Properties of Jointly-Blue Noise Masks and Application on Color Halftoning

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Abstract

It has been shown that dithering with blue noise is useful for producing visually pleasing halftone images. For color halftoning, the goal of blue noise mask design is to generate a set of blue noise masks which produce high quality blue noise patterns when they are used individually or jointly. In this paper, an approach is proposed which is based on digital filter techniques and can be used to generate a set of jointly-blue noise masks. Each mask from the set of the masks will be applied to one color plane. The jointly blue noise masks possess the properties such that each individual mask is blue noise, also the combinations of the masks produce color images with blue noise characteristics, e.g., the dots of different color are mutually exclusive and maximally dispersed on the combined plane at highlight levels. Several other schemes which have been developed are also reviewed in this paper. Examples of output color images created by the approach and other schemes are given.

1. Introduction

Color halftoning is an extension of grey scale halftoning, however, it entails additional complications. Color rendering is the synthesis of halftoning processes in several color planes. Typically, Cyan, Magenta, Yellow and optional Black and ”high fidelity” or accent colors are halftoned and combined on a single page to produce color hardcopy. The combination of color planes is not a simple superimposition of all the color dots. The appearance of color images greatly relies on the interactions of color planes. For color halftoning using conventional periodic screens, such as cluster dot halftoning, the combinations of successive patterns result in artifacts such as Moiré patterns. Early work on color halftones with periodic dithering focused on eliminating such artifacts. The solution is to rotate halftone screens so that the screens used for different color planes are oriented in different directions. The artifacts caused by the combinations of periodic screens can be avoided by using blue noise halftoning instead. In color blue noise halftoning, combinations of stochastic patterns eliminate the interference of periodic low frequency components.

Compared with the studies of blue noise on grey scale halftoning, the properties of the analysis and synthesis of blue noise patterns have received less attention, despite the critical importance. The goal in synthesis of blue noise is to somehow generate a halftone scheme that will, for example, create a visually pleasing cyan pattern (when called for by a highlight cyan region), and create a visually pleasing magenta pattern where necessary, and also create a visually pleasing joint pattern of cyan plus magenta where this combination is required. Thus, we require that the quality of blue noise is preserved in each individual color plane, and also that the resulting combination patterns exhibit high quality blue noise appearance, at least in the ideal case.

In this paper, we first review the current schemes which apply blue noise mask (BNM) to color halftoning. Then a new algorithm which utilizes digital filtering technique in BNM design is proposed. The concept of jointly-blue noise mask (JBNM) is introduced to describe the property of a set of BNM’s, that they are individually blue noise and also blue noise when they are combined on a single image plane. Finally, the results and evaluation of applying the current schemes and JBNM are given.

2. Current Color halftoning schemes with Blue Noise Mask

A number of different schemes have been proposed to utilize one or more blue noise masks for color halftoning (Yao and Parker[1], Yu and Parker[2]). Other descriptions also have been given by Mulligan[3], Spaulding, Miller and Schildkraut[4], and Lin and Allebach[5].

2.1. Dot-on-Dot

An intuitive and simplest realization of color dithering is the ”dot-on-dot” scheme. In this scheme, the same BNM mask is used for each color channel. Although this method is easy to implement, it is rarely used in practice because it results in the highest level of luminance modulation and the color reproduction will be vulnerable to registration errors.

2.2. Shifted masks

Spatially shifted versions of masks can be used to each color channel to minimize number of the dots that are overlaid. For example, a blue noise mask can be used for the cyan color channel. Then the mask is shifted by some number of pixels and then applied to magenta channel. This shift is circularly periodic and can be implemented on either of the vertical or horizontal directions or both. A new mask for yellow or other color planes can be acquired by shifting different number of pixels. Care must be taken when choosing shift values so that no inadvertent low-frequency patterns will be introduced when color planes are combined.

