Suppressing sampling moiré by least-squares prefiltering in color printing

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Abstract

Moiré patterns are undesirable artifacts in printing applications. Sampling moiré is caused by aliasing due to image resampling from one lattice to another. In color printing each color separation uses its own halftone lattice. Therefore, moiré patterns display an unexpected new frequency and orientation, but also influence the color appearance itself. These artifacts are frequently encountered in commercial (even high quality) printing since the interpolation algorithms used in RIPs are fairly simple (e.g., bilinear interpolation). Additionally, high-resolution images become everyday fare which increases the chance of high-frequency components and so moiré patterns. Approaches such as simple low-pass filtering unacceptably blurs the edges, while manual smoothing by an operator is very time-consuming.

This paper proposes an optimal prefilter which is based on a least-squares resampling technique. Such an approach requires a suitable discrete/continuous model and computes the reconstruction function which minimizes the error between the continuous representations of the images on the source and target lattice. The reconstruction function jointly takes into account the Nyquist areas of the color separations and can be used as an optimal prefilter before halftoning. Experimental results show that after prefiltering, the images are much less prone to moiré and look as sharp as without prefiltering.

Introduction

Printing techniques are based upon a common principle. Since they can only put ink or not (i.e., a binary process), they need to rely on the limited spatial resolution of the human visual system (HVS) to create the perception of an intermediate shade of the ink's color [1, 2]. Halftoning techniques distribute small bi-level features on the paper. We focus on classical halftoning or AM (amplitude modulation), which places dots of varying sizes upon a regular lattice. This technique is still frequently used and very robust against ink-spreading problems.

Also color printing technology is using an important property of the HVS which allows to synthesize (almost) any color using a combination of three primary ink colors: cyan (C), magenta (M), and yellow (Y). Black ink is also added for technical and economical reasons [3]. Every color separation uses its own halftone lattice, but they are mutually rotated. Interaction of these periodic structures could easily give rise to moiré-patterns (interseparation moiré). A common approach to minimize interseparation moiré is by maximizing the angles of rotation. Typically, the black separation is at 45°, cyan at 105°, magenta at 75°, and yellow (which is the least visible) at 90°. If the separations are correctly aligned, a rosette structure becomes visible which is acceptable. Good techniques to obtain moiré-free separations are found in literature [3, 4].

Unfortunately, interseparation moiré is not the only way moiré patterns arise in color printing [5]. Since the original image is resampled for each color separation to the corresponding lattice, aliasing due to resampling can give rise to sampling moiré. Current resampling algorithms used in RIPs are fairly simple, e.g., nearest neighbour interpolation, bilineair interpolation or cubic convolution [6], and therefore they do not prevent high frequency components to be turned into moiré patterns. The advent of advanced scanners and digital cameras increases the availability of high-resolution images and even so the chance of high frequency components. Typical "dangerous" image content are fine textures, fabrics in clothes, and grills. One approach to prevent sampling moiré is to apply low-pass filtering in order to suppress these high-frequency components. However, such a method unacceptably blurs edges. Another way is to let the operator manually blur "dangerous" regions in the image, but such areas are difficult to predict and the job is time-consuming [7].

In this paper we propose a new linear prefilter based on a least-squares approximation between two signal models, one for the source and one for the target lattice. The next section briefly introduces the generalized spline model needed to derive the prefilter. Next, the least-squares approximation is presented. Finally, some experimental results show the feasibility of the proposed method.

Generalized spline signal model

A continuous/discrete model allows us to construct a "smooth" signal based on the samples. Splines are a family of basis functions, which have a limited size of support, and expands as the order of the spline model increases. One of the most important spline families are the B-splines: piecewise polynomial functions which are symmetric [8]. They are not orthogonal, but they form a Riesz basis and satisfy the partition of unity condition. It is also interesting to mention the convolution property, which enables us to construct splines of the next order by convolving the spline with the first-order spline. Note that first-order spline interpolation is better known as "nearest neighbour" interpolation; second-order spline interpolation as bilinear interpolation.

These models are appropriate for one-dimensional signals and can be extended to two-dimensional rectangular lattices by means of the tensor-product. We propose to construct a spline basis suitable for general periodic lattices. The first-order spline function on a lattice $\mathbf{R} = [\mathbf{r}_1|\mathbf{r}_2]$, defined by the lattice vectors $\mathbf{r}_1$ and $\mathbf{r}_2$, is given by the indicator function of the Voronoi cell of the lattice:

$$\chi_{\mathbf{R}}(\mathbf{x}) = \begin{cases} 1, & \mathbf{x} \in \text{Voronoi cell} \\ 1/m, & \mathbf{x}\ \text{edgeVoronoi cell} \\ 0, & \mathbf{x} \notin \text{Voronoi cell}, \end{cases} \tag{1}$$

