Modified Jointly Blue Noise Mask Approach Using S-CIELAB Color Difference

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The current paper proposes a modified jointly-blue noise mask (MJBNM) method using the S-CIELAB color measure. Based on an investigation of the relation between the pattern visibility and the chromatic error of a blue noise pattern, a halftoning method is proposed that reduces the chromatic error, while preserving a high quality blue noise pattern. Although the jointly-blue noise mask (JBNM) method provides a visually pleasing pattern for single and multiple color planes, the halftone outputs of a JBNM mask exhibit a higher chrominance error. Accordingly, 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. Using the calculated low-pass filtered error, 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 is selected. Experimental results demonstrated that the proposed algorithm can produce a visually pleasing halftoned image with a lower chrominance error than the JBNM method.


Introduction

For digital image rendering applications, the output devices need to be able to produce perceptually high quality images with a limited number of output states. As such, digital halftoning techniques have been an active research area over the last three decades in an effort to meet this challenge. Digital halftoning techniques include ordered dithering, error diffusion, blue noise masks (BNM), etc.1-4

In conventional color halftoning, a clustered-dot screen is used to control the color placing on the paper. The same screen is also used to halftone the cyan, magenta, yellow, and black planes separately. One immediate problem with this scheme is that a noticeable spatial artifact, often referred to as a Moiré, occurs in halftoned color images. To reduce Moiré patterns, each screen is typically oriented at different angles. However, there is a limit to the number of the orientation angle selections. Therefore, it can be difficult to apply conventional color halftoning techniques to high-fidelity color printing.

In a blue noise halftoning method, the problems related to Moiré patterns in conventional screen designs are replaced by color image quality issues related to the overlay of blue noise patterns. A number of different schemes have been proposed for generating one or more blue noise masks for color halftoning. These schemes include the Dot-On-Dot scheme, Shifted Mask scheme, Inverted Mask scheme, and Four-Mask scheme.5 However, none of these schemes involves an analysis of the properties of the overlaid blue noise binary patterns and the interaction between the color channels is only partially considered.

In the current study, 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. Using the calculated low-pass filtered error, the patterns are then updated by either adding or removing dots from the multiple binary patterns. Finally, the pattern that shows the lower S-CIELAB chrominance error is selected. The whole procedure is as follows: Three initial patterns are created from the input binary pattern power spectrum matching algorithm (BIPPSMA) mask. To make the gray level of a pattern one level down, randomly selected white dots are changed into black dots for each pattern. Thereafter, four combined patterns are created from the three single patterns, three double patterns are created by combining two single patterns, and one triple
pattern is created by combining all three single patterns. The error array and binary patterns are updated using Gaussian LPF. Then the seven S-CIELAB errors of the three single patterns, three double patterns, and one triple pattern are calculated. If the computed color error drops, the creation of the combined patterns is repeated. After the downward mask generation is completed, the upward mask generation is carried out, starting from the initial gray level. Finally, when the gray level reaches L, all mask components are completely built and the whole mask generation procedure stops. The proposed algorithm can produce a visually pleasing halftone image with a lower chrominence error than the JBNM method. In addition, the JBNM produces a higher chrominence error than the proposed method. Based on experiments, the S-CIELAB error and CIELAB error were both measured and Table I shows that the proposed method produced a smaller color difference between the original patches and the halftoned patches than the JBNM method. Plus, Table II shows that the proposed method exhibited a lower luminance and chrominence error.

### Jointly-Blue Noise Masks

Wang and Parker suggested an algorithm that generates a set of JBNMs. They inspected various combinations of binary patterns and 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 a high quality blue noise pattern whether they are used individually or jointly. In addition, Wang and Parker also attempted to make three independent masks that preserve good blue noise characteristics in each single pattern, while yielding a high quality blue noise appearance in combined patterns. As a result, they used digital filtering techniques to design a set of joint blue noise masks to provide high quality color halftone outputs with minimal visibility to the human eye. 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. However, the halftone outputs of JBNM show a higher chrominence error.

