Halftoning Method Using Dispersed CMY Dithering and Blue Noise Mask

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This article proposes a halftoning method using dispersed CMY dithering with blue noise masks (BNM) to print CMY dots instead of black (K) dots in a bright gray region in a black-and-white (B/W) image. To reduce high granularity in a bright region, dispersed CMY dots using a BNM instead of K dots are spatially assigned to a bright region. First, a threshold is determined to avoid the granularity caused by K dots. Below this threshold, the image made by the BNM is composed of CMYK dots, whereas above the threshold, a dispersed CMY image is made from mutually exclusive C, M, and Y patterns, defined by the stacking constraint of the BNM. To make mutually exclusive C, M, and Y patterns, modified jointly-blue noise masks (MJBNMs) are generated for a grayscale image. As a result of processing a grayscale image, the low-pass filtered error for single and triple patterns where the three mask patterns overlap is minimized. As such, single and triple patterns are used. Experiments demonstrated that the bright regions produced by the proposed method were uniform and sufficiently pleasing when compared to conventional results.

Journal of Imaging Science and Technology 48: 37–44 (2004)

Introduction

Recent advances in color ink jet printer technology now offer high quality images at a low cost. Digital image halftoning in a color ink jet printer is an essential technique used to make an equivalent binary image from a scanned photo or graphic image. This technique uses the low-pass filtering characteristic of the human visual system (HVS) to obtain the effect of spatial averaging of a local area, consisting of black and white pixels in the case of gray images. Various digital halftoning techniques have already been developed, including ordered dither,[1,2] error diffusion,[3–5] direct binary search (DBS),[6–9] and BNMs.[10–13]

With the growing popularity of color ink jet printers, halftoning has been developed to allow a B/W binary image to be expressed as a color image. When a black-and-white (B/W) halftoning method is simply applied to color halftoning, unwanted effects can sometimes occur, preventing precise color reproduction. In particular, since most color printers use under color removal (UCR) or gray component replacement (GCR) to reduce ink consumption and strengthen the contrast in the achromatic component, the K dots in a bright region create granular patterns, to which the HVS is sensitive. Sometimes grayscale images or composite images, including color and grayscale, are printed by a color ink jet printer. When a color ink jet printer processes a grayscale image, it uses K ink to save on ink, prevent the misregistration problem of CMY planes, and avoid spreading due to dot overlapping when printing with CMY ink. As a result, the ink cost is reduced and the image quality improved. However, the usage of only K ink produces certain phenomena, such as granularity in a highlight region. In particular, the usage of K ink in a bright region increases the granularity effect. Also, the HVS is sensitive to K dots in a bright region.

Color halftoning providing the best possible dispersed-dot textures in which the interaction of the different colorant dots is developed. Lee et al.[14] proposed color design criteria for uniform color textures and a new colorant-based color halftoning method. This method is to set the total dot arrangement first, and then to color the dots optimally without altering the total dot arrangement by solving via the swap-only direct binary search heuristic. Wang et al.[15] generated a set of jointly blue noise masks (JBNMs), where each mask is applied to one color plane. The combination of JBNMs produces color images with blue noise characteristics and the dots from different color planes are mutually exclusive and maximally dispersed at highlight levels. Kwon et al.[16] proposed a MJBNM method using the S-CIELAB color measure. To reduce the chrominance error, the low-pass filtered error and S-CIELAB chrominance error are both considered during the mask generation procedure and calculated for single and combined patterns.

This study uses an MJBNM to disperse CMY dots instead of K dots in bright regions. First, the threshold value is set at 170 to avoid the granularity caused by K dots in a bright

Original manuscript received March 7, 2003

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region. This value is selected to avoid the overlap of C, M, and Y dots. As such, below this threshold, a grayscale image is separated into CMYK channels, where each channel is halftoned by a CMYK–MJBNM. Above the threshold, a dispersed CMY image is made from C, M, and Y patterns generated by mutually exclusive MJBNMs, defined by the stacking constraint of the BNM. Finally, an output image composed of C, M, Y, and K dots is printed. Experiments are performed to compare the results of the proposed method with various conventional methods, including a grayscale BNM method, error diffusion, and JBNM method. The proposed method was found to produce a visually pleasing halftone image with a lower granularity than the other methods.

Jointly-Blue Noise Masks

Wang and Parker[15] suggested an algorithm that generates a set of JBNMs. They explored the elementary properties of combinations of blue noise binary patterns. As a result, they proposed an algorithm that makes three individual masks jointly. The masks produce high quality patterns whenever they are used individually or combined jointly. In addition, an attempt was made to make three independent masks that preserved good blue noise characteristics within each single pattern, and a double pattern and triple pattern based on combining each pattern. Since the JBNM algorithm is focused on achieving minimally visible halftone patterns, the halftone outputs are visually pleasing and exhibit a lower luminance error than BNM schemes.

