Color Halftoning with Blue Noise Masks

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Abstract

Color halftoning using a conventional screen requires rotating the screen by different angles for different color planes to avoid Moiré patterns. With the Blue Noise Mask (BNM), which is a stochastic screen that produces visually pleasing blue noise, Moiré patterns are not produced and therefore screen angles are not required. We have developed several strategies to apply our masks to color planes as following:

1. the Dot-on-Dot scheme, which uses the same mask on all color planes.
2. the Shifting scheme, which uses shifted versions of same mask on different planes.
3. the Inverting scheme, which applies one mask and its inverted version to two planes, with an optional adaptive algorithm for other planes.
4. the Four Masks scheme, whereby four distinct masks are generated for each of the CMYK planes. These masks are anti-correlated in a mutually exclusive manner so that color dye is maximally dispersed.

These schemes are applied to color images, and the results are studied in the CIELAB space based on human visual model. Comparisons against error diffusion results are also presented.

Introduction

Color image halftoning is much more complicated than halftoning a greyscale image. All the qualities required of black and white halftone images apply to color halftone images that are composed of multiple color planes, but, in addition, the interactions between color planes must be controlled. Color halftoning is the process of generating halftone images for the different color planes, for example, cyan, magenta, yellow and/or black for a printing device. A straightforward way of halftoning a color image would be to use the same halftone technique that is applied to a greyscale image, to the color planes separately. For example, the same clustered-dot kernel can be used to halftone the C, M, Y, K planes separately to obtain four halftone images. These four halftone planes are then used to control the placing of color on paper. This technique is simple and easy to implement, but it has its problems. In conventional clustered-dot halftoning, one immediate problem of such simple technique is the appearance of Moiré patterns where misregistration problems occur. Moiré patterns are caused by the low frequency components of the interference of the color planes. To avoid Moiré patterns, the screens are typically oriented at different angles, usually about 30º apart. At 30º separation, the Moiré is at about half the screen frequency, thereby producing a high-frequency “rosette”-shaped beat pattern.[1] Typically, cyan and magenta are oriented at ±15º, yellow at 0º, and black at 45º in order to minimize visible rosette beat patterns. This angle selection for clustered-dot halftoning can be a limitation in the case of hi-fi color printing. Recently, one direction of research on color printing is the introduction of more colors in the printing process to expand the color gamut imposed on the CMYK colors. These extra colors must be assigned a rotation angle to eliminate Moiré patterns. However, there is a limit to the number of angle selections, otherwise Moiré patterns will arise when two color planes are not sufficiently rotated. Stochastic halftoning such as the Blue Noise Mask (BNM)[2] and error diffusion[3] eliminates this problem completely. The dots created by stochastic screening are placed in an unstructured pattern, thus screen rotation is unnecessary in halftoning color images. But stochastic screening has its own problems in halftoning color images. For error diffusion, the resulting correlated patterns can be objectionable; for the BNM, periodic tiling patterns can be more noticeable as more color planes are overlapped.

To improve the visual quality of color halftoning using error diffusion, Miller and Sullivan[4] treat the color image as a vector space. Instead of halftoning the color components separately, they halftone each pixel as a color vector (also called vector error diffusion). The color image is first converted to a nonseparable color space (for a separable color space, vector error diffusion gives the same results as scalar error diffusion), and the pixel is assigned to the halftone color that is closest to it in the color space. The vector error is distributed to neighboring pixels in the same manner as scalar error diffusion. Klassen et al[5] also proposed a vector error diffusion technique that minimized the visibility of color noise. It is based on the property of the human visual system that the contrast sensitivity decreases rapidly with increasing spatial frequency.[6] Thus the minimum contrast for which noise is visible rises rapidly with increasing spatial frequency. One approach to achieve increased spatial frequency is to avoid printing pixels that have a relatively high contrast with the pixels in their neighborhood. Thus, light grey is printed using non-overlapping cyan, magenta, and yellow pixels, along with white ones.

Color halftoning using a BNM has been studied by Yao and Parker.[7] In the next section, we will review different strategies that have been proposed to apply BNMs to color planes. Then we will use a human visual model to evaluate these halftone methods in CIELAB space in terms of perceived color error.