### Color Image Fidelity Metric

The CIELAB metric is a widely used color metric that works reasonably well in applications involving large uniform patches viewed under standard illuminants. The effects of visual adaptation are partially included in the original CIELAB metric. Yet, standard CIELAB calculations do not clarify the performance well (Wandell and Brainard), therefore, Fairchild and Berns proposed a set of computations to improve on the original CIELAB definitions.

Zhang and Wandell introduced a new color image fidelity metric, a spatial extension of CIELAB, called the S-CIELAB metric. They included the spatial-color sensitivity of the human eye in the metric to account for how a spatial pattern influences color appearance and color discrimination. The S-CIELAB metric incorporates the different spatial sensitivities of the three opponent color channels by adding a spatial pre-processing step before the standard CIELAB calculation. An input image is initially converted into an opponent color format. Each component image is then passed through a spatial filter that is selected according to the spatial sensitivity of the human eye for that color component. Two goals were involved in designing the S-CIELAB error measure. The first was to simulate the spatial blurring of the human visual system by applying spatial filtering to a color image. The second was to create a consistent extension to the basic CIELAB calculation when an input image has large uniform areas. Therefore, the S-CIELAB measure not only produces a better error prediction than CIELAB for textured or patterned images like printed halftone patterns, but also provides a consistent extension to the basic CIELAB measure for images that include large uniform areas. An S-CIELAB color difference value greater than 1 implies that the color difference is detectable by humans.

### Relation of Pattern Visibility and Chromatic Error

A high quality blue noise pattern should be minimally visible to the human eye, without low frequency components, texture, or other artifacts. When a blue noise pattern is used for reproducing black and white images, the number of black pixels in the pattern has the most impact on the reproduced average lightness level. The only other factor controlling the production of a high quality image is the shape of the array of black and white dots. As such, the best choice is a blue noise pattern with a minimally visible dot pattern. Therefore, the pattern visibility of a blue noise pattern is the core problem in both black and white halftoning and color halftoning. Several schemes, including the shifted mask scheme, inverted mask scheme, and four-mask scheme, have been proposed in relation to the use of blue noise masks in color image rendering. The common goal of these schemes is to minimize the pattern visibility and minimize the low frequency energy introduced due to color plane overlapping. In the four-mask scheme mutually exclusive seed patterns were used as the initial patterns, thereby achieving non-overlapping color planes at highlight levels.

When a blue noise mask is applied to color image halftoning, a good reproduction of the color value of the original image is also an important point as well as the pattern visibility of the blue noise pattern. In Fig. 1, the overlaid pattern (g) resulting from the three blue noise patterns (a), (b), and (c) shows more low frequency components than the overlaid pattern (h) resulting from patterns (d), (e), and (f). In addition, pattern (g) has an 11.5% dot overlap, while pattern (h) has a 0% dot overlap. However, the color pattern that includes the three color values of (a), (b), and (c) shows a lower S-CIELAB color error than the color pattern that includes the three color values of (d), (e), and (f). This example demonstrates that minimum pattern visibility does not lead
Figure 1. Example showing that minimum pattern visibility does not guarantee a lower chrominance error. The combination of a blue noise pattern of 228 out of 255 gray levels (a), blue noise pattern of 222 (b), and blue noise pattern of 233 (c) produced a color halftoned output with a 5.338 S-CIELAB value. Meanwhile, the combination of a different 228 pattern (d), 222 pattern (e), and 233 pattern (f) produced a color halftoned output of 6.298.
to minimum color error. As such, there should be some controls to achieve both goals.

In the JBNM method, jointly optimized blue noise patterns are produced for three color channels using filtering concepts. In the procedure of generating an optimized JBNM, only the optimality of the multiple dot patterns themselves is taken into consideration. Although the use of a low-pass filtering technique is sufficient to achieve either single or combined patterns that exhibit less visible high blue noise characteristics, there is no consideration of the output chrominance error. As a result, the JBNM method produces visually pleasing halftoned outputs with a lower luminance error, yet creates higher chrominance error outputs. Accordingly, the next section introduces modifications to the JBNM method to provide control over chrominance error reduction, while also preserving the minimum visibility of the blue noise patterns using the S-CIELAB error measure.