Modified Jointly-Blue Noise Masks for Grayscale Image

Kwon et al.[16] proposed a MJBNM method using the S–CIELAB color measure for color halftoning. Based on an investigation of the relation between the pattern visibility and the chromatic error of a blue noise pattern, a halftoning method was proposed that reduces the chromatic error, while preserving a high quality blue noise pattern. To reduce the chrominance error, the low-pass filtered error and S–CIELAB chrominance error are both considered during the mask generation procedure and calculated for single, double, and triple patterns.

In this study, an MJBNM is generated for the dispersed CMY dithering of a grayscale image. In the case of color halftoning, single, double, and triple patterns are considered to express all the combination patterns of the color image during the mask generation. To generate BNMs for a grayscale image, single and triple patterns are used. Because a grayscale image is processed, the low-pass filtered error for single patterns and triple patterns where the three mask patterns overlap is minimized. Therefore, three error arrays for single and triple patterns are constructed as follows:

$$\begin{aligned} E_1 &= E_{LPF}(S_1) + E_{LPF}(T) \\ E_2 &= E_{LPF}(S_2) + E_{LPF}(T) \\ E_3 &= E_{LPF}(S_3) + E_{LPF}(T) \end{aligned} \quad (1)$$

where $E_{LPF}()$ denotes the low-pass filtered error of each single (S) and triple (T) pattern. The E_1 error array reflects the effects on the single and triple patterns when the single pattern is changed. Similarly, E_2 is associated with the single pattern and E_3.

The S–CIELAB chrominance error is considered during the mask generation procedure and calculated for single and combined patterns. The procedure of calculating the S–CIELAB color difference is exactly the same as the CIELAB ΔE method. The total S–CIELAB error is

$$E_c = \sum_i S\Delta E(S_i) + S\Delta E(T) \quad (2)$$

In this equation, $S\Delta E(\,)$ is the S–CIELAB error. Using the low-pass filtered error calculated by Eq. (1), the patterns are then updated by either adding or removing dots from the multiple binary patterns. Finally, the pattern exhibiting the lower S–CIELAB chrominance error computed by Eq. (2) is selected.

Dispersed CMY Dithering

Although the purpose of using K dots is to save on inks, prevent the misregistration problem of CMY planes, and avoid the spreading of CMY dots, the expression of K dots in a bright gray region increases the granularity. Also, the HVS is sensitive to black dots in a bright region. Therefore, to reduce the high granularity in a bright region, BNMs are used to spatially disperse CMY dots instead of K dots in a bright region. In the BNM method, when patterns are constructed from the current gray level to the next gray level, the pattern of the next gray level is constructed without changing the current pixel positions, referred to as the stacking constraint. Based on this constraint, if the input value to be printed is a gray level between 171 and 255, in the upper 1/3 of the whole dynamic range, the number of dots is multiplied by 3 compared to the number of dots for the input gray level, and CMY dots are assigned instead of K dots. If the size of the mask is $N \times N$ and the total number of levels is L, then

$$P = N \times N/L \quad (3)$$

For an $N \times N$ mask size, P dots are needed to print one gray level. If a gray value above this threshold is printed using CMY dots, no artifacts, such as granular patterns, are noticeable. Thus, CMY dots can be printed uniformly in the corresponding printed image.

The proposed algorithm is as follows. First, the threshold is decided to avoid any pixel overlap. Below this threshold, the image halftoned by the BNM is composed of CMYK dots, whereas above the threshold, patterns are generated to make dispersed CMY dots. To disperse CMY dots, mutually exclusive Cyan (C)-MJBNM, Magenta (M)-MJBNM, and Yellow (Y)-MJBNMs are used. In the BNM, when the current mask pattern updates the next mask pattern, the dots in the next mask pattern are assigned to a non-overlapped position. For example, with an $N \times N$ mask, P dots are needed to increase one gray level. As such, the mask pattern for the 254 (L-2) gray level is composed of P dots. The (L-3) mask pattern has 2P dots and the (L-4) mask pattern has 3P dots. As a result, the overlapping of mask patterns can be avoided. To express the (L-2) gray level using spatially dispersed CMY dots, the (L-2) pattern generated by the C-MJBNM is assigned to the C channel, then to avoid any overlapping, the (L-2) mask pattern by the M-MJBNM is assigned to the M channel, and the (L-2) mask pattern generated by the Y-MJBNM is assigned to the Y channel.