Blue Noise Mask Techniques in Color Halftoning

The Dot-on-Dot Scheme

We mentioned that using the same halftone screen on the different color planes is the simplest way to produce color halftoned images. This technique can be used directly with the BNM color halftoning. We call it the dot-on-dot technique. Unlike a clustered-dot screen or the Bayer's dither array which generate structured dot patterns, the dots produced by the BNM are unstructured, thus reducing Moiré patterns to the minimum. A potential problem of this technique occurs when a misregistration of the color planes occurs, which will have a disturbing banding effect. Thus, the dot-on-dot technique may be inappropriate for some printers.

The Shifting Scheme

To decrease the correlation of the color planes, we can use shifted BNMs. This will also increase the spatial frequency of the printed dots. For example, we can use a BNM on the cyan plane, then shift the BNM in the horizontal and vertical directions in a wrap-around manner and use the shifted BNM on magenta. Similarly, the BNM can be shifted by different amounts to be applied to yellow and black. This technique will tolerate misregistration problems, however, low frequency structures may appear when a pattern is overlapped with its shifted version.

The Inverting Scheme

In this case, we apply one mask to one color plane and its inverted version to another with an optional adaptive algorithm for other planes. Inverting a BNM means taking the complement of a BNM:

$$m_i(i, j) = 255 - m(i, j)$$

where $m_i(i,j)$ is the inverted mask. This scheme results in the arrangement of color dots with the highest spatial frequency. However, this strategy is appropriate for only two BNMs, a BNM and its inverted version, whereas a color image has three or more color planes. An adaptive algorithm to halftone the third or fourth color plane together with this inverting scheme is currently under study.

The Four Masks Scheme

This scheme is actually an extension of the invert technique. This approach is based on the same idea, i.e., increasing the spatial frequency of the pattern of dots, but this technique will not limit the number of BNMs that can be used as the invert technique does, so it is more appropriate for halftoning color images with multiple color planes.

In this case, four distinct masks are generated for each of CMYK planes. These mask are anti-correlated in a mutually exclusive manner so that color dye is maximally dispersed to achieve high spatial frequency. For detailed procedures to generate these four masks, please refer to reference 8.

Color Halftone Evaluation using an HVS Model in CIELAB Space

A simple color test pattern is generated and then halftoned using above schemes as well as error diffusion for comparison. The resulting halftoned images are enlarged and printed with a color printer. Because of reproducibility problems, we are unable to provide those color printings for this publication. Instead, we will use number to represent different output colors for illustration. In Figure 1, we use number 1-8 to represent the 8 sets of different color dye combinations. All the halftoned images should have a size of 64 by 64, we only show the up left 16×16 portion of each image because of space limit.

As we can see, the dye placement in each patterns is quite different from the others with an unique color error between original image and each halftoned image. To study this perceived color error for each scheme, we evaluate the results in CIELAB space with a human visual model.

There are various models that approximate the response of the human visual system. One of them is the model by Daly [refer to Sullivan et al, 1991]. This model is basically a low-pass filter and has the following mathematical expression:

$$V_{ij} = \left\{ \begin{array}{ll} a\left(b + c\tilde{f}_{ij}\right)\exp\left(-\left(c\tilde{f}_{ij}\right)^{d}\right), & \text{if } \tilde{f}_{ij} > f_{max} \\ 1.0 & \text{otherwise} \end{array} \right\} \tag{1}$$

where a = 2.2, b = 0.192, c = 0.114 and d = 1.1; $\tilde{f}_{ij}$ is the radial spatial frequency in cycles/degree and f_{max} is the frequency at which the function peaks.

To make use of the human visual model, we need to do a conversion from cycles/degree to cycles/inch. Let P be the printer resolution, d the viewing distance from the eye to the object, $N \times N$ the support of the image, (i,j) a location in the FT domain and f_i, f_j the spatial frequency in cycles/degree in the two dimensions. It can be shown that [Lin, 1993]:

$$\tilde{f}_i = \frac{2idP}{N}\tan(0.5^\circ) \tag{2}$$

and

$$\tilde{f}_j = \frac{2jdP}{N}\tan(0.5^\circ) \tag{3}$$

The radial frequency is given by:

$$\tilde{f}_{ij} = \sqrt{\tilde{f}_i^2 + \tilde{f}_j^2} \tag{4}$$

To incorporate the decrease in sensitivity at angles other than horizontal and vertical, the radial frequency is scaled such that $\tilde{f}_{ij} \rightarrow \tilde{f}_{ij}/s(\theta)$, where

$$s(\theta) = \left(\frac{1-w}{2}\right)\cos(4\theta) + \left(\frac{1+w}{2}\right) \tag{5}$$

where w is a symmetry parameter. $\tilde{f}_{ij}$ can then be substituted into Equation (1). With this conversion, the human visual model can be applied directly on a digital image.

