ELECTRONIC PUBLISHING, VOL. 6(3), 207–212 (SEPTEMBER 1993)

Digital halftoning with texture control

THOMAS SCHEERMESSER AND OLOF BRYNGDAHL

Physics Department
University of Essen
D-45117 Essen, Germany

SUMMARY

Depending on the characteristics of the output device and the specific application, various expectations from halftoned images exist. Good reproduction of average grey values is usually demanded from images intended for visual perception. Because textures can drastically influence the appearance of a binary image, it is desirable to control their occurrence. In this paper we present a spectral approach to this problem, and an algorithm which is able to control the occurrence of specific textures as well as ensuring good continuous-tone reproduction.

KEY WORDS Halftoning Texture Fourier spectrum

1 INTRODUCTION

The digital halftoning process is used to display continuous-tone images on output devices which are only capable of producing black or white pixels. Since such devices are in widespread use, halftoning procedures have gained much attention in the recent past. Different halftoning algorithms have been developed, with different properties and fields of application. Such algorithms are often designed to preserve the grey value averaged over a given number of pixels, i.e. the average intensity in a region should be identical in both the original and the binary image. The reason for this approach — which can also be regarded as introducing quantization noise, preferably at high frequencies — is the human visual system, which itself performs lowpass filtering. If all the quantization noise introduced during the halftoning process is of sufficiently high frequency, the visual system is not able to distinguish between the continuous-tone and the binary image [1,2]. In general this can only be realized approximately, because a binary image with the desired lowpass characteristics does not necessarily exist.

There are some aspects that make it necessary to consider not only the spectral characteristics of the image but also the local arrangement of the pixels — the *texture*. Particularly with low and medium resolution devices, the pixel structure may be visible, so that textural effects play an important role. Textures can be classified into categories which give an idea about their visual impression. For example, there are dispersive textures and others tending to build clusters; there are highly ordered textures, like those resulting from a Bayer dither [3], and stochastic ones, which result from a random clip.

Whenever textures with different properties are adjacent there is a probability that the borderline between them will be visible, even though the average grey level does not change. Such a break in texture may also occur when the texture remains the same but is

CCC 0894–3982/93/030207–06 Received 1 September 1993
Revised 3 December, 1993
©1993 by John Wiley & Sons, Ltd.
© 1998 by University of Nottingham.

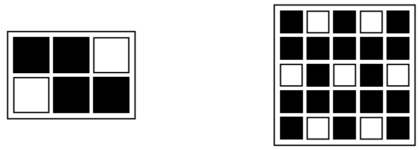

Figure 1. (a) 'Knight's move' texture consisting of two pixels; (b) hexagonal texture consisting of seven pixels

shifted by one pixel, or when the orientation of the texture changes. A break in texture may be visible even when the resolution of the output device is well beyond that of the imaging system, e.g. between a dispersive and a clustered texture.

Apart from direct perception of the texture, there are other effects when dot shape and dot overlap are considered. Since in general the area covered by the dots is a function of their relative orientation, the average grey level becomes a function of texture. This obviously influences grey-level perception even for high-resolution devices, and should be considered in addition to the filtering approach described above.

Because of the influence of texture on the perception of binary images, texture control should be incorporated into the halftoning process. In this paper we present a spectral approach to the problem, and a halftoning algorithm that allows the combination of texture control with lowpass control.

2 TEXTURES IN BINARY IMAGES

Textures can often be characterized by the local arangement of a few pixels which define a texture element called a *texel*. The spatial repetition of this texel in a predictive or random manner forms a textured area in the image. In the case where dot effects are neglected in a binary image, a texel $t(x,y)$ may be written as

$$t(x,y) = \sum_{(\eta,\chi)\in \mathsf{T}} \delta(x-\eta, y-\chi), \tag{1}$$

where T is an index set of spatial coordinates denoting the relative positions of the pixels in the texel. For example, the 'knight's-move' texture which is responsible for the visual artefacts in Floyd-Steinberg error diffusion [4,5] is characterized by the index set $\mathsf{T} = \{(0,0),(2,1)\}$ (see Figure 1a). Another example is a hexagonal texture with an index set $\mathsf{T} = \{(0,0),(2,0),(-2,0),(1,2),(-1,2),(1,-2), (-1,-2)\}$ consisting of seven elements, which is shown in Figure 1b. Of course the choice of T is ambiguous, because every pixel belonging to the texture may be regarded as the reference point with $(\eta,\chi) = (0,0)$.