2.3. Inverted masks

Another approach is to use an ”inverted mask” to apply to one or more of the channels. The inverse mask is generated by inverting or taking the 255 complement of a mask (assume a 8 bit plane image), i.e.,

$$m_{inv}(i,j) = 255 - m(i,j) \tag{1}$$

where $m(i,j)$ is a BNM and $m_{inv}(i,j)$ is the inverted mask.

This inverted mask is also a blue noise mask. Applying a mask and its inverted version to different color planes will reduce the number of dots that are overlaid for two of more color planes. In light grey level, the dots for the second channel will typically be placed to the voids of those of second color channel, thus resulting in the non-overlaying distribution. However, this scheme can be applied to only two color planes. For the other color planes, shifted version masks can be used.

2.4. Mutually exclusive masks (Four-mask)

The Dot-on-dot, Shift, Invert, Cumulative masks use either a single blue noise mask or a blue noise mask and some transformations of that mask. In four-masks, a set of independently derived masks is acquired. In order to decorrelate the masks, complementary random seeds are used as the initial patterns in the blue noise generating process. These masks have the properties of being mutually exclusive at some level g. For example, in a 4 color CMYK system with 4 masks, at 25% color fill in any plane, the pixel positions receiving ink from one color are mutually exclusive from the pixel positions receiving from other colors. The four mutually exclusive seed patterns can be generated by thresholding a blue noise mask, in which the dots belonging to the levels of [0,63], [64,127], [128,191] and [192,255] correspond to one seed pattern of level of 25%, respectively. With the four mutually exclusive seed patterns, four blue noise masks are constructed independently. The dots of the four color planes are mutually exclusive when the level of each color plane is less than 25%. The intermediate patterns [64,127] and [128,192] are not high quality blue noise patterns, so slight adjustments and swapping operations may be utilized to improve the quality of the two seed patterns.

3. Constructing jointly-blue noise masks

The resultant combinations of unstructured patterns can be various. For example, the addition of two blue noise patterns can be a poor quality binary pattern, whereas the superimposition of a good blue noise pattern and a relative ”grainy” pattern can produce a high quality blue noise pattern, etc. Among the several possible combinations, our desired type is high quality combined patterns constructed from high quality binary patterns. More specifically, at highlight levels, we want the color dots from different color planes not to overlap each other. Furthermore, the color dots should possess the blue noise characteristics whenever they are exhibited on each individual color plane or on the combined plane. This requires that the resultant combined patterns from different masks must be considered in the BNM design, as well as the single BNM.

The algorithm proposed in this section is based on digital filter technique [6] [7] and can be used to generate a set of blue noise masks. In greyscale halftoning, one blue noise mask is created by successively adding or removing dots on a single blue noise pattern, whereas in color halftoning, three or four dithering masks are required for most of the color halftoning applications. The steps to generate jointly optimized blue noise masks are outlined as follows. For the sake of illustration, assume three masks are needed for three color output channels.

1. Create three initial masks, m_1, m_2 and m_3, based on three mutually exclusive blue noise binary patterns of same level g.

2. Specify an integer M, which is the number of black and white dots to be swapped at each iteration.

3. Construct three binary blue noise patterns s_1, s_2 and s_3 by thresholding the three masks with the level g, and mark the locations of black dots. Change K white dots to black dots for each mask. K is the number of pixels to be changed in order to decrease the grey level by one. For example, if the size of the mask is N by N and the total number of levels is L, then $K = N * N/L$. The K pixels on each mask can be selected randomly as long as they are mutually exclusive on the combined plane at some given levels. This restriction is similar to that described later in step 7.