Figure 2 shows the block diagram of the scheme. The color pattern is halftoned in the CMY space. Both the halftone and the original color pattern are passed through the human visual model, and then converted to the CIELAB space. The CIELAB color difference is given by:

$$\Delta E^{*}ab = [(\Delta L^{*})^{2} + (\Delta a^{*})^{2} + (\Delta b^{*})^{2}]^{1/2} \tag{6}$$

where ΔL^* , Δa^* and Δb^* are corresponding difference between two colors. This color difference can further be broken up into components of lightness ΔL^* and chroma ΔC^*.[9] Figure 3 shows the plots as a function of printer resolution of the normalized error of ΔE^* as well as ΔL^* and ΔC^* components between the filtered original and halftoned image using the dot-on-dot scheme, the shift scheme with a (1,2) shift for magenta and a (2,1) shift for yellow, the 4 masks scheme (only using three of four in this case) and the scalar error-diffusion scheme.[7] The BNMs used are 128×128 in size. A viewing distance of 20 inches is assumed.

As we can see, when we apply BNMs to color halftoning, the dot-on-dot scheme results in minimum chrominance error, but maximum luminance error whereas the 4-mask scheme results in minimum luminance error but maximum chrominance error. The shift scheme generally produces perceived color error somewhere in between the results produced by dot-on-dot and 4-mask schemes. Error diffusion results in less error at low printer resolutions, however, at high resolutions, color halftoning using BNMs result in less error.

Conclusion

We have reviewed different schemes to halftone color images using BNMs. An evaluation of these schemes is given in CIELAB space using a human visual model. Our analysis shows that different perceived errors are produced by different color halftone techniques. The optimal choice depends in part on the printer resolution and implementation issues. Investigation is currently underway to develop a better human visual model for color halftoned images.

Reference

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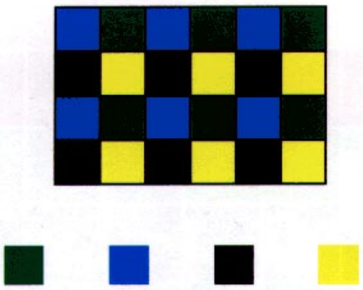

Figure 1. Halftone patch generated by an idealized color printer. Four different pixels used in the halftone pattern are shown as perfect squares.

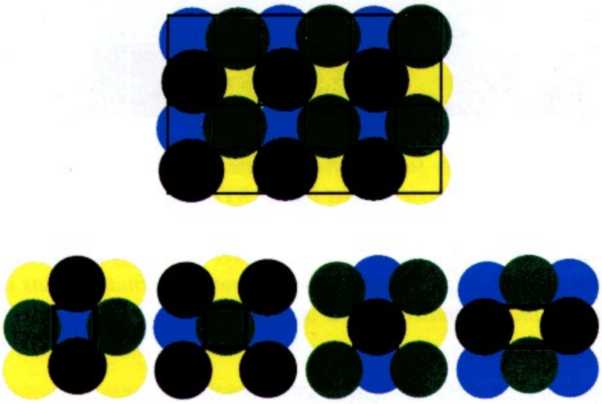

Figure 2. Halftone patch generated by a color printer with the conventional circular-dot model. Four different overlapping patterns are shown and each one is specified by a circular dot at the center of the square pixel and other eight dots surrounding the pixel.