Let $b(x,y)$ be a binary image in which the texture element $t(x,y)$ occurs at the positions $\hat{x}_j,\hat{y}_j$, with $j \in \{1,\ldots,J\}$. $b(x,y)$ can then be written as

$$b(x,y) = \sum_{j=1}^{J} t(x-\hat{x}_j, y-\hat{y}_j) + b'(x,y). \tag{2}$$

All pixels that do not belong to one of the texels have been included in $b'(x,y)$. If the texture $t(x,y)$ is predominant in the image, which means that the image is composed almost entirely of this texture element, $b'(x,y)$ can be neglected.

To include this knowledge in a binarization process, it is of advantage to consider the Fourier transform $B(\mu,\nu)$ of $b(x,y)$:

$$\begin{aligned} B(\mu,\nu) &= \mathcal{F}\left[b(x,y)\right] \\ &= T(\mu,\nu)\sum_{j=1}^{J} e^{-i2\pi(\hat{x}_j\mu+\hat{y}_j\nu)} + B'(\mu,\nu), \end{aligned} \tag{3}$$

with

$$\begin{aligned} T(\mu,\nu) &= \mathcal{F}\left[t(x,y)\right] \\ &= \sum_{(\eta,\chi)\in\mathsf{T}} e^{-i2\pi(\eta\mu+\chi\nu)}. \end{aligned} \tag{4}$$

Again, if $t(x,y)$ predominates in the image, $B'(\mu,\nu)$ can be neglected. This means that the Fourier spectrum is modulated by $T(\mu,\nu)$, which we will call the *texture filter*. The more often the texture occurs in the image, the more the first term in Equation 3 will dominate over the second and the more significant the modulation will be.

3 BINARIZATION WITH TEXTURE CONTROL

From the above considerations a procedure for texture control in a halftoning process can be derived. To synthesize a binary image in which a specific texture is to be enhanced, the image spectrum has to be controlled either directly or indirectly. Since destruction of most of the image information is undesirable, only the part of the Fourier spectrum due to the quantization noise, and not the entire spectrum, should be modulated with the texture filter. Some examples of this are given later. In a similar way it is possible to suppress a specific texture by modulating with the inverse texture filter [5].

Normally one does not want to generate an arbitrary binary image with a specific texture predominating or absent (which would be easy), but an image in which valuable information from the continuous-tone image is also preserved. Due to the function of the visual system and the structures of many images, correct reproduction of a lowpass spectral region is most often desired. In other words, the quantization noise spectrum should be of low amplitude in the central region of the spectrum, and higher towards the outsides. It should appear to be modulated by a highpass filter $D(\mu,\nu)$, so that after lowpass filtering by the imaging system most of the quantization noise is removed or reduced. The specific choice of $D(\mu,\nu)$ depends on the application.

By combining the texture filter with the highpass filter and modulating the quantization noise spectrum accordingly, it is possible to achieve images that have a good lowpass characteristic, and thus good continuous-tone reproduction as well as the desired texture properties. This leads to the modulated texture filter

$$T'(\mu,\nu) = D(\mu,\nu)\left((1-\alpha) + \alpha T(\mu,\nu)\right). \tag{5}$$

The parameter α allows a weighted combination of both filters, and thus the controlled enhancement of textures in the image. For $\alpha = 0$ only $D(\mu,\nu)$ remains, and a lowpass