4. Create the combined patterns. There are total seven combinations for a three mask set: three single patterns s_1, s_2 and s_3, three patterns by combining two single patterns,

D_1, D_2 and D_3, and one triple pattern which is the combination of all the three single patterns T. The combined patterns are defined by:

$$\begin{aligned} D_1 &= w_{11} * s_1 \oplus w_{12} * s_2 \\ D_2 &= w_{22} * s_2 \oplus w_{23} * s_3 \\ D_3 &= w_{31} * s_1 \oplus w_{33} * s_3 \end{aligned} \tag{2}$$

$$T = w_1 * s_1 \oplus w_2 * s_2 \oplus w_3 * s_3 \tag{3}$$

The symbol "$\oplus$" is the superimposition or overlay operation of minority pixels. The factors w_{11-33} and $w_{1,2,3}$ are weighting factors of the contribution from each single binary pattern. The weighting factors can be chosen according to the requirements of the application. For example, if s_1 corresponds to Cyan color plane in the halftoning, w_{11}, w_{31} and w_1 can be chosen in proportion to its relative contribution to luminance. The weighting factors provide us a flexibility to fulfill some specific requirements in the mask design.

5. Specify three 2-D low-pass filters L_s, L_d and L_t which are appropriate for single, double and triple patterns, respectively. The cut-off frequencies of the filters should be determined by the grey level of single and combined patterns[8]. Apply the filters to the corresponding patterns to obtain seven filtered patterns.

6. Construct three error arrays by:

$$\begin{aligned} E_1 &= L_s(s_1) + L_d(D_1 + D_3) + L_t(T) \\ E_2 &= L_s(s_2) + L_d(D_1 + D_2) + L_t(T) \\ E_3 &= L_s(s_3) + L_d(D_2 + D_3) + L_t(T) \end{aligned} \tag{4}$$

E_1 reflects the synthetic effects on single, double and triple patterns by changing s_1. Likewise, E_2 associates with s_2 and E_3 associates with s_3.

7. Update the three binary patterns sequentially, that means, in one iterative operation, the three patterns are updated one by one.

First, update the first pattern, s_1. Sort error array E_1. Find M black dots which have the largest error values and are not marked in step 3, and swap these M black dots with M white dots which have the smallest error values.

Similarly, sort error arrays E_2 and E_3 and update s_2 and s_3 accordingly.

In the above operations, a restriction applies in the process of making the joint masks. For a level higher than a predetermined value, which corresponds to a highlight value, if a pixel is selected by one of the patterns as a black dot, that pixel is not allowed to be selected by the other two patterns any more. The other two patterns have to seek for appropriate candidates other than the pixels which have already been picked. This restriction ensures that the binary patterns of the three masks are mutually exclusive, and that the minority dots disperse maximally. If the level is decreased to the level that some minority pixels must overlap, this restriction will not apply.

8. Compute the summation of the MSE of the seven patterns. If the MSE drops, go back to step 4 and repeat the same process. If the MSE increases but $M \neq 1$, set $M = M/2$, and go back to step 4, otherwise, reset M to the initial value as specified in step 2, then go to the next step.

9. Update the three masks based on the three updated pattern s_1, s_2 and s_3, decrease level by 1, and go back to step 3, until the desired level is reached.

This algorithm creates a set of blue noise masks and the correlation between the masks are controlled to tend to eliminate the redundant energy for the combined level. Both of the resulting single patterns and combined patterns exhibit the blue noise characteristics with a desired energy distribution. We call the set of jointly constructed masks "jointly-blue noise masks (JBNM)". The properties of JBNM is that it can produce high quality blue noise patterns whether it is used individually or jointly. This is realized by specifying different low-pass filters to single and combined patterns and by minimizing the synthetic errors of all the possible single and combined patterns. The restriction in step 7 ensures that there are no overlapped dots on the combined output image plane at highlight levels. The flowchart of this algorithm is illustrated in Figure 1.

Figure 2 provides an example of the patterns created by 3-jointly-blue noise masks. The quality of the jointly-blue noise patterns is close to that of the regular blue noise patterns. They produce visually pleasing patterns whenever they are used individually or jointly.

4. Results of halftoning a color patch

Figure 3 shows the results of applying different schemes to render a neutral color solid patch with grey level of 246 (out of 256). The rendered patches, from left to right, are produced by shift masks, invert and shift masks, four masks and jointly-blue masks, respectively. By inspection, the JBNM results in a least visible pattern, with few clumps and very little texture. All the color dots are not only mutually exclusive but also they disperse maximally on the image plane.