Modified Jointly-Blue Noise Mask Method

The proposed method for color halftoning produces a set of blue noise masks for three color channels. When the blue noise mask set is made, it can be used to provide high quality color halftoning outputs with a reduced chrominance error and minimal visibility to humans. To introduce the effect of chrominance error minimization into the process of mask generation, the S-CIELAB error measure is applied using a digital filter technique. The low-pass filtered error and S-CIELAB error are both calculated for single and combined patterns. Using the calculated low-pass filtered error, the patterns are then updated by either adding or removing dots from the multiple binary patterns. Next, the S-CIELAB error is calculated for the updated patterns and examined. The pattern that shows the lower S-CIELAB error is finally selected.

Constructing MJBNM Masks

Figure 2 shows a flowchart for the construction of the proposed MJBNM. The input is a mask generated by BIPPSMA. The output is three masks for three color channels. The whole procedure is as follows:

**Initial Pattern Generation**

The quality and optimality of the initial pattern is crucial for mask generation. Since the screen or mask technology must satisfy the stacking constraint, there is a strong dependence between the design level textures. Therefore, the quality of the initial pattern affects the entire process. Three initial patterns $p_1$, $p_2$, and $p_3$ are created from the input BIPPSMA mask. These three patterns are made mutually exclusively so as to minimize any low frequency energy resulting from color pane overlapping in the highlight levels. If the initial gray level is set at 171, in order to accomplish full mutual exclusivity between the three color channels, the minimum boundary of the gray level will also be 171. Set the gray level of $p_1$ to the initial gray level. To obtain three mutually exclusive single patterns, set the gray level of $p_2$ at a gray level where the number of black dots becomes exactly twice that of the $p_1$ pattern. Similarly, set $p_3$ at a gray level where the number of black dots becomes exactly three times that of the $p_1$ pattern.

Each pattern is thresholded by the BIPPSMA mask. Then, where the $p_1$ pattern has black dots at the same location as in the $p_2$ pattern, change those $p_2$ pattern black dots into white dots. Similarly, where the $p_3$ pattern has black dots at the same location as in the $p_1$ or $p_2$ pattern, change those $p_3$ pattern black dots into white dots. Finally, the three initial patterns $p_1$, $p_2$, and $p_3$ are constructed using the same gray level. As a result, mutual exclusivity can be guaranteed in the initial single patterns.

Mutual exclusivity is necessary to minimize any low frequency energy resulting from color pane overlapping in the highlight levels. Therefore, to maintain the blue noise characteristic, three initial non-overlapping patterns are created from the input BIPPSMA mask. Plus, the patterns for all the gray levels are designed to maintain the blue noise characteristic. Low-pass filtering is used to consider the blue noise characteristic and S-CIELAB error measure.
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Next Lower Gray Level

The current three patterns are stored as \( S_3p \), \( S_2p \), and \( S_1p \). To make the gray level of a pattern one level lower, the selected \( K \) white dots are randomly changed into black dots for each pattern. If the size of the mask is \( N \)-by-\( N \) and the total number of gray levels is \( L \), then

\[
K = N \times N/L.
\]

Thus, if \( N \) is 64, generating 64 \( \times \) 64-sized MJBNM masks, and \( L \) is 256, the value of \( K \) will be 16.

Creation of Combined Patterns

From the three single patterns \( S_1, S_2, \) and \( S_3 \), four combined patterns are created. Three double patterns \( D_1, D_2, \) and \( D_3 \) are created by combining two single patterns, and one triple pattern \( T \) is created by combining all three single patterns. In a combined pattern, a pixel can only be white when all the pixels in the single patterns are white at the same location. If any one of the pixels in the single patterns is black, the pixel will be black in the combined pattern.