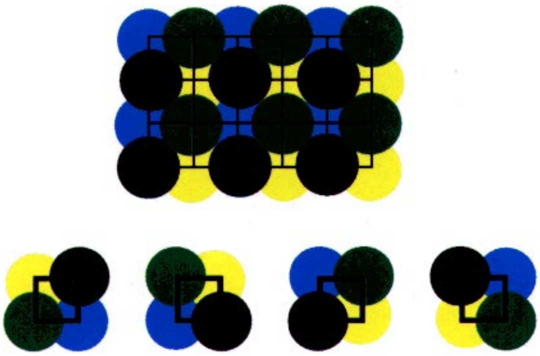

Figure 3. Halftone patch generated by a color printer with the 2x2 centering cencept model. Four different overlapping patterns are shown and each one is fully specified by four circular dots at the corners of the square pixel. The four patterns are mirror images of each other and have the same average color appearance.

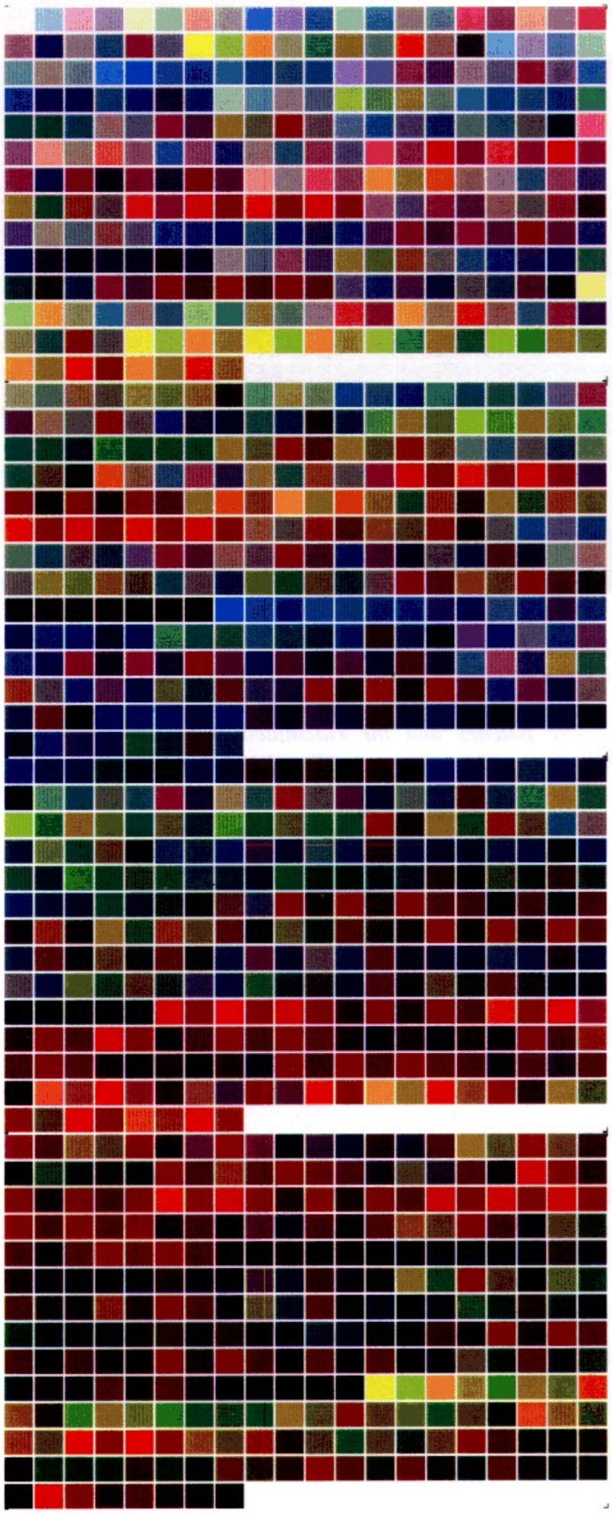

Figure 4. One thousand and seventy-two 2x2 patches printed by a Xerox 5790 color laser printer in 400x400 DPI mode. A CIE XYZ look-up table is generated from color measuring and used for the algorithm-independent color calibration.