The perceived luminance and chrominance errors of these halftoned images are listed in Table 1. Human visual system model was applied on the halftoned images and the luminance and chrominance errors compared with the continuous image were evaluated in CIE$L^*a^*b^*$ space. In the calculation, it is assumed that the resolution is 300

scheme	ΔL	ΔC
shift	3.3936	11.7600
invert + shift	3.3573	11.8331
four	3.3513	11.8997
joint	3.1390	12.5731

Table 1: *Luminance and chrominance errors of the color images in Figure 3*

dpi and the viewing distance is 10 inches. The JBNM results in the minimal luminance error and its chrominance error is a little higher than those of other schemes.

In the color halftoning schemes discussed in Section 2, either single or multiple blue noise masks are applied to several color planes. These schemes use different strategies to produce multiple blue noise masks. The inverted mask and shifted mask are themselves blue noise. The Four Masks are derived from four mutually exclusive initial blue noise patterns, so they are anti-correlated to each other at highlight levels, and thus the combinations of such masks reduce the correlations between the color planes. Although the idea of applying different versions of masks or mutually exclusive derived masks implies the correlations of different planes, no specific designs or controls on the correlations between color planes are applied in producing those multiple masks, so the optimality of those schemes is not warranted.

The JBNM starts from jointly blue noise seed patterns. In the procedure of constructing masks, specific low-pass filters are applied to both the single and combined patterns and the jointly-optimizing procedure is applied to the masks for all the levels, so the JBNM is optimal for not only some specific levels but also for a wide range of levels.

5. Conclusion

In this paper, the current schemes which apply the BNM on color halftoning are reviewed. A new approach is proposed which can be used to generate a set of jointly-blue noise mask. The algorithm provides a way to control the correlation between the single patterns in the procedure of updating blue noise mask. The jointly-blue noise masks are generated simultaneously and they are optimized to minimize the visibility of both the single patterns and combined patterns. Thus they produce not only a visually pleasing pattern for a single color plane, but also a visually pleasing joint pattern for the combined color plane.

References

[1] M. Yao and K. J. Parker, ”Color halftoning with blue noise masks”, in *Proceedings, IS&T's Eleventh International Congress on Advances in Non-Impact Printing Technologies,*, IS&T, 1995

[2] Q. Yu and K. J. Parker, ”Adaptive color halftoning for minimum perceived error using the blue noise mask”, in *Color Imaging: Device-Independent Color, Color Hard Copy, and Graphics Arts II, Proc., SPIE* vol. 3018, pp. 272-277, 1997

[3] J. B. Mulligan, ”Digital halftoning methods for selectively partitioning error into achromatic and chromatic channels”, in *Human Vision and Electronic Imaging: Models, Methods, and Applications, Proc., SPIE* vol. 1249, pp. 261-270, 1990

[4] K. E. Spaulding, R. L. Miller and J. Schildkraut, ”Methods for generating blue-noise dither matrices for digital halftoning”, *Journal of Electronic Imaging,* Vol. 6, no. 2, pp 208-230, 1997

[5] Q. Lin, J. Allebach, ”Color FM screen design using DBS algorithm”, *Proceedings of SPIE - the International Society for Optical Engineering*, vol.3300, pp.353-61, 1998

[6] T. Mitsa and K. J. Parker, ”Digital halftoning using a blue noise mask,” *Journal of the Optical Society of America A,* vol. 9, pp. 1920-1929, Nov. 1992.

[7] M. Yao and K. J. Parker, ”Modified approach to the construction of a blue noise mask,” *Journal of Electron. Imaging,* vol. 3, no. 1, pp. 92-97, 1994.