Second, below the threshold, the input image is separated into CMYK channels:

$$\begin{aligned} C_o &= C_i - UCR_C(K_i), \\ M_o &= M_i - UCR_M(K_i), \\ Y_o &= Y_i - UCR_Y(K_i), \\ K_o &= BG(K_i), \end{aligned} \quad (4)$$

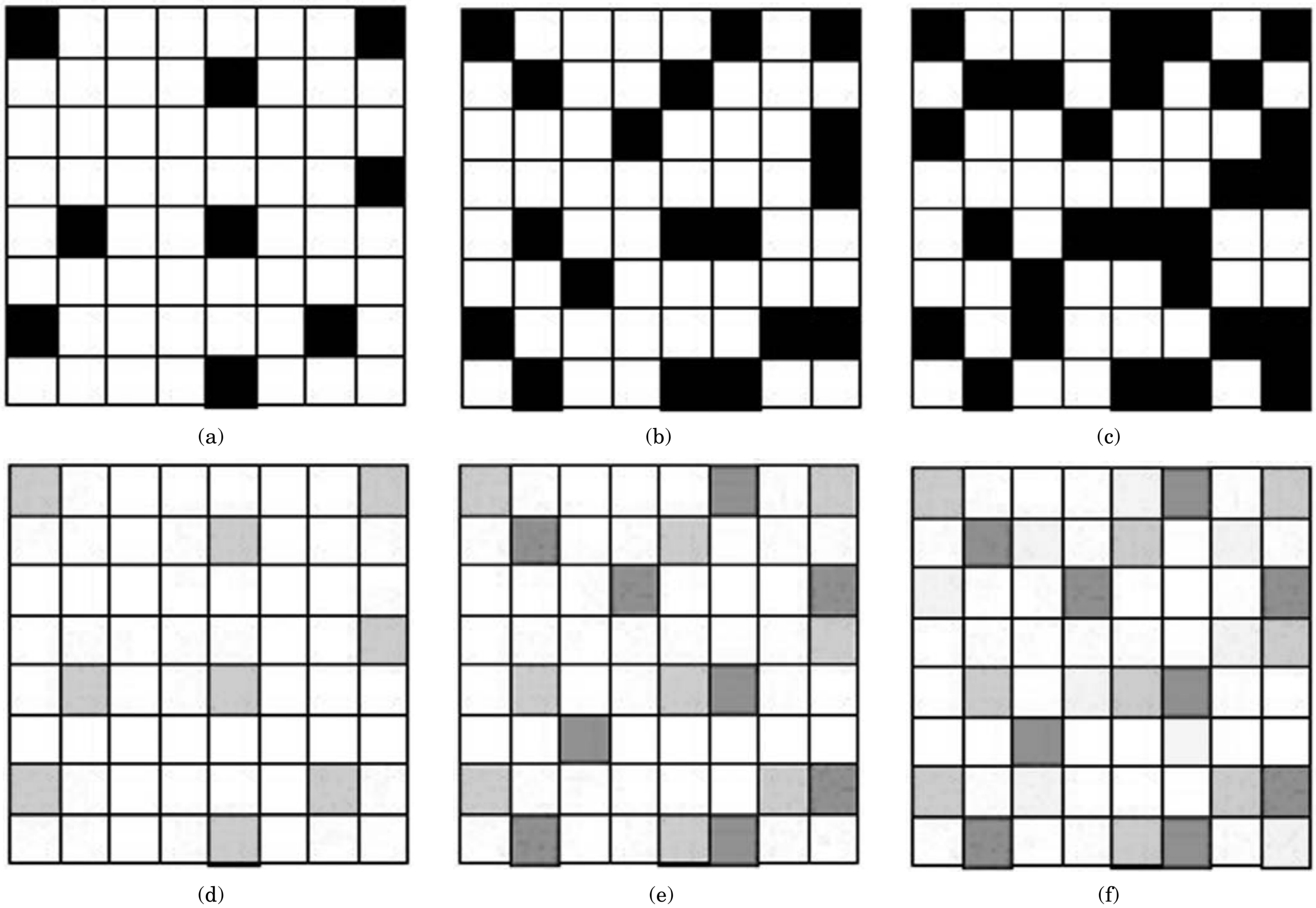


Figure 1. Graphical example of dispersed CMY dithering (a) single pattern; (b) double pattern; (c) triple pattern; (d) assigning C to single pattern; (e) assigning C and M to double pattern; and (f) assigning C, M, and Y to triple pattern.

