Color Halftoning with Stochastic Dithering and Adaptive Clustering

Luiz Velho, Jonas Gomes
IMPA – Instituto de Matematica Pura e Aplicada
Rio de Janeiro, BRAZI

Introduction

The reproduction of color images is a problem of great importance in business, scientific and industrial applications. A comprehensive overview of this problem can be found in [6]. Different areas, and a great diversity of applications, lead to the necessity of using different media in the color reproduction process: film, paper, monitor screens, video, etc. In this paper we are concerned with the reproduction of color images on paper. We should point out that in spite of the advances in the area of continuous tone digital printing technology (e.g. dye sublimation printers), halftoning techniques for color printing still have a long way to evolve. This technology is essential for the color printing industry, because of the adequacy of the offset printing process to rapidly reproducing colors with great flexibility, and low cost. Also, halftoning techniques will continue to be used on a wide range of color reproduction devices (inkjet printers, laser printers, wax transfer printers etc.).

In this paper we introduce a new halftoning technique for color reproduction. The algorithm adapts to a wide range of color reproduction processes that use halftoning in order to account for the elimination of quantization contours: inkjet printers, laser printers, wax transfer printers and the offset color printing process. We focus the applications and examples of the algorithm on low cost color inkjet printers, and on high resolution phototypesetters.

The remaining of the paper is as follows: first we discuss the color printing pipeline and the screening methods for digital halftoning; next we review the space filling curve halftoning method, then we describe how to use the halftoning method with space filling curve for color printing; and finally we make some final comments and point to future research in this area.

Background

Color Separation and Halftoning

Color printing is based on a reflective light process. The ink on the paper modulates the reflectance as a function of wavelength of the incident light, and as a result, a different color is reflected from the inked paper. This process is similar to the generation of color using a subtractive system: as we add different colors to the paper, light of different wavelength will be reflected, producing a great diversity of new colors.

Theoretically, by combining the three primary colors Cyan (*C*), Magenta (*M*), and Yellow (*Y*) to emulate a subtractive color system, we could be able to reproduce on paper a wide gamut of colors. Nevertheless, several considerations, of different nature, support the necessity of using Black, *K*, as an additional color in the printing process (see [11] or [18]).

The process of taking a color digital image and transform its color space to the *CMYK* color space, is called *color separation*. Since, at least theoretically, we are able to generate the black component from the CMY primaries, we face the problem of trading off between CMY and K values in the color separation process. The literature about this topic is abundant. The interested reader should consult [11] for a good overview, or [8] for a more comprehensive discussion of the problem.

Figure 1 shows a printed color image, and Figure 2 shows the contents of each of its CMYK channels. Figure 1 is essentially obtained by overprinting each of the CMYK channels in Figure 2.

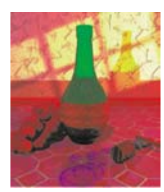

Figure 1: reproduction of a color image.

Figure 2: Cyan, Magenta, Yellow and Black channels of the image in Figure 1

We will return to this overprinting process later on. For the moment we should make an important remark: in order to print each of the channels CMYK, we must quantize it to a bitmap image. This remark points to us the necessity of using halftoning techniquesin the quantization of each CMYK channel (see [14]), after the color separation process. Halftoning techniques avoid the perception of the severe contouring artifacts produced by the 1-bit quantization process.

Screening Methods for Color Halftoning

Traditional screening methods, either analog or digital, obtain a dithered image by creating regular clusters of points, the black and white dot patterns inside the clusters has a variable size, according to the image tonal values. For this reason, these techniques are known by the name of *amplitude modulated* dithering technique, or simply *AM dithering*.

Dispersed dithering algorithms use a fixed point size and modulate the spatial distribution of black and white points to render the tonal values of the image. In contrast to AM dithering techniques, these algorithms are called *frequency modulated* dithering, or simply *FM dithering*. FM dithering techniques have been introduced recently into the raster image processor of high resolution phototypesetters.

Regular Screening

When a regular screening method is used, a halftoned image of each of the separated CMYK channels is created. During the halftoning process the cluster grids are conveniently rotated in order to avoid full overprinting of the clusters from each of the CMYK channels.

This is illustrated in Figure 3 where we show an amplification of a detail of the image printed in Figure 1.