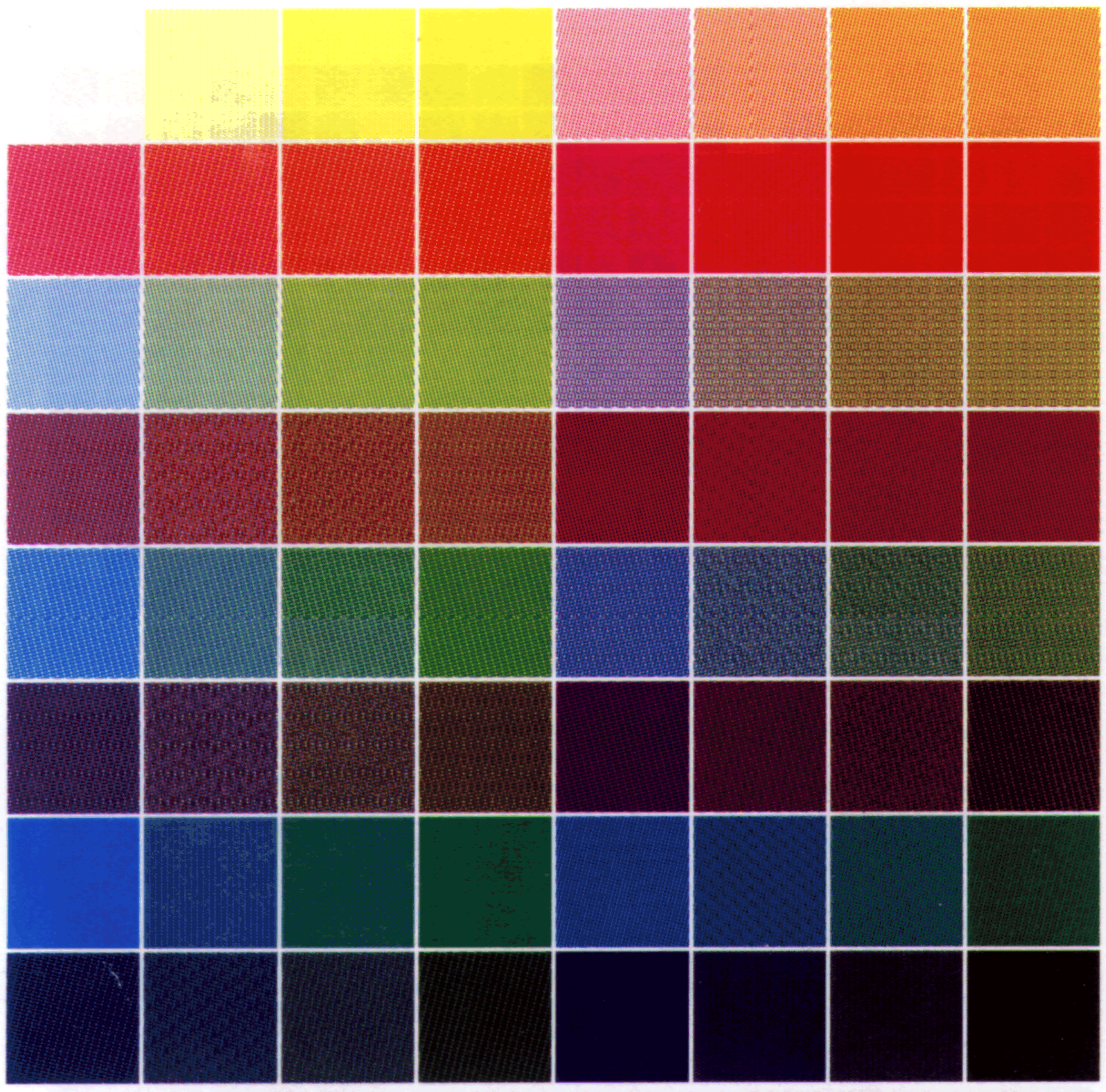

Figure 5. Sixty-four halftone patterns generated by given CMY dithering screens. The inputs are sampled at 0, 85, 170 and 255 in CMY space. The color difference between the measurement of these patches and the calculated prediction by the 2x2 calibration is 4.9 in average ΔE and 12.0 in maximum.

Figure 7. Sixty-four halftone patterns generated by the 2x2 vector error diffusion. The inputs XYZ values used in the error diffusion are predicted color appearances of the 64 dithering output shown in Figure 5. The average color difference between the desired outputs and the measurement of actual outputs is 4.5 in ΔE and the maximum DE is 12.6.