where *UCR( )* is the UCR function for each CMY channel and *BG( )* is the black generation(BG) function for the K channel. The minimum for the input C, M, and Y channels is computed by

$$K_i = \min(C_i, M_i, Y_i). \tag{5}$$

The UCR and BG functions are as follows:

$$\begin{aligned} UCR_C(K_i) &= c_C \times \left(\frac{K_i - 85}{255 - 85}\right)^{\gamma_C}, \\ UCR_M(K_i) &= c_M \times \left(\frac{K_i - 85}{255 - 85}\right)^{\gamma_M}, \\ UCR_Y(K_i) &= c_Y \times \left(\frac{K_i - 85}{255 - 85}\right)^{\gamma_Y}, \\ BG(K_i) &= c_K \times \left(\frac{K_i - 85}{255 - 85}\right)^{\gamma_K}, \end{aligned} \tag{6}$$

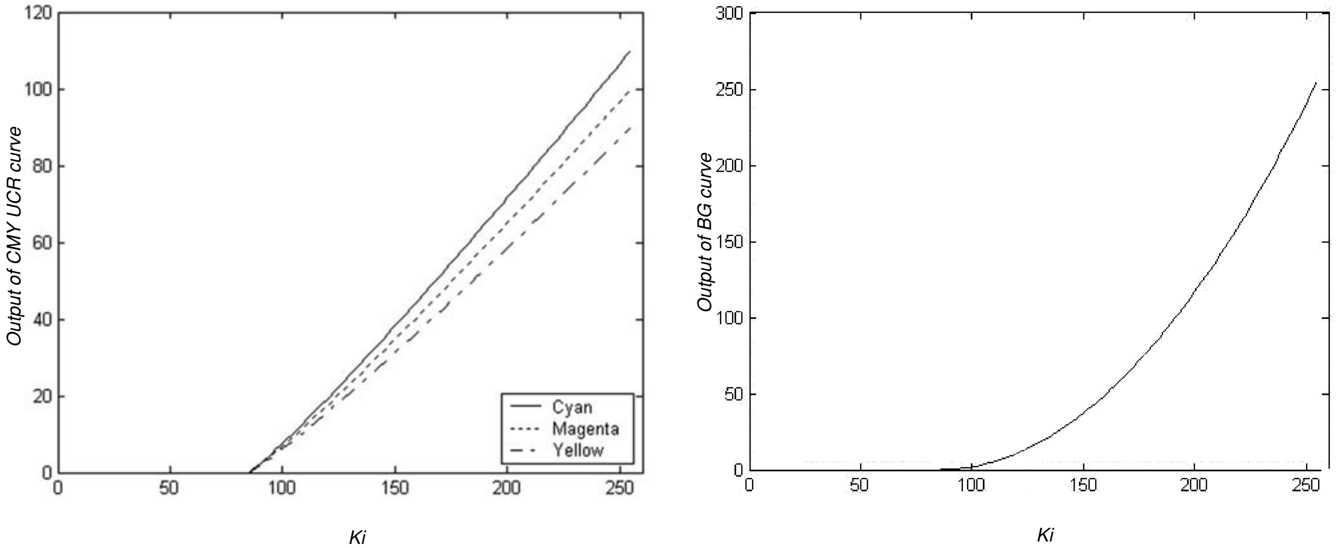
where c_C, c_M, c_Y, c_K are 110, 100, 90, and 255 and γ_C, γ_M, γ_Y, γ_K are 1.1, 1.1, 1.1, and 2.0, respectively. These parameters values are based on experimental results. Finally, an output image composed of C, M, Y, and K dots is printed. Figure 1 shows a graphical example of dispersed CMY dithering. Figures 1(a), 1(b), and 1(c) show single, double, and triple patterns, respectively. Figures 1(d), 1(e), and 1(f) show the patterns assigned to CMY dots.

Generation of CMY UCR and BG Curves

In the proposed method, the threshold value is set at two-thirds of the full dynamic range, which determines the selection of CMY or CMYK. If K dots are printed in the gray levels above the threshold, they generate grainy patterns and poor quality halftone patterns are perceived. To make a visually pleasing pattern, CMY UCR and BG curves are generated. To create these curves, at the black level, 100% K is used and the amounts of CMY inks are significantly reduced. The CMY amounts at the black level have to be reduced to satisfy the total colorant coverage limits. As the gray level becomes higher, the amount of K ink is decreased abruptly and the CMY inks are diminished slowly. Through experiments, CMY UCR and BG curves appropriate for dispersed CMY dithering were generated. Figure 2 shows the CMY UCR and BG curves used to determine the CMYK output response.