where m is the number of lattice points to which $\mathbf{x}$ is equidistant. Note that $\chi_{\mathbf{R}}(\mathbf{x})$ tiles the plane. We denote the first-order spline as $\beta^0(\mathbf{x}) = \chi_{\mathbf{R}}(\mathbf{x})$. Spline functions of higher order are constructed by subsequent convolutions:

$$\beta^n(\mathbf{x}) = \frac{\beta^0 \otimes \beta^{n-1}(\mathbf{x})}{|\det(\mathbf{R})|}, \quad n \geq 1, \tag{2}$$

where each spline function is normalized by the surface area of the Voronoi cell $|\det(\mathbf{R})|$. The model $s(\mathbf{x})$ for a function $g(\mathbf{x})$ is given by

$$s(\mathbf{x}) = \sum_{\mathbf{k} \in \mathbb{Z}^{2\times 1}} c(\mathbf{k}) \beta^n(\mathbf{x} - \mathbf{R}\mathbf{k}), \tag{3}$$

where the spline coefficients $c(\mathbf{k})$ must make $s(\mathbf{R}\mathbf{k}) = g(\mathbf{R}\mathbf{k})$. For the first and second order this condition is easy to satisfy by choosing $c(\mathbf{k}) = g(\mathbf{R}\mathbf{k})$, while higher orders need an inverse filter operation to obtain the right values for $c(\mathbf{k})$. For this paper we only consider first and second order spline models.

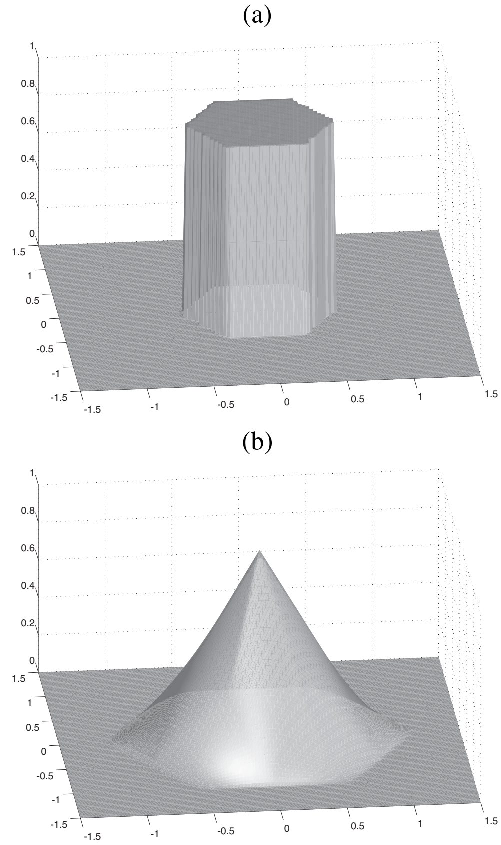

Figure 1: *The generalized spline functions for a hexagonal lattice. (a) First-order. (b) Second-order.*

As an illustration, consider the regular hexagonal lattice. We first define the first-order hexagonal spline as the indicator function of the Voronoi cell of the lattice. Figure 1 (a) shows the first-order hexagonal spline. Note that it fills up the two-dimensional space if it is copied upon each lattice site (i.e., the partition of unity condition is fulfilled). A convolution of this spline with itself (and a proper normalization) results into the second-order spline, shown in Fig. 1 (b). We have proven that this spline family fulfills the necessary conditions to be a sensible continuous/discrete model. Additionally, the order of approximation corresponds to the nomenclature we introduced. An analytical expression was derived up to and including the third-order hexagonal spline. For more in-depth treatment of these generalized splines, we refer to upcoming papers [9].

Least-squares based prefiltering

Artifacts in color printing caused by sampling moiré are very undesirable because they introduce new frequency components (a new frequency and a new orientation) and also new color tints. Since the Nyquist areas of the lattices of each color separation are different (i.e., mutually rotated), moiré patterns are different in each color separation and might interfere with each other. We illustrate this idea by using a coarse halftone lattice (available in Adobe PhotoShop). Figure 4 shows the result of the test image "zoneplate" (a two-dimensional frequency sweep) after regular halftoning. Severe moiré patterns appear differently for each color separation; the combination also shows new colors.