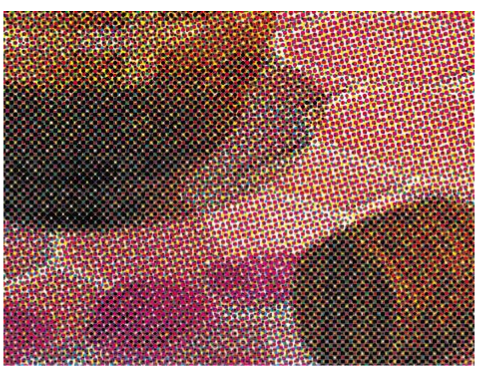

Figure 3. Detail of the printed CMYK channels from Figure 1.

The spatial distribution of the halftoning clusters on a regular screen is prone to producing moirée artifacts in the overprinting of the CMYK channels. Moirée patterns are illustrated in Figure 4. On the top, we print a grayscale synthetic image that resembles the texture pattern of a cloth. In the middle, we print a 1-bit, halftoned, version of the image, using a regular screen with an angle of 6 degrees. At the bottom, we show another halftoned version using an screen of 5 degrees. Moirée patterns are quite noticeable, specially on the image at the bottom. Detailed discussion of moirée patterns can be found on [2] and [3].

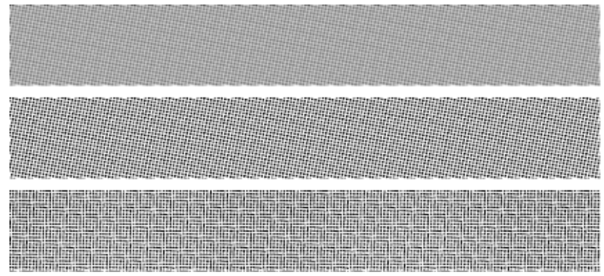

Figure 4. Moirée patterns.

Stochastic Screening

The first attempt to avoid the perception of quantization contours was done in [9]. In this paper it was introduced the use of white noise to decorrelate the quantization error. It is for this reason that dithering techniques that use regular patterns of clusters are known by the name of *ordered dithering*.

The idea of using noise to decorrelate the quantization error, and to avoid the perception of the quantization contours is in the right direction. The problem with white noise is that it is completely uncorrelated.

The use of correlated noise to distribute spatially the black and white dots over the image domain, is quite opposite to techniques that use a regular screen for the spatial distribution of the dot patterns. For this reason, noise correlated dithering algorithms are also known by the name of *stochastic screen halftoning*.

Since FM dithering algorithms do not use clustering, they do not perform well on printing devices which do not have a very good precision in the dot size and positioning. In this paper we will describe an algorithm that encompasses the characteristics from FM and AM dithering techniques: it uses clustering; it performs error diffusion; and it employs stochastic screening.

Besides the above properties, the algorithm also is able to change the cluster size according to the rate of change of the image color intensities.

One of the main advantages of FM dithering techniques resides in the fact the it does not use regular screens. This avoids the classical problem of moir\'ee patterns in the color printing process with halftoning techniques.

Stochastic Screening with SFC

In this section we review the dithering with space filling curves ({SFC) published by [16]. The method takes advantage of the characteristics of space filling curves to perform neighborhood operations essential to the spatial dithering process.

Space Filling Curves

A continuous plane curve is a continuous from the unit interval of the real line to the two-dimensional euclidean plane. The image *c(I)* is called the trace of the curve *c*. A *space filling curve* is a continuous curve such that its trace covers the unit square of the plane.

Therefore, for each point p in the square there exists a real number t in the interval I such that $c(t) = p$. Intuitively, this means that the curve provides an ordered way to visit all points of the square as the parameter t moves from 0 to 1.

The mathematical construction of a space filling curve c is done as a limiting process. We consider a sequence of curves c_n in the unit square. The curves c_n constitute approximations of c, and as we increase n it visits a greater number of points in the unit square. It is possible to construct space filling curves for which each curve c_n is simple, i.e. the map is 1-1. This means that it does not visit a point in the square more than once.