[8] R. A. Ulichney, ”Dithering with blue noise”, in *Proceedings of the IEEE,* vol. 76, pp. 56-79, 1988

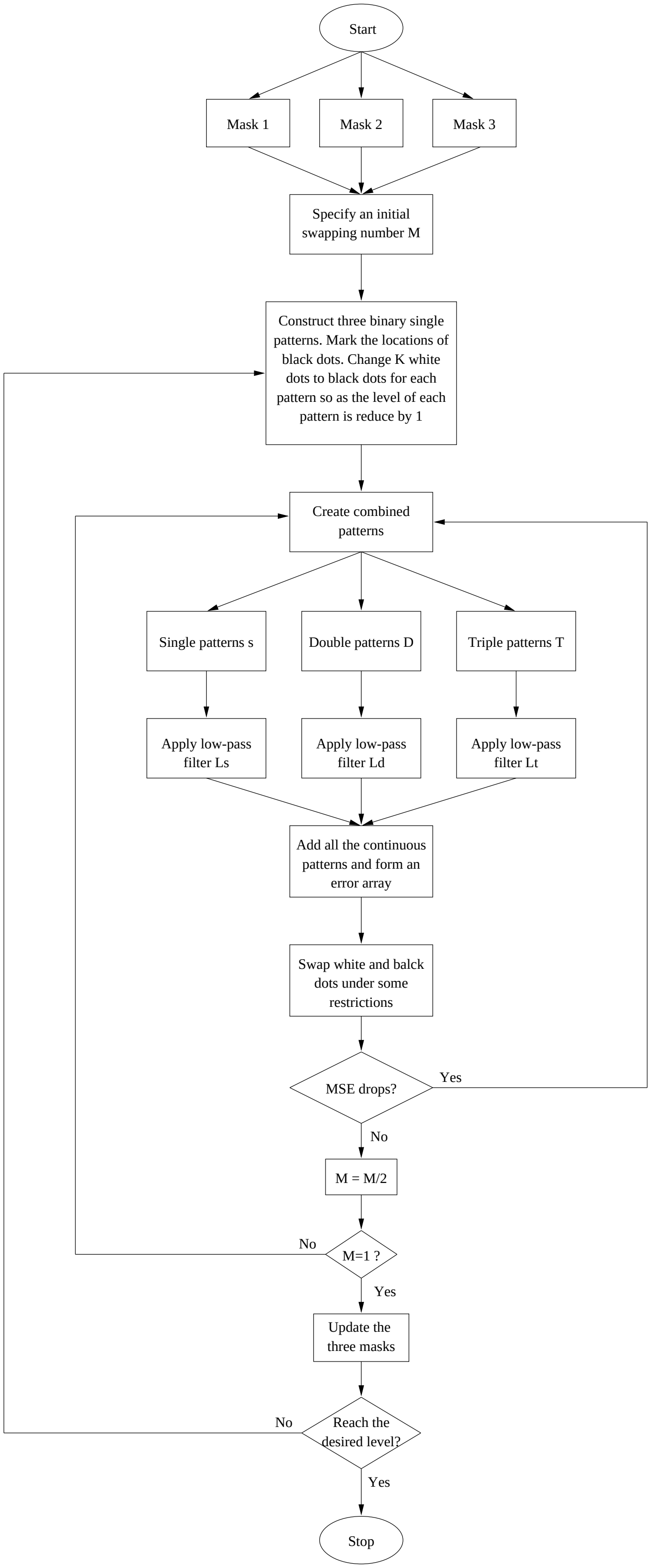

Figure 1: *Flowchart of the jointly-design blue noise masks algorithm*

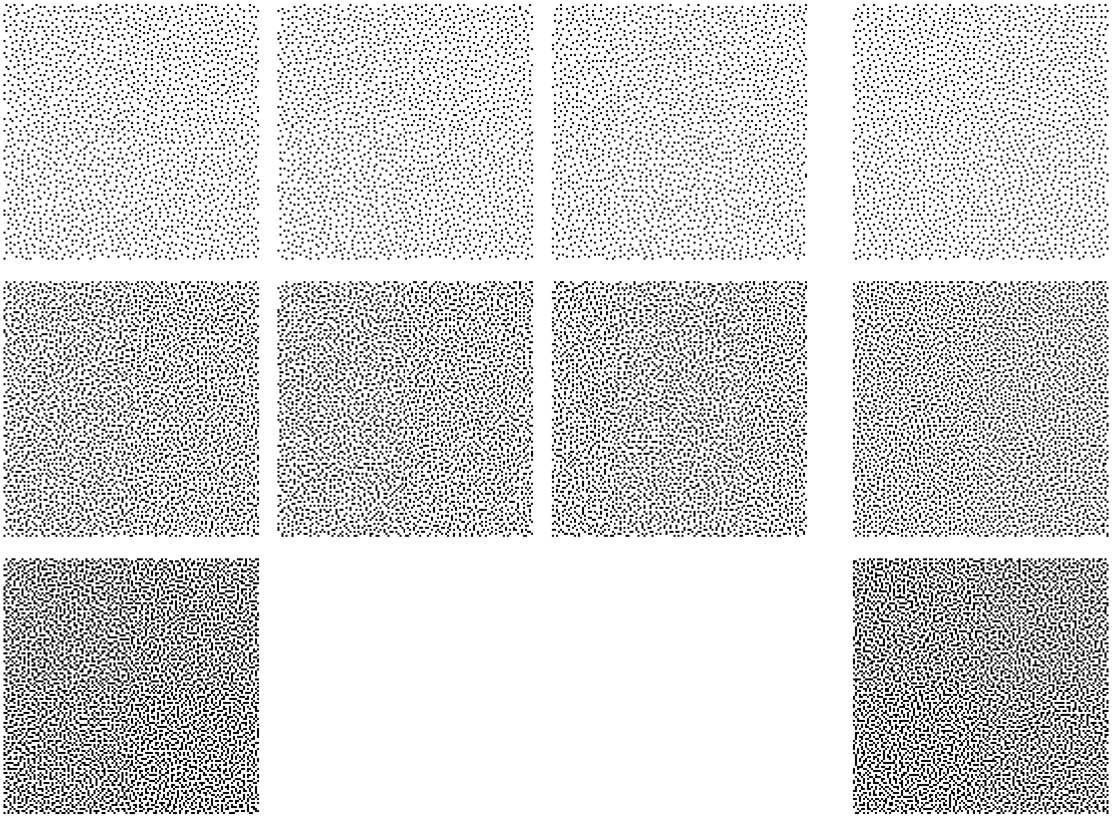

Figure 2: *Patterns created by the 3-jointly-blue noise masks A, B and C and patterns created by a regular blue noise mask. The first row: patterns of $g = 224$. From left to right, patterns created by mask A, B and C, and the pattern created by the single blue noise mask, respectively. The