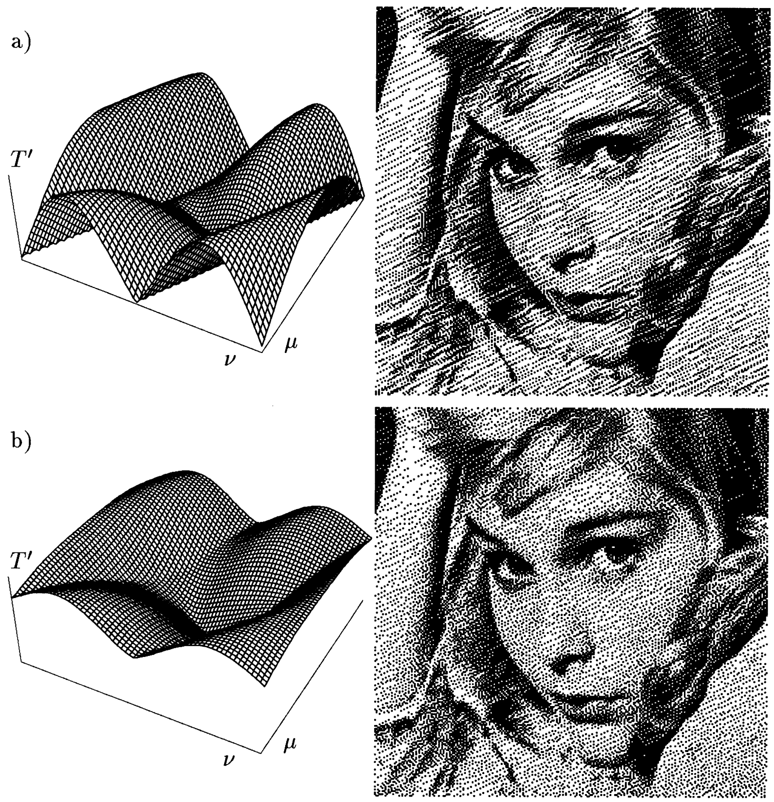

Figure 2. (a) Combination between 'Knight's move' texture filter and Floyd-Steinberg filter with $\alpha = 1$, and corresponding binary image; (b) same as (a), with $\alpha = 0.25$

optimization is performed without additional texture control. For $\alpha = 1$ both filters are weighted equally, which results in a strong predominance of the texel $t(x,y)$.

For the algorithmic implementation of this concept we have chosen an iterative Fourier transform algorithm. While other optimization algorithms, or error diffusion, could also be used, the iterative Fourier transform algorithm has the advantage of allowing direct access to the image spectrum during the quantization process, and thus allows a broad spectrum of constraints to be realized [6,7,8].

The algorithm is based on a cyclic forward and backward Fourier transform. In every cycle, operations on the image and its spectrum are performed in the spatial and frequency domains respectively. The specific choice of these operations ensures convergence of the algorithm to a distribution with the desired properties. In our case the operation in the spatial domain consists of a modified random clip. If the value at one pixel in the image is below some value Δ_r, it is set to zero. If it is above $1 - \Delta_r$, it is set to one. (The images are supposed to be normalized between zero and one.) Otherwise a random clip is performed. The image resulting from this operation is always binary.

In the Fourier domain the operation is as follows. The modified texture filter $T'(\mu,\nu)$ is used to define a probability that the value at a certain position in the image spectrum is

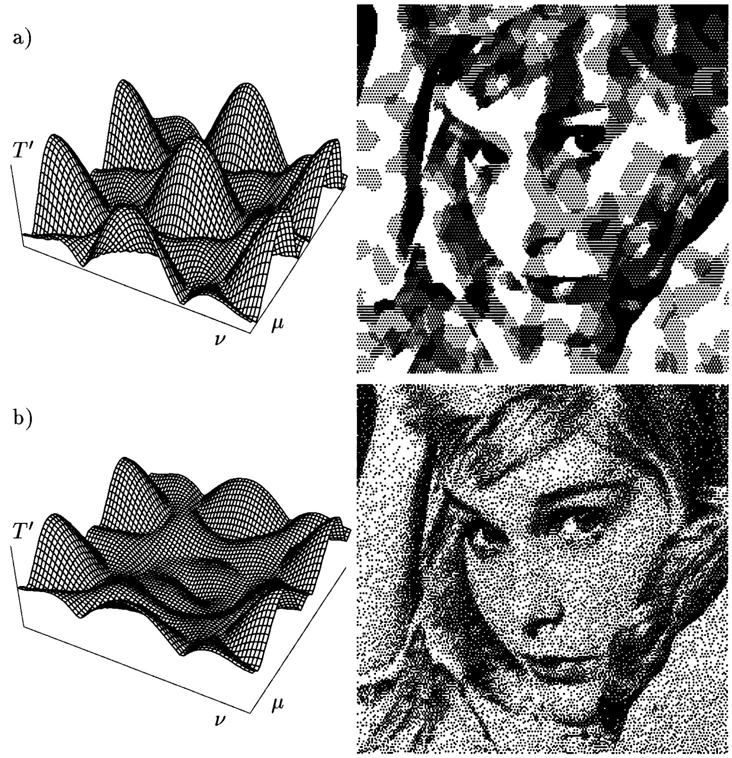

Figure 3. (a) Hexagonal texture filter and corresponding binary image; (b) combination between hexagonal texture filter and Floyd-Steinberg filter with $\alpha = 0.5$, and corresponding binary image