The path of a space filling curve approximation is used to scan the image, generating a parametrization of the image elements satisfying two properties:

- continuity: two consecutive pixels along the path of the space filling curve are in the same 4-connected neighborhood;
- non-directionality: in general, three consecutive pixels along the space filling curve path are not aligned.

We observe that the traditional scanline traversal of the image elements has an exaggerated horizontal directionality and does not have continuity.

Steps of the Method

The dithering method with space filling curves consists of four steps:

1. subdivide the image domain into cells;
2. compute the average image intensity inside each cell;
3. generate a black and white dot pattern with the cell average intensity;
4. position the dot pattern inside the cell to generate the cluster

Image Subdivision

The subdivision of the image domain into cells is performed by following the path of the space filling curve until the number of elements visited is equal to the cell size.

Dot Pattern Generation

The dot generation strategy is a direct consequence of scanning the image with a space filling curve. The trace of the space filling curve determines a relationship between the area of the cell region and the length of the curve. The curve interval is subdivided into two segments such that one of them is proportional to the average intensity of the image over the cell. The pixels in the cell corresponding to this subinterval are set to 1, while the other pixels are set to 0. In this way the average intensity of the quantized cell is the same as the original image.

The dot configuration produced by the space filling curve method results in an aggregate of pixels connected not only sequentially by the curve, but also in other directions because of the intertwined way the space filling curve traces the region. Consequently, the cluster of dots obtained is confined within the limits of a ball that has an area close to the area of the region. As a whole, the patterns generated by this type of dots are evenly distributed but not periodic.

Dot Positioning

The last step of the algorithm positions the black and white dot pattern within the cell to generate the cluster. The choice we take consists in positioning the central pixel of the black pattern at the pixel inside the cell which has the highest black intensity level. This positioning method results in a cluster that provides a much better rendition of the image details, without sacrificing the low frequency textures.

We should observe that besides the non-directionality implied by the space filling curve traversal, the method used above to construct the cluster introduces a randomness to the distribution of the clusters over the image domain. Also, it is important to mention that the quantization error in a cell is propagated by the algorithm to the neighbor cell, along the path of the space filling curve. This characterizes the algorithm as a clustered-dot dithering with stochastic screening.

In brief, the dithering algorithm with space filling curves uses clustering similar to the traditional amplitude modulated (AM) algorithms, but at the same time it performs error diffusion, and disperses the clusters along the path of the space filling curve. Therefore, it incorporates characteristics of FM dithering techniques.

Adaptive Stochastic SFC Screening

The usual expedient to minimize the loss of image detail on the halftoning process, consists in performing an image enhancement, either as a preprocessing step, or incorporated in the dithering algorithm prior to quantization. Although this alleviates the problem, it is an ad-hoc solution and the results are far from being optimal.

Much better results can be obtained by a careful application of dithering where it is needed. In image areas where the intensity changes slowly there is only shading information. In image areas with abrupt changes of intensity there is also shape information that is often manifested in the form of edges. Therefore, when dithering is applied to image areas of low contrast it generates patterns of dots conveying the impression of gray tones with no loss of information. But, when it is applied to image areas of high contrast the dither eliminates edges destroying spatial information.

In order to preserve spatial detail it is necessary to constrain the contours created by transitions between black and white areas to align as much as possible with the real edges of the original image. This must be done without changing the overall image contrast.

In the case of dispersed-dot dither these goals can be achieved by various methods that try to use some type of correlated noise. In the case of clustered-dot dither the best method to obtain a faithful reproduction of image details it to use an adaptive method to change the cluster size according to the variation of the image intensity values. In fact, with a fixed cluster size it is difficult to capture features smaller than the size of the halftone screen dots. The best strategy is to make the size of clusters vary according to rate of change in intensity over regions of the image.

In this section we will review the adaptive dithering algorithm from [17]. This method will enable us to incorporate a variable cluster size, that along with the above mentioned properties creates a dithering texture similar with the granularity found in photography.

Adaptive Criteria

The space filling curve algorithm subdivides the image domain into cells, and at each cell it approximates the image function $f(x,y)$ by some bi-level image function $b(x,y)$. The approximation criterion is a perceptual one, based on pixel intensities. The adaptive clustering dithering consists of changing the size of each cell, and therefore of its associated cluster, based on some adaptive criteria, in order to get a better binary approximation of the image function.