The first step of the derivation of a sensible prefilter is to choose a discrete/continuous signal model to represent the sampled images on their source and target lattice [10]. An interesting approach to resampling is the least-squares approximation: the reconstruction function minimizes the least-squares error between the continuous model for the image on the source lattice and the model for the image on the target lattice [11]. Based on the generalized splines, we derived an expression for the reconstruction function which performs the least-squares approximation between both models. If the spline function on the source lattice is given by $\beta^n(\mathbf{x})$ and the spline function on the target lattice by $\tilde{\beta}^n(\mathbf{x})$, the reconstruction function which minimizes the error between

$$\begin{aligned} s(\mathbf{x}) &= \sum_{\mathbf{k}} c(\mathbf{k})\beta^n(\mathbf{x}-\mathbf{R}\mathbf{k}), \\ \tilde{s}(\mathbf{x}) &= \sum_{\mathbf{k}} \tilde{c}(\mathbf{k})\tilde{\beta}^n(\mathbf{x}-\mathbf{R}\mathbf{k}), \end{aligned}$$

is given by

$$\frac{\left(\beta^n_{\mathbf{R}}\right)^{-1} \otimes \beta^n \otimes \tilde{\beta}^n \otimes \left(\tilde{\beta}^{2n+1}_{\tilde{\mathbf{R}}}\right)^{-1} \otimes \tilde{\beta}^n_{\tilde{\mathbf{R}}}(\mathbf{x})}{|\det(\mathbf{R})|}, \tag{4}$$

where the subscript $\mathbf{R}$ refers to a sampled version on the lattice $\mathbf{R}$:

$$\beta^n_{\mathbf{R}}(\mathbf{x}) = \beta^n(\mathbf{x}) \sum_{\mathbf{k}} \delta(\mathbf{x}-\mathbf{R}\mathbf{k}). \tag{5}$$

For more details on the derivation and the computation of Eq. (4) we refer to [9]. Figures 2 (a) and (b) show an example of first-order spline signal representations on the source and target lattice. The corresponding least-squares reconstruction function is given in Fig. 2 (c).

Instead of proposing a different reconstruction function based on each lattice for a color separation (in a least-squares sense), we propose a joint criterion. Figure 3 shows the frequency domain and each of the Nyquist areas of the color separations and their largest enclosed circle. The lattice which covers most efficiently the surface area of the circle has an hexagonal primitive cell (and so is its reciprocal cell in the frequency domain) [2, 12, 13]. We

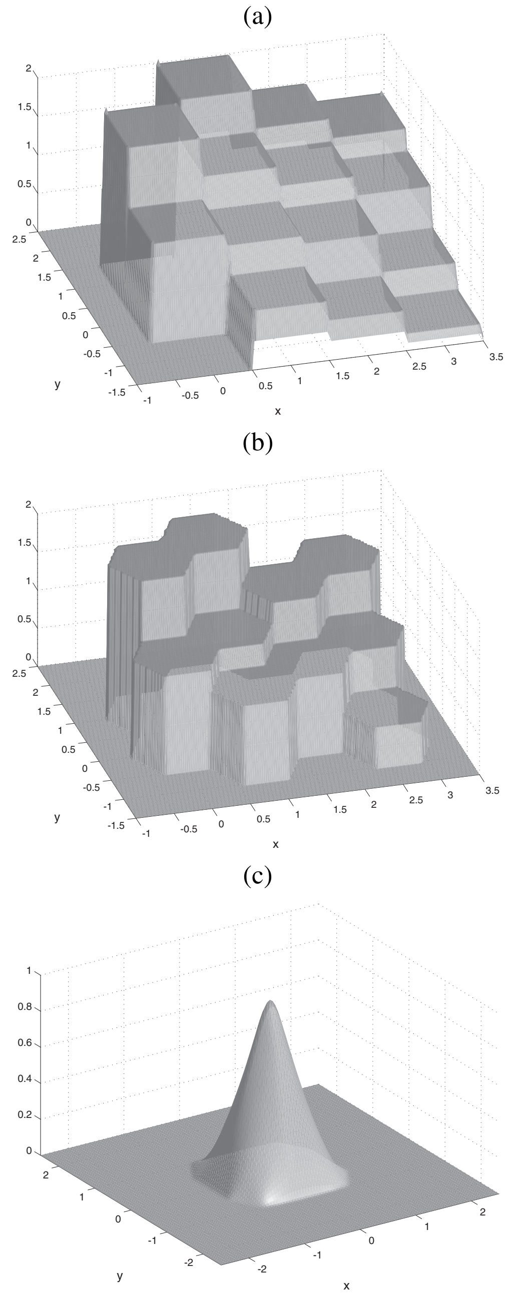

Figure 2: The least-squares method minimizes the squared error between the signal representations for a given signal model. For example, by using first-order splines on the (a) source and (b) target lattice. (c) The first-order least-squares reconstruction function.

