halftoning is described in detail as follows:

① Get one segment at (i, j), which consists of three or four color intensities.
② Find the dot profile in the halftoning database using the intensity of one color component.
③ Compute the column number, s, to start indexing for the color component in manner of the proposed circularly shifted indexing.
④ Bring a a binary value at $(i, j+s)$ of the dot profile. If the size of dot profile is smaller than that of the original image, the location in the dot profile is given as (i modulo N_i , $(j+s)$ modulo N_j).
⑤ Apply this zero or one to the same color plane in the halftone image at the same location (i,j) as the original image.
⑥ Repeat the same procedures ② to ⑤ for other color components.
⑦ If the halftoned C, M, Y values in one segment are all the same which cause a composite black, then replace the pixel with true black (K).
⑧ Repeat ① to ⑦ for all segments of a color image.

5. EXPERIMENTAL RESULTS

Figure 3 shows the color halftone image produced by the proposed algorithm using 64x64 dot profiles. Halftone images from color ordered dither method using 16x16 rotated screens and error diffusion using Stucki's error filter[2] are given in Figs. 4 and 5, respectively. The original color image has spatial resolution of 300 dpi (dots per inch) and 8 bits per each color component[9]. The target device is HP 850K inkjet printer (Hewlett-Packard co.). Even though this printer has 600 dpi resolution of K component and 300 dpi resolution of C, M, and Y components, the resolutions of all CMYK components are handled with 300 dpi. The paper of color printing is A4-MJ/SIJ inkjet-paper (Samsung Electronics, Korea). The image quality of the proposed algorithm is perceptually similar to that of error diffusion, but the ordered dither produces color cast and grainy image. The number of computations for each algorithm is compared in Table 1. The proposed algorithm is the fastest method, which does not require any thresholding and multiplication operations.

The monochrome halftone-image of the proposed algorithm is also presented in Figure 6. The test image is a center part of the Lena image whose resolution is 256x256 with 256 gray levels. The halftone images from ordered dither and error diffusion are also given in Figs. 7 and 8, respectively. For objective evaluation, the MSEs between the original Lena image and the filtered halftone-images are measured and given in Table 2. The comparison result of MSE shows that the proposed algorithm produces better image quality than the ordered dither.

For choosing the optimal size of the dot profiles, several halftoned Lena images using different sizes of dot profiles are evaluated with respect to MSE. The tested sizes of dot profiles are 16x16, 32x32, 64x64 and 128x128, and the results are shown in Fig. 9. It is shown that the MSE is almost saturated from 32x32 in Fig. 9.

The memory size and the number of computations are important factors when the algorithm is implemented in hardware and software. The required memory size is $N_i \times N_j \times (g_{\max}+1) / 8$ bytes. In the proposed color halftoning, the perceptual image quality can be improved as the dot profile size increases, because the correlation between dot profiles of color components can be reduced. In this paper, 64x64 dot profiles are used for color halftoning so that the required memory size is about 128 Kbytes for color halftoning.

6. CONCLUSIONS

The proposed color halftoning is based on the optimization of dot profiles and new indexing scheme. The optimization is to distribute the dot profiles in consideration of human visual perception as well as to make correlation between dot profiles of all gray levels. The new indexing scheme allows the color halftoning using a single database of dot profiles, which is shared for all color components. The proposed halftoning algorithm was proposed to support the fast processing time with a simple computation requirements as well as good image quality. Comparison studies of MSE and computation requirements were performed in order to verify that the proposed halftoning is the optimized algorithm in image quality without any thresholding and multiplication operations among the other conventional halftoning algorithms.

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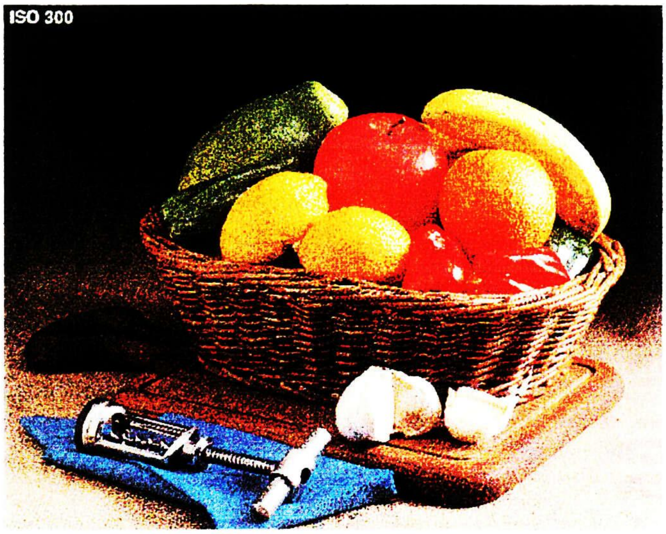