replaced by the corresponding value in the spectrum of the original continuous-tone image. Wherever $T'(\mu,\nu)$ is low, many values are replaced (where $T'(\mu,\nu) = 0$, all are replaced); where it is high, fewer are replaced. Since different values are replaced in each cycle, and a coupling exists between the values in the image spectrum [9], this results after a sufficient number of cycles (between 50 and 100) in a relatively smooth noise distribution modulated in the desired way.

4 EXAMPLES

Some examples of binary images are shown in Figures 2 and 3. For $D(\mu,\nu)$ the Floyd-Steinberg filter was used, which is known to shape the noise in a Floyd-Steinberg error diffusion process and can be stated analytically [10]. The first example in Figure 2a shows the filter resulting from a combination between the 'knight's-move' texture in Figure 1a and $D(\mu,\nu)$ with $\alpha = 1$, and the corresponding binary image. The texture obviously dominates the image strongly, with adjacent texels forming diagonal lines. Nevertheless, due to the additional lowpass control, good continuous-tone rendition is achieved. In Figure 2b the parameter α was reduced to 0.25. The average continuous-tone reproduction is even better than in the previous example, while the dominance of a specific texture is not so apparent.

A closer examination reveals that a high percentage of this image also consists of the 'knight's-move' texture. This also forms diagonal lines, but shorter ones than in Figure 2a, and only when this does not prevent correct reproduction of the average grey level.

To show what happens when the lowpass control is omitted, an image was synthesized using only the texture filter of the hexagonal texture in Figure 1b. The resulting filter and image are shown in Figure 3a. The image consists almost entirely of hexagonal texels and combinations of them. Due to the absence of lowpass control much of the image information has been lost, in particular most of the locally-averaged continuous-tone information. The last example in Figure 3b shows the combination of the hexagonal texture filter and the Floyd-Steinberg filter with $\alpha = 0.5$. Again, the continuous-tone rendition is fairly good, while the image consists mostly of the hexagonal texture or fragments and combinations of it.

5 CONCLUSIONS

Textures in binary images can heavily influence their visual appearance. It is thus desirable to be able to influence image textures while controlling other parameters, like continuous-tone rendition, as well. We have presented an iterative algorithm that combines lowpass characteristics with texture control in the spectral domain and allows a controlled enhancement or suppression of specific textures.

REFERENCES

1. R. A. Ulichney, 'Dithering with blue noise', *Proceedings of the IEEE*, **76**(1), 56–79, (1988).
2. M. Broja, F. Wyrowski, and O. Bryngdahl, 'Digital halftoning by iterative procedure', *Opt. Commun.*, **69**, 205–210, (1989).
3. B.E. Bayer, 'An optimum method for two-level rendition of continous tone pictures', *Proc. IEEE*, **1**, 26, (1973).
4. R. W. Floyd and L. Steinberg, 'An adaptive algorithm for spatial greyscale', *Proc. Soc. Inf. Disp.*, **17**(2), 75–77, (1976).
5. S. Weissbach and O. Bryngdahl, 'Control of halftone texture by error diffusion', *Opt. Commun.*, **103**, 174–180, (1993).
6. R. Mrusek, M. Broja, and O. Bryngdahl, 'Halftoning by carrier and spectrum control', *Opt. Commun.*, **75**, 375–380, (1990).
7. M. Broja, F. Wyrowski, and O. Bryngdahl, 'Significance of spectral phase in synthesis of binarized images', *Opt. Commun.*, **95**, 205– 209, (1993).
8. T. Scheermesser, M. Broja, and O. Bryngdahl, 'Adaption of spectral constraints to electronically halftoned pictures', *J. Opt. Soc. Am.*, **10**, 412–417, (1993).
9. T. Scheermesser, M. Broja, and O. Bryngdahl, 'Restrictions of spectral constraints in quantization of images', *Opt. Commun.*, **99**, 264–273, (1993).
10. S. Weissbach and F. Wyrowski, 'Error diffusion procedure: theory and applications in optical signal processing', *Appl. Opt.*, **31**, 2518–2534, (1992).