Experiments and Discussion

Airplane and Bicycle images were used for the experiments. RMS granularity was used as an objective evaluation of the granularity in bright regions when using the proposed method. The subjective quality was evaluated by observers. 64 × 64 size MJBNM masks were generated and used in



(a) (b)

Figure 2. CMY UCR and BG curves to determine CMYK output response: (a) CMY UCR curves and (b) BG curve.

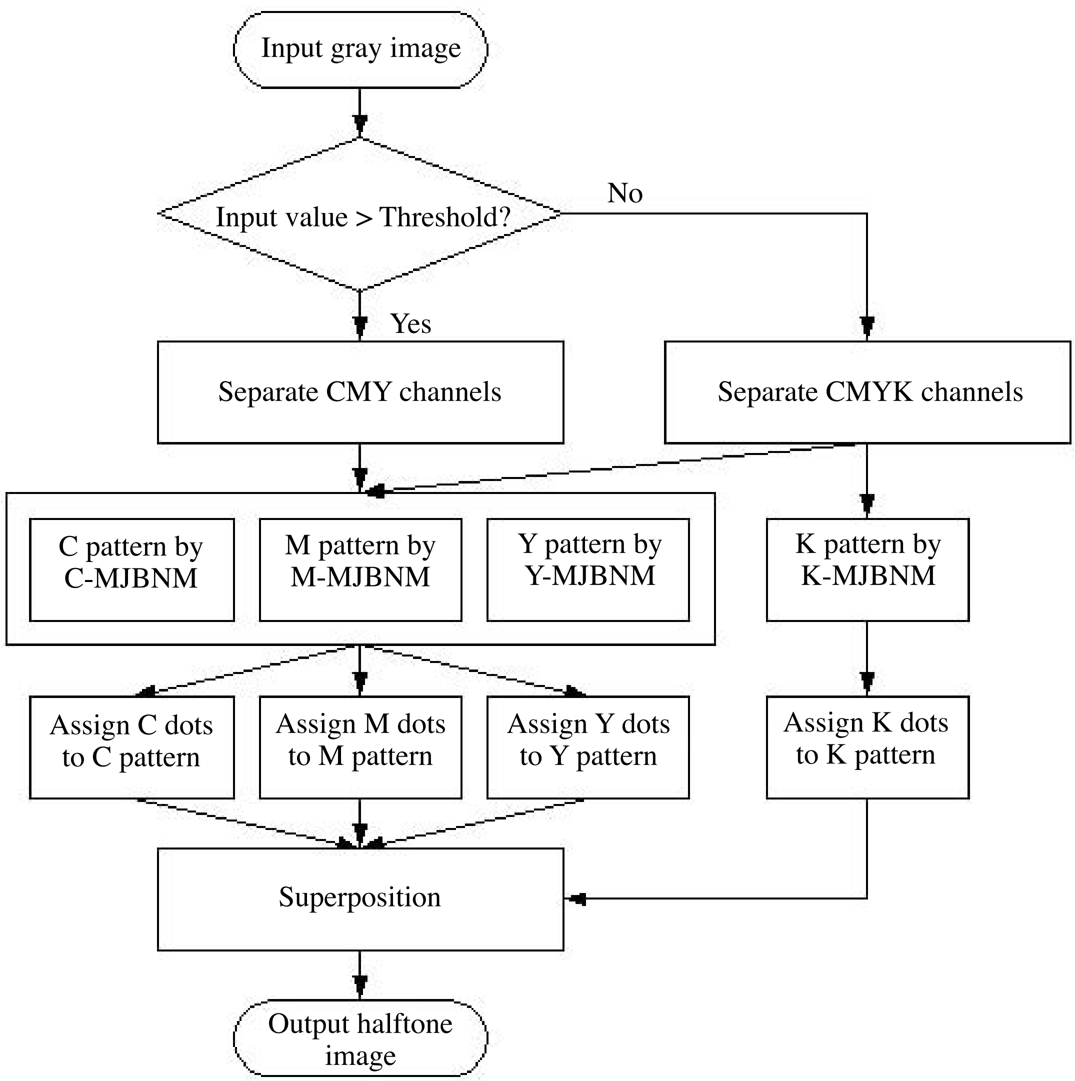


Figure 3. Flow chart for proposed method.

all the experiments. Each image was printed by an HP DeskJet 948c at 600 dpi.