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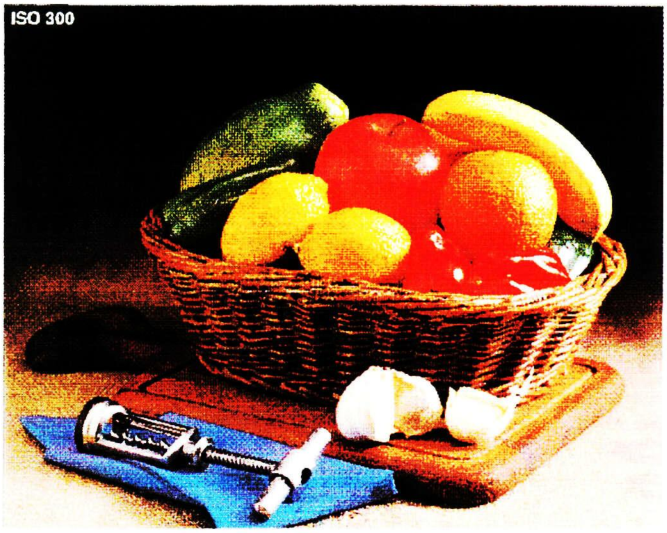

Fig. 4. Halftone color image generated by the dispersed-dot ordered dither using 16x16 matrix.

Fig. 5. Halftone color image generated by the error diffusion using Stucki's error filter.

Fig. 6. Monochrome image generated by the proposed halftoning using 32x32 dot profiles.

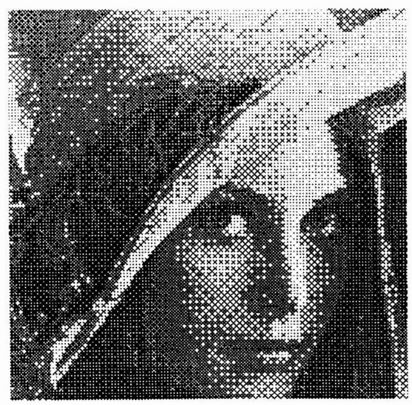

Fig. 7. Monochrome image generated by the ordered dither.

Fig. 8. Monochrome image generated by the error diffusion.

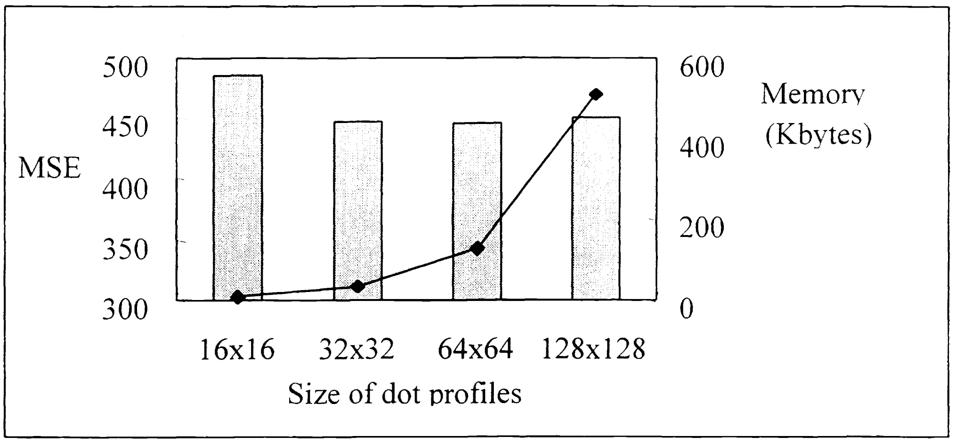

Fig. 9. Mean square error (black bar) of the halftone Lena image generated by the proposed algorithm and the required memory size (solid line) for hardware implementation of various sizes of dot profiles.

	Proposed color algorithm (Basic)	Color ordered dither (Rotated)	Color error diffusion (Stucki)
Summation	2	2	39*
Multiplication	None	2	66*
Comparison	None	3	3*
Buffering	None	None	3 Line*

(* : Floating point operation)

Table 1. Comparison of computation requirements for color halftoning of a pixel, which has three color components.

	Proposed algorithm	Ordered dither (16x16)	Error diffusion (Stucki)
MSE	438	632	394

Table 2. Mean square error (MSE) comparison of various halftoning methods for Lena image.