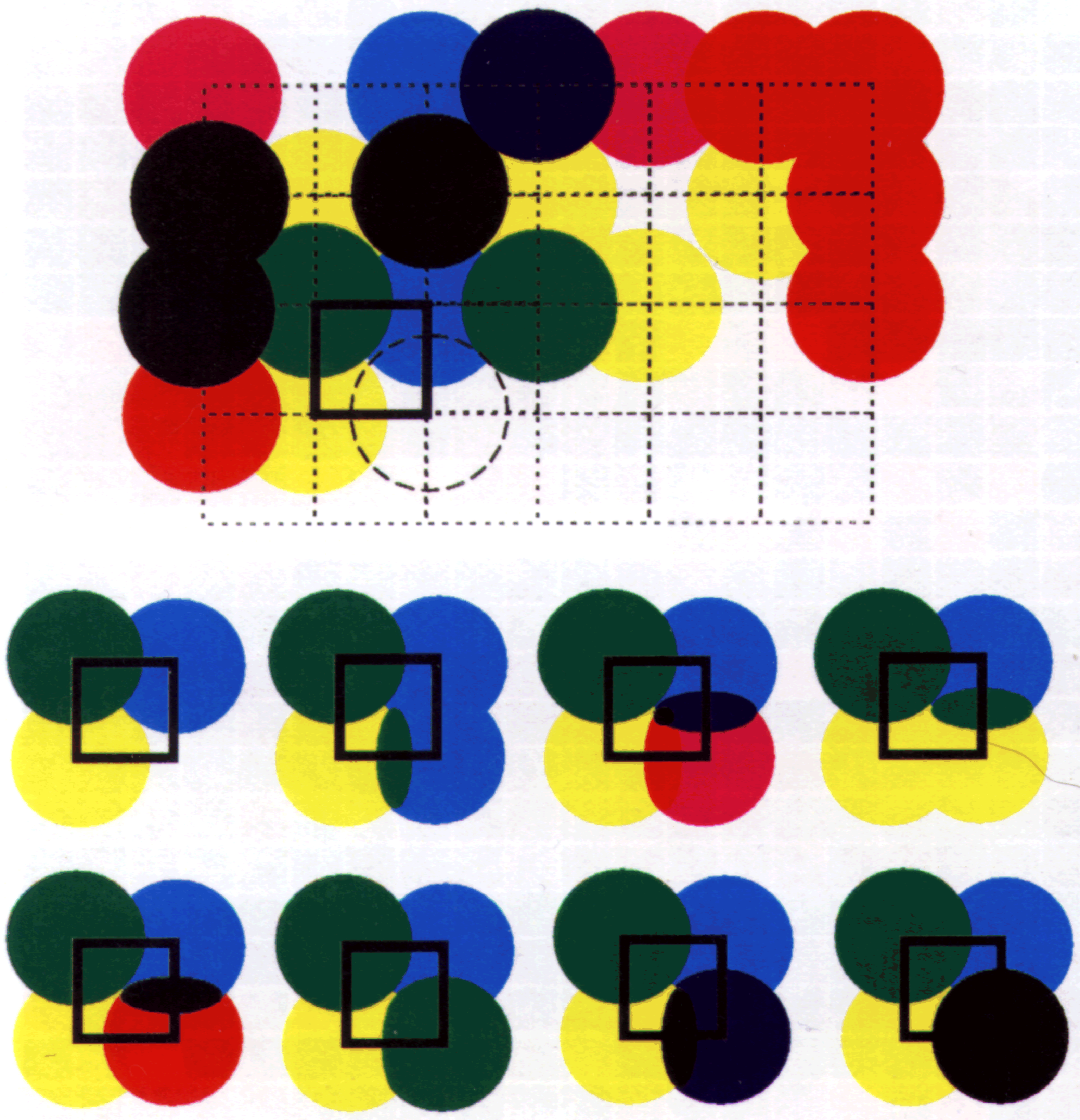

Figure 6. Vector error diffusion processing in the 2x2 centering concept model. Pixels specified in XYZ values are drawn in squares and dots specified in binary CMY signals are represented by color circles. The input pixel, in heavy black lines, is surrounded by three previously determined dots, green, cyan and yellow, and the currently processed one, in dash line. The eight options of 2x2 patterns are also shown above.

Figure 8. A halftone picture generated by the vector error diffusion and the 2x2 centering concept calibration.