Generation of Gaussian Filter

A Gaussian function is used to generate the low-pass filters. In this case, the low-pass filter should be designed so that its cutoff frequency changes according to the gray level of the pattern. The principal frequency \( f_g \) varies from gray level \( g \) and its form is

\[
f_g = \begin{cases} \sqrt{g}, & \text{for } g \leq 1/2 \\ \sqrt{1-g}, & \text{for } g > 1/2. \end{cases}
\]

Gaussian low-pass filters are shaped by adjusting the sigma value according to the gray levels of the pattern:

\[
F(u, v) = e^{-(u^2 + v^2)/2\sigma^2}
\]

where \( \sigma = f_g/S \). In this equation, is employed for general use.

Error Array and Binary Pattern Update

Three error arrays are constructed as follows:

\[
E_1 = LF(S_1) + LF(D_1) + LF(D_2) + LF(T),
E_2 = LF(S_2) + LF(D_2) + LF(D_3) + LF(T),
E_3 = LF(S_3) + LF(D_3) + LF(D_3) + LF(T),
\]

where \( LF( ) \) denotes the low-pass filtered error of the pattern. The \( E_1 \) error array reflects the effects on the single, double, and triple patterns when the single pattern \( S_1 \) is changed. Likewise, \( E_2 \) is associated with the single pattern \( S_2 \) and \( E_3 \) with the single pattern \( S_3 \).

After constructing the error arrays, they are sorted. For the \( S_1 \) single pattern, \( M \) black dots, which have the largest error values in the sorted error array \( E_1 \), and the white dots at the same locations in the saved \( S_{1p} \) are identified. The value of \( M \) was chosen to be 16 so as to match the value of \( K \). Next, these \( M \) black dots are swapped with \( M \) white dots with the smallest error values. Similarly, the single patterns \( S_2 \) and \( S_3 \) are also updated according to the sorted error arrays \( E_2 \) and \( E_3 \), respectively. As a result, the method is not susceptible to a local minimum because \( M \) black dots with the largest error values in the sorted error array are swapped with \( M \) white dots after constructing the error arrays using low-pass filtering.

By selecting the black dots that have white dots at the same location in the stored patterns \( S_{1p}, S_{2p}, \) and \( S_{3p} \), the stacking constraint is satisfied in the resulting masks. The stacking constraint provides a correlation between successive levels. For a level that is higher than

![Figure 2. Flowchart of MJBNM construction.](image-url)
the initial gray level, mutual exclusivity is automatically achieved if the stacking constraint is satisfied. This automation is also related to the mutual exclusivity of the initial single patterns.

**Computing S-CIELAB Error**

The seven S-CIELAB errors for the three single patterns, three double patterns, and one triple pattern are calculated. The three single patterns $S_1$, $S_2$, and $S_3$ are considered as cyan, magenta, and yellow patterns, respectively. As such, the double patterns are considered as colored patterns that only have two color components, while the triple pattern is considered as a gray pattern.

The calculation of the S-CIELAB error for the patterns is performed according to the following procedure. A color transformation converts each pattern, specified in terms of the tristimulus values, into CIE 1931 XYZ values. The color transformation is as follows:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} 0.430574 & 0.341550 & 0.178325 \\ 0.222015 & 0.706655 & 0.071330 \\ 0.020183 & 0.129553 & 0.939180 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}, \quad (5)$$

Then, each pattern of XYZ values is converted into three opponent-color planes that represent the luminance, red-green, and blue-yellow values. After obtaining the three opponent-color planes, a spatial low-pass filtering technique is used to account for human spatial color sensitivity. The viewing conditions for the spatial low-pass filtering were a viewing distance of 20 inches and resolution of 300 dpi. The data in each plane are filtered using two-dimensional separable spatial kernels. The filtered patterns are then reconverted into XYZ values and then back into CIELAB values.

In this equation, $\Delta E$ is the S-CIELAB error. The total S-CIELAB error is

$$E_T = \sum_i \Delta E(S_i) + \sum_i \Delta E(D_i) + \Delta E(T) \quad (6)$$

In this equation, $\Delta E$ is the S-CIELAB error.

**Upward Mask Generation**

When the downward mask generation is completed, the upward mask generation is performed, starting from the initial gray level. This procedure is basically the same as the downward mask generation, except that the white dots are replaced with black dots. Finally, when the gray level reaches $L$, all mask components are completely built and the whole mask generation procedure stops.