RMS Granularity for Objective Evaluation

It is important that an objective parameter is evaluated as an output parameter for the image quality. Miyata's method computes the RMS granularity using digital image data,[17] however, this method can only be applied when K dots are used. Since the proposed method uses CMYK dots in the printed image, an HVS-based characteristic was considered. The human visual characteristic is more sensitive to luminance than chrominance. Whereas Miyata only considers intensity in a grayscale image, the proposed method places more weight on the luminance rather than the chrominance as follows:

$$D = (1 - \alpha)L + \alpha C \tag{7}$$

where D is the weighted color value between the luminance and the chrominance, L is the luminance, C is the chrominance, and α is the constant. Because the ratio between luminance and chrominance in the human visual characteristic is 4:1, α was set at 0.2, and C was computed as follows:

$$C = \sqrt{a^{*2} + b^{*2}} \tag{8}$$

The weighted color value D for C, M, Y, R, G, B, K, and W was computed by Eq. (7). After the kind of ink dot is assigned, $D(i,j)$ for each pixel position is defined as follows:

$$D(i,j) = D_p, \quad \text{for } p = C,M,Y,R,G,B,K, \text{ and } W \tag{9}$$

where D_C, D_M, D_Y, D_R, D_G, D_B, D_K, and D_W are the weighted color values for 8 primary color patches. Table I presents the L*, a*, b*, and D_p values for the 8 primary color patches. The RMS granularity was used to compare printing by K dots with printing by CMY dots, thereby evaluating how noticeable the dots were to the HVS.

$$R_g = \sqrt{\frac{1}{MN}\sum_{i=0}^{M-1}\sum_{j=0}^{N-1}\left(D_m(i,j) - D(i,j)\right)^2} \tag{10}$$

where M and N are the row and column of the image, and $D_m(i,j)$ is the average value of $D(i,j)$ in a 9 × 9 window size. When the granularity of the proposed method and other conventional methods was computed by Eq. (10), R_g was 25.14 for the BNM method, 22.82 for the Fan's error diffusion method, 14.87 for the JBNM method, and 14.24 for the proposed method. Table II shows the RMS granularity values for the proposed method and other methods. The lower the RMS granularity, the more uniform the patterns distributed. Thus, the lower RMS granularity value produced by the proposed method represented a more uniform dot distribution in the bright region.

Comparison of Subjective Quality

The images used in this experiment were a grayscale version of Airplane and Bicycle. Figures 4(a) and 5(a) are the resulting images when using the BNM method, Figs. 4(b) and 5(b) are the resulting images with the error diffusion method, Figs. 4(c) and 5(c) are the resulting images with the JBNM method, and Figs. 4(d) and 5(d) show the resulting images when using the proposed method. For the bicycle image, the wheel spokes were presented more clearly by the proposed method, and the smooth tone was more pleasing to human eyes, as CMY dots were used in the background region. Similarly, the outline of the airplane and text on the airplane could be seen in detail with the proposed method. As such, when only K dots are processed, a narrower dynamic range is used and the HVS is sensitive to K dots in bright regions. However, when presenting the same gray level, the proposed method can provide a better presentation of spatial information than conventional methods with only K dots. The resulting pattern is also more pleasing to the human visual characteristic. While conventional methods have a high granularity and narrow dynamic range, the proposed method has a low granularity, wide dynamic range, and high contrast properties. Since the proposed method uses three times more dots than conventional methods, it can express more spatial information even when presenting a similar gray level. Moreover, the proposed method produces a better quality image than the JBNM method using CMY dots. The proposed method has a low granularity in a bright region, yet expresses high contrast in a dark region.

The subjective quality was also quantitatively analyzed using 10 observers, who were asked to rank the best quality image to the worst quality image among 4 printed images of the two test images. The score for the best quality image was 5, and the worst was 2. Table III shows the results of the psychophysical test for the Bicycle and Airplane images. Each value is the mean value based on averaging 10 scores. The proposed method produced higher scores than the other halftoning methods, indicating visually pleasing and good quality images.

TABLE I. L*, a*, b*, and D Values for C, M, Y, R, G, B, K, and W

	L*	a*	b*	D_p
C	53.6	–38.26	–46	54.84
M	42.2	71.28	–7.02	48.08
Y	84.18	4.39	84.45	84.25
R	42.77	63.25	31.75	48.37
G	45.99	–56.9	21.11	48.92
B	24.71	17.76	–41.39	28.77
K	20.83	–4.87	–6.21	18.24
W	91.61	2.1	–7.79	74.90