The adaptive criteria to compute the cluster size depends on the desired effect to be obtained by the halftoning method. In our case, the goal is to achieve the best rendition of image detail without compromising tonal reproduction. Therefore, we should use an adaptive criteria that varies the cluster size according to the rate of change of the image intensity. In order to accomplish for this, we need to measure the variation of image intensities as we scan the image.

Since we are using the CMYK color space, the rate of change of the image color values along the space filling curve can be measured by the derivative of the image function. Since we are scanning the image along the path of the space filling curve, the norm of the directional derivative along the curve furnishes a good measure for the rate of change of the image intensities along the scanning direction. The discrete computation of the derivative employs a central difference template at every pixel along the path of the space filling curve.

Changing the Cluster Size

After deciding that the directional derivative will take care of the adaptiveness criteria, it remains to obtain the correct relationship between the cluster size and the directional derivative vector. As the norm of the derivative vector gets bigger, image intensities change faster and, therefore, the cluster size should get smaller.

We first observe that the intensities distribution in a dithered image must follow a perceptual criteria. Also, the eye response to intensity changes obeys a logarithmic law (see [10]). Based on these two remarks, we conclude that we should vary the cluster size exponentially with the gradient magnitude. This rule maintains a linear relationship between the perceptual intensity inside each cluster and the directional variation of the image intensity.

We should remark that there are different variations when using the above method to obtain an adaptive change of the cluster size for color image halftoning. We will return to this topic later on.

Color Halftoning with SFC

In this section we will describe the different possibilities of the use of stochastic screening with space filling curve, for color printing. According to the techniques we discussed in the previous sections we have two methods of choice:

1. color printing with fixed cluster size;
2. color printing with an adaptive cluster size.

In the first case the cluster size is fixed for each of the image channels C, M, Y, and K. In the second method we use an adaptive procedure to change the cluster size for each of the four channels.

By combining the two methods above we are able to devise different algorithms for color printing using space filling curves. These algorithms take into account the two possibilities above, with the fact that it is possible to vary the dot pattern position to generate the cluster for each of the channels C, M, Y, and K. We will describe these methods below.

Color Halftoning with Fixed Cluster Size

By fixing the cluster size we have two possibilities for the cluster position:

- independent cluster position;
- correlated cluster position.

In the first method, there is no relationship between the position of the cluster for each of the CMYK channels. In the second method the position of the cluster for each of the CMY channels are influenced by each other.

Independent Cluster Position

This method subdivides into two different options. The first option consists in positioning the cluster randomly inside each cell, for each of the CMYK channels. We have discarded experiments with this method because it gives no control over color cluster overlapping in the printing process. This would certainly give poor final results.

The other possibility arising from independent cluster positioning, consists in centering the cluster within the cell in each of the channels CMYK taking into account only the image intensity information of the given channel.

Correlated Cluster Position

The strategy of this method consists in devising a correlation of the cluster position in order to minimize color overlapping in the printing process. From the previous section we know that the clusters of the black channel should be centered at the pixel of highest black intensity within the cell in order to obtain a better rendition of image details.

Therefore, a good strategy consists in positioning the black cluster to obtain a better definition of image details, and position the C, M, and Y clusters in such a way to minimize color overprinting between these channels.

More precisely, the positioning strategy is done in the following way (see Figure 5):

1. center the cluster of the black channel at the pixel of highest black intensity within the cell;
2. subdivide the cell into three subcells, and position the center of the cluster of each of the C, M, and Y channels at the center of each of the three subcells.

Note that, the subcells may overlap, depending of the average value of the image in each color channel. Nonetheless, the correlation guarantees that the subcells will be as widely spaced as possible and evenly distributed along the interval.