**Experiments and Discussion**

The proposed method was simulated using color patches and natural images. For the color patches, the S-CIELAB error and CIELAB error were both measured, whereas for the natural images, the S-CIELAB error was measured and the visual quality of the halftone outputs was observed. 64 × 64-size MJBNM masks were generated and used in all the experiments. For a comparison with the proposed method, the JBNM method developed by M. Wang and K. J Parker was used. All the JBNM masks were generated without the S-CIELAB metric, and the value of M was chosen to be 16 so as to match the value of K.

**Color Patch Experiments**

Patches (256 × 256) were made using MacBeth ColorChecker values. Figure 3 shows the halftoned
patches created by the JBNM and MJBNM methods. The RGB values of the original image were 128, 128, and 197, respectively. The left patch showed structured patterns or low frequency patterns, whereas the right patch showed less structured patterns and a pleasing result. Table I shows that the MJBNM method produced a smaller color difference between the original patches and the halftoned patches than the JBNM method. Plus, the MJBNM method succeeded in producing less perceptual color difference than the JBNM method.

The color error between the patches on the monitor screen and the hardcopies from the printer was measured based on the CIELAB measure using a Minolta CA-100 chromameter and Minolta CM-3600d spectrophotometer. Table II shows the luminance error, chrominance error, and CIELAB color difference for the halftoned patches produced by the JBNM and MJBNM methods. The halftoned patches using the MJBNM method exhibited a lower luminance and chrominance error.

Natural Image Experiments
Airplane, Bicycle, and MacBeth Color Checker images were used for the natural image experiment. Figures 4(a), 5(a), and 6(a) are hardcopies of the halftone outputs using the JBNM method, while Figs. 4(b), 5(b), and 6(b) are hardcopies of the halftone outputs using the MJBNM method. Each image was printed by an HP DeskJet 895Cxi at 300dpi. Table III shows the S-CIELAB errors of the halftone output images in Figs. 4, 5 and 6. The halftone outputs using the MJBNM method had a lower S-CIELAB error than those using the JBNM method. However, for Figs. 4 and 5, since the differences between the error values were smaller than 1, it is hard to see any chromatic difference between the halftone outputs when using the JBNM and MJBNM methods. Although, for Fig. 5(b), the curtain on the left is smoother and a different color compared to that in Fig. 5(a). Meanwhile, for Fig. 6, the difference between the S-CIELAB error values was larger than 1, therefore, a chromatic difference can be seen between the two halftoned outputs. These results agree with the color patch experiment results.

Conclusion
A halftoning algorithm was presented to reduce the chromatic error in halftone outputs, while preserving the minimum visibility of multiple blue noise patterns. When the relation between pattern visibility and chrominance error in halftoned outputs was explored, it was found that minimum pattern visibility did not result in the minimum chromatic error.

Accordingly, the MJBNM method that uses the S-CIELAB color difference measure was introduced. The proposed algorithm provides a means of controlling the chromatic error that occurs in the halftoned output as a result of constructing a set of blue noise masks. The S-CIELAB error measure is introduced to reduce the chromatic error in the halftoned outputs. As such, in the pattern generation process, the low-pass filtered error is used to make a minimally visible pattern, while the S-CIELAB error is used to evaluate the suitability of the updated pattern from the angle of chrominance error minimization. In experiments, the proposed method

<table>
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<th>Figure 4</th>
<th>Figure 5</th>
<th>Figure 6</th>
</tr>
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<tbody>
<tr>
<td>JBNM</td>
<td>11.703</td>
<td>11.879</td>
<td>16.501</td>
</tr>
<tr>
<td>MJBNM</td>
<td>11.021</td>
<td>11.601</td>
<td>15.440</td>
</tr>
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Figure 4. Result images for Airplane: (a) JBNM, (b) MJBNM. Supplemental Materials—Figures can be found in color on the IS&T website (www.imaging.org) for a period of no less than two years from the date of publication.
produced halftoned images with a lower chrominance error than the JBNM method, while also achieving visually pleasing color halftoned outputs.

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