TABLE II. RMS Granularity Values

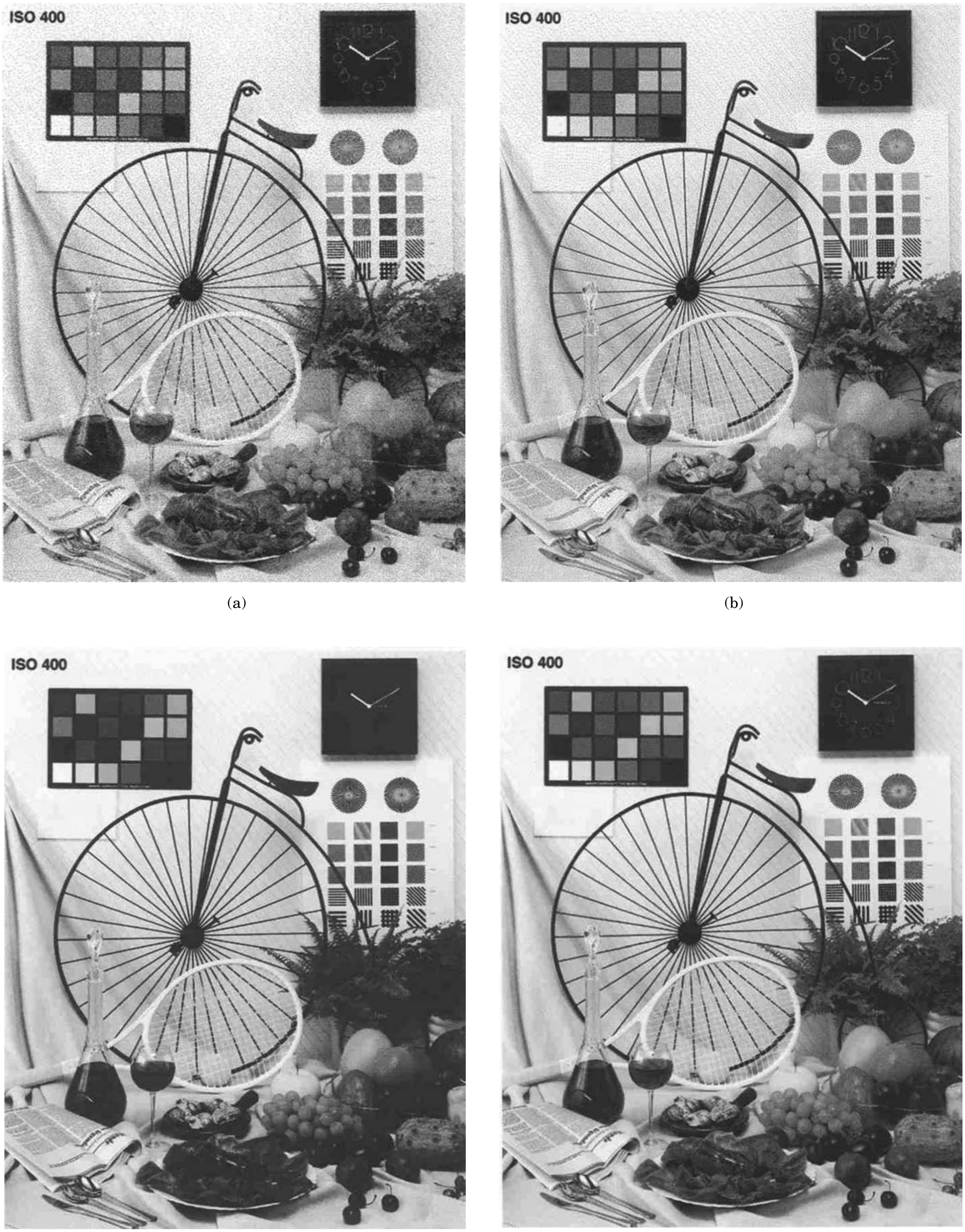
	BNM	Fan's Error Diffusion	JBNM	Proposed method
R_g	25.14	22.82	14.87	14.24

TABLE III. Results of Psychophysical Test

	BNM	Fan's Error Diffusion	JBNM	Proposed method
Bicycle	2.3	3.1	3.9	4.7
Airplane	2.2	3.3	3.9	4.6