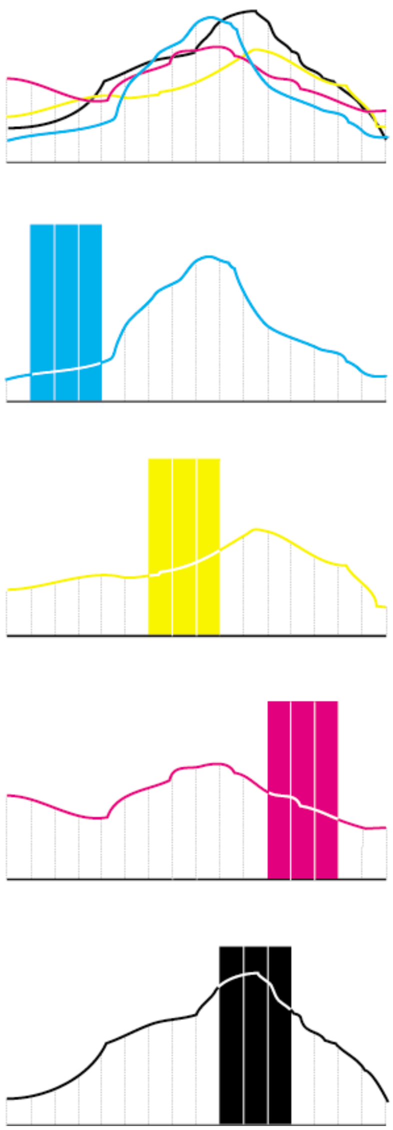

Figure 5. Correlated positioning of the CMYK channels (from top to bottom: cyan, yellow, magenta and black)

We illustrate the above cluster positioning method for the two-dimensional case in Figure 6: Figure 6(a) shows the cell subdivision into three subcells, and Figure 6(b) shows the position of the C, M, and Y clusters center within each subcell. Notice that the order of the cyan, magenta and yellow clusters along the path of the space filling curve is C < Y < M. This order turns out to give better results. Changing it, will result in a subtle color shift on the printed image.

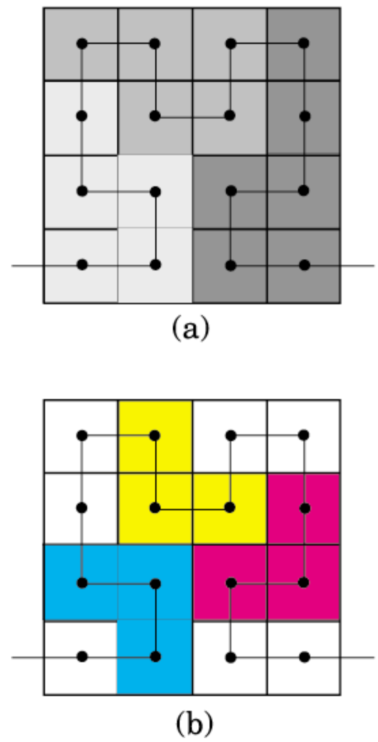

Figure 5. Two dimensional correlated cluster positioning. (a) areas corresponding to cyan, yellow and magenta subcells (b) colored dots corresponding to the subcells in the

As we remarked before, the positioning of the CMY clusters is done in such a way to minimize color overlapping in the printing process. In Figure \ref{f-sync2} there will be an overlapping of CMY clusters only if the cluster size is greater than 5 pixels.

Color Halftoning with Adaptive Cluster Size

In the previous section we described how to use the directional derivative of the image function to obtain an adaptive variation of the cluster size. Using this method, we can devise three different procedures for color halftoning with the adaptive space filling curve algorithm: independent cluster; constrained cluster; correlated cluster.

Independent Cluster

In this method the adaptiveness of the cluster size is performed independently for each of the four channels CMYK. The cluster is positioned in the pixel of highest intensity inside the cell.

Constrained Cluster

In this method we compute the adaptive size of the cluster for the black channel, replicate this size to each of the CMY channels, and position the clusters in the pixels of maximum intensity within the cell.

Correlated Cluster

In this method we use a constrained cluster size as described in the previous section, and we position the CMYK clusters according to the correlation method illustrated by Figures 5 and 6.

We concluded after several tests that, from the three methods described above, the correlated cluster method performs better than the others. This is because it distributes the halftoning dots in a very uniform fashion and, at the same time, with minimum overlap.

Conclusions and Future Research

In this paper we introduced a halftoning method for color reproduction that incorporates characteristics from both AM and FM halftoning techniques. Therefore, the algorithm uses dot-clustering, stochastic screening, performs error diffusion and is able to change the cluster size according to image color variation.