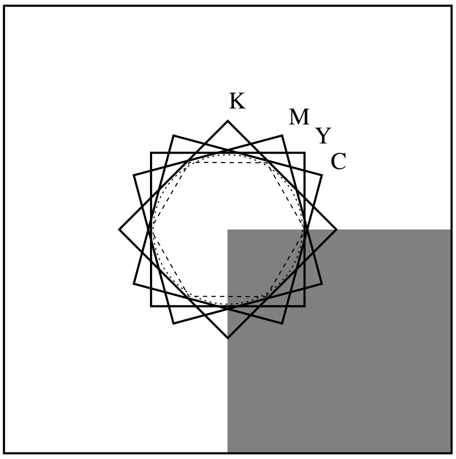

Figure 3: The outer square is the Nyquist area of the original image, while the small rotated square are the Nyquist areas of the color separations. A hexagonal cell is able to cover the largest enclosed circle most efficiently. The gray square corresponds with the frequency region of the "zoneplate".

computed the least-squares reconstruction function for resampling from the source square lattice to this hexagonal target lattice, and used it as a prefilter before halftoning. The order of the filter is related to the order of each model.

Experimental results

Figure 5 shows the test image "zoneplate" after prefiltering and halftoning. The moiré patterns are very well suppressed in both color separations. The influence of the order of the models used for original and resampled image is almost unnoticeable. In fact, high orders are undesirable: (1) the size of the support of the prefilter increases, (2) the frequency response gets sharper and ringing artifacts might appear. Of course, it's important to examine that the filter does not deteriorate normal images by blurring the edges. Figure 6 shows no apparent difference between a "normal" image after halftoning with and without prefiltering.

Conclusions

Moiré patterns in color printing are dreaded artifacts. The advent of advanced scanners and digital cameras increases the availability of high-resolution images and even so the chance of high frequency components. Resampling techniques such as nearest neighbour and bilinear interpolation are common practice, but they do not incorporate the properties of the target lattice and are prone to introducing moiré patterns due to aliasing. In the case of color printing, these moiré patterns display new frequencies, orientations and colors. Based on a generalized two-dimensional spline model, we propose a least-squares reconstruction function. Experimental results show moiré patterns are well suppressed while there is no visual loss of edge sharpness.

References

[1] Brian A. Wandell, *Foundations of Vision*, Sinauer Associates, 1995.

[2] Robert A. Ulichney, *Digital Halftoning*, MIT Press, 1987.

[3] Henry R. Kang, *Digital Color Halftoning*, SPIE Optical Engineering Press, 1999.

[4] Isaac Amidror, *The Theory of the Moiré Phenomenon*, vol. 15 of *Computational Imaging and Vision*, Kluwer Academic Publishers, 2000.

[5] Paul A. Delabastita, "Recent trends in digital halftoning," in *SPIE Proceedings Series*, 1996, vol. 2949, pp. 318–331.

[6] R. G. Keys, "Cubic convolution interpolation for digital image processing," *IEEE Transactions on Acoustics, Speech, and Signal Processing*, vol. 29, no. 6, pp. 1153–1160, Dec. 1981.

[7] Marc D. Miller and Randy Zaucha, *The Color PC—Production Techniques*, Hayden Books, 1995.

[8] Michael Unser, Akram Aldroubi, and Murray Eden, "B-spline signal processing," *IEEE Transactions on Signal Processing*, vol. 41, no. 2, pp. 821–848, Feb. 1993.

[9] Dimitri Van De Ville, Wilfried Philips, and Ignace Lemahieu, "Least-squares spline resampling to a hexagonal lattice," *Signal Processing: Image Communication*, submitted.

[10] M. Unser, "Sampling—50 years after Shannon," *Proceedings of the IEEE*, vol. 88, no. 4, pp. 569–587, Apr. 2000.

[11] M. Unser, A. Aldroubi, and M. Eden, "Enlargement or reduction of digital images with minimum loss of information," *IEEE Transactions on Image Processing*, vol. 4, no. 3, pp. 247–258, Mar. 1995.

[12] R.M. Mersereau, "The processing of hexagonally sampled two-dimensional signals," in *Proceedings of the IEEE*, June 1979, vol. 67, pp. 930–949.

[13] D.P. Petersen and D. Middleton, "Sampling and reconstruction of wave-number-limited functions in N-dimensional Euclidean spaces," *Information and control*, vol. 5, pp. 279–323, 1962.

[14] ISO 12640:1997, "CMYK standard colour image data," CD-ROM, 1997.

Biography

Dimitri Van De Ville received his Engineering Degree in Computer Sciences from Ghent University in July 1998. Currently he is working towards a Ph.D. at the Medical Image and Signal Processing research group (MEDISIP) at the Department of Electronics and Information Systems (ELIS) at the same university. He received a Research Assistant grant from the Fund for Scientific Research (FWO, Flanders). His work has primarily focused on linear and non-linear resampling techniques for image and video processing.