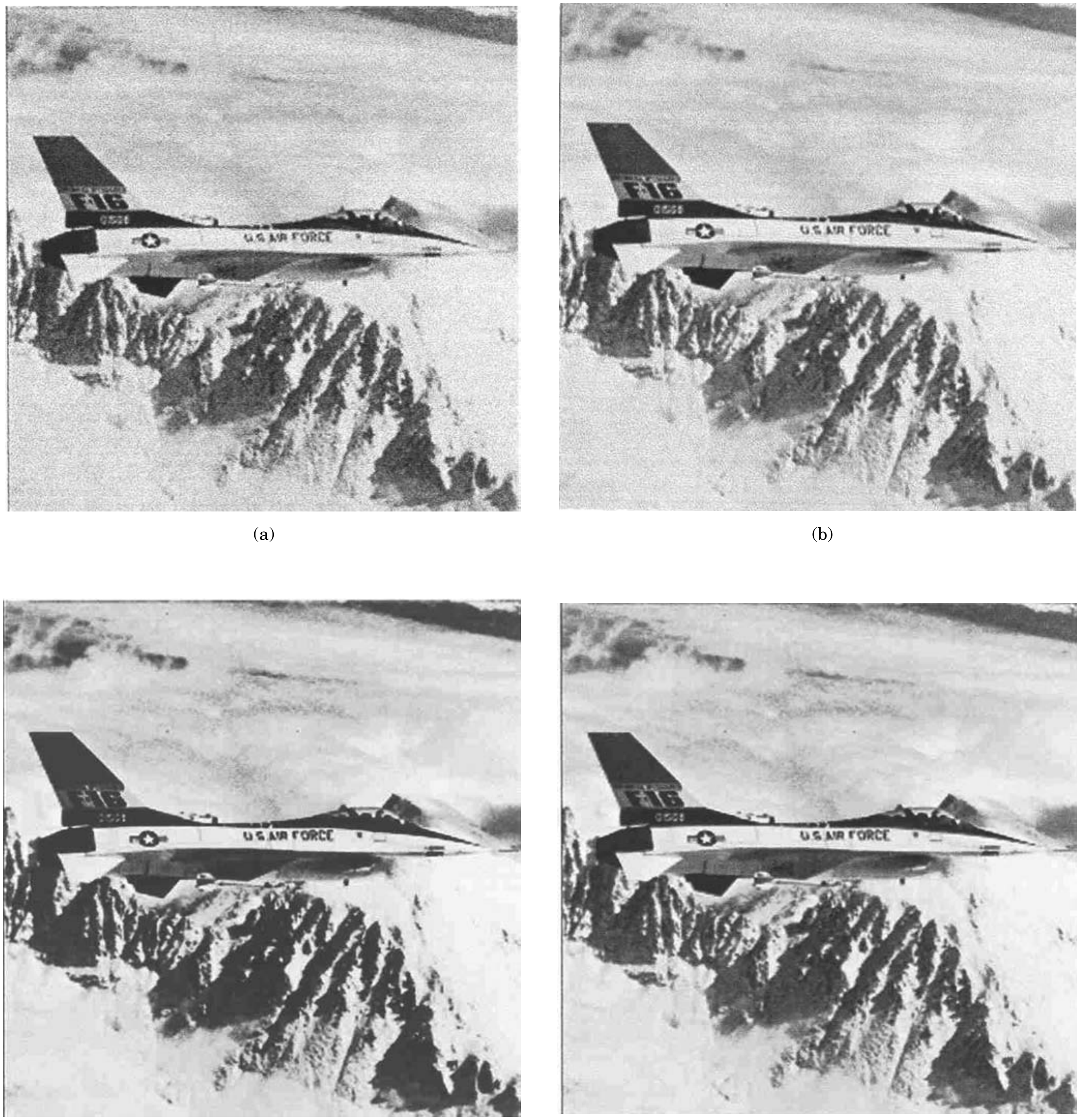
Conclusions

This article proposed a halftoning method using dispersed CMY dithering with a BNM to express CMY dots instead of K dots in a bright gray region in a B/W image. Although the purpose of using K ink is to save on ink, prevent the misregistration problem of CMY planes, and avoid spreading with CMY ink, printing K dots in a bright gray region increases the granularity. Also, the human visual system (HVS) is sensitive to black dots in a bright region. Thus, dispersed CMY dots instead of K dots are spatially assigned to a bright region using a BNM. First, a threshold is determined to avoid the granularity caused by K dots in



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

Figure 4. Resulting Bicycle images: (a) BNM, (b) Fan's error diffusion, (c) JBNM, and (d) proposed method.



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

Figure 5. Resulting Airplane images: (a) BNM, (b) Fan's error diffusion, (c) JBNM, and (d) proposed method.

a bright region. Below this threshold, the image made by the BNM is composed of CMYK dots, whereas above the threshold, a dispersed CMY image is made from mutually exclusive C, M, and Y patterns, defined by the stacking constraint of the BNM. To make mutually exclusive C, M, and Y patterns, MJBNMs are generated for a grayscale image. Since a grayscale image is processed, the low-pass filtered error for single and triple patterns where the three mask patterns overlap is minimized. As such, single and triple patterns are used. The proposed method results in a less granular pattern in bright regions in a B/W image, and the printed image has a better quality and contrast compared to other halftoning methods. In experiments, the gray regions in the resulting image were uniformly printed and less granular compared to conventional results.

Acknowledgement. This work was supported by grant no. M10203000102-02J0000-04810 from the National Research Laboratory Program of the Korean Ministry of Science & Technology.

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