second row: patterns of $g = 192$. From left to right, patterns of combining A and B, combining B and C, combining C and A, and the pattern created by the single blue noise mask, respectively. The third row: patterns of $g = 160$. Left: the pattern of combining A, B and C. Right: the pattern created by the single blue noise mask.*

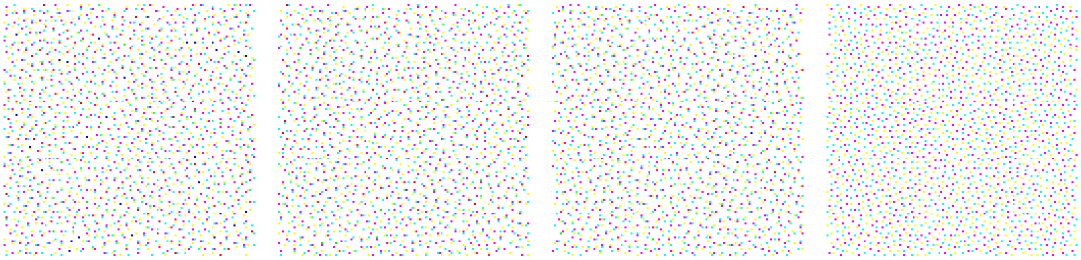

Figure 3: *A neutral color patch halftoned with different schemes. From the left to the right: shift masks, invert and shift masks, four masks and joint masks.*