These features result in a very flexible color halftoning technique, which is able to adapt to a wide range of printing devices. This is shown by some of the experiments with the algorithm we included in the paper. In comparison with other aperiodic dither algorithms, the adaptive clustering method provides more control over the dot size with the same level or better rendition of both tonal variations and image details.

Since the algorithm uses stochastic screening, it avoids the occurrence of moir{\'e}e patterns, when we overprint each of the halftoned color channels. Therefore, it is a natural halftoning technique for printing with any number of process colors. We intend to make some experiments with the algorithm for hi-fi color printing.

Acknowledgements

This work was done during the period the authors visited the Hewlett-Packard Labs in Palo Alto.

We wish to thank Ricardo Motta who provided us with the working environment necessary for doing this research. The visit to HP was sponsored by the RHAE project from MCT/CNPq in Brazil.

References

1. Allebach, J.P. 1976. Random quasi-periodic halftone process. *J. Opt. Soc. Am*., 66:909-917.
2. Amidror, I. 1991.The moirée phenomenon in color separation. In *Raster Imaging and Digital Typography II*, *Proceedings of the 2nd Int. Conf. Raster Imaging and Digital Typography*, volume 6, pages 98-119.
3. Amidror, I., Hersch, R., and Ostromoukhov, V. 1994. Spectral analysis and minimization of moirée patterns in color separation. *Journal of Electronic Imaging*, 3(3):295-317.
4. Bayer, B. E. 1973. An optimum method for two-level rendition of continuous-tone picutres. In *International Conference on Communications, Conference Record*., pages (26-11)-(26-15).
5. Gomes, J. and Velho, L. 1996. *Image Processing for Computer Graphics*. Springer Verlag.
6. Hunt, R. E. G. 1987. *The Reproduction of Color in Photography, Printing and Television*. Fountain Press
7. Mitsa, T. and Parker, K. J. 1992 . Digital halftone technique using a blue noise mask. *J. Opt. Soc*., pages 1920--1929.
8. Molla, R. K. 1988 . *Electronic Color Separation*. RK Printing and Publishing Company, West Virginia, USA.
9. Roberts, L. G. 1962 . Picture coding using pseudo-random noise. *IRE Trans. Infor. Theory*, IT-8:145--154.

10-. Rosenfeld, A. and Kak, A. C. 1976. *Digital Picture Processing*. Academic Press.

11. Stone, M. C., Cowan, W. B., and Beatty, J. C. 1988 . Color gamut mapping and the printing of digital color images. *ACM Transactions on Graphics*, 7(3).
12. Sullivan, J. and Ray, L. 1993. Digital halftoning with minimum visula modulation patterns.U.S. Patent No. 5,214,517.
13. Sullivan, J., Ray, L., and Miller, R. 1991. Design of minimum modulation halftone patterns. *IEEE Trans. Syst. Man Cyber*., pages 33--38.
14. Ulichney, R. 1987. *Digital Halftoning*. MIT Press, Cambridge, Ma.
15. Ulichney, R. 1993. The void-and-cluster method for dither array generation. *Proc. SPIE*, pages 332--343.
16. Velho, L. and Gomes, J. 1991. Digital halftoning with space filling curves. *Computer Graphics*, 25(4):81--90.
17. Velho, L. and Gomes, J. 199. Stochastic screening dithering with adaptive clustering. *Computer Graphics - Annual Conference Series*, pages 273-276.
18. Yule, J. A. C. 1967. *Principles of Color Reproduction*. John Wiley and Sons, New York..

Color Halftoning with Stochastic Dithering and Adaptive Clustering

Luiz Velho, Jonas Gomes
IMPA – Instituto de Matematica Pura e Aplicada
Rio de Janeiro, BRAZIL

Abstract

We introduce an algorithm for color halftoning using stochastic dithering. This algorithm has three distinguished features: it uses clustering, it performs error diffusion and it employes an adaptive criteria to change the cluster size according to the variation of the image color values.
The method incorporates features from the traditional amplitude modulated (AM) digital halftoning methods, along with the advantages of the frequency modulated (FM) techniques, recently introduced into the raster image processors of high resolution photo-typesetters.
The method is derived from the space filling curve digital halftoning algorithm published by the authors [1].

Keywords

color printing, stochastic screen, adaptive clustering, space filling curve, electronic printing.