

MULTILEVEL HALFTONE SCREEN DESIGN: KEEPING TEXTURE OR KEEPING SMOOTHNESS?*

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ABSTRACT

Multilevel halftoning algorithms are becoming increasingly important as the capabilities of image output devices improve. The traditional approach to multilevel halftoning is hampered by the appearance of contouring in the vicinity of native tones of the output device. To overcome this limitation, we propose a novel framework based on maintaining a consistent periodic, clustered-dot halftone texture across the tone scale. We develop metrics for granularity and structure dissimilarity, and show how these can be used to guide the manner in which the halftone texture evolves from native tone to native tone, across the tone scale. Experimental results confirm the benefits of our new approach.

Index Terms— Multilevel halftoning, screen, contouring artifact, texture consistency

1. INTRODUCTION

Halftoning is used to render continuous-tone images with output devices that are capable of directly printing or displaying only two or a small number of different gray levels. For example, inkjet systems may have light and dark pens for a given color and/or they may be capable of placing 0, 1, or 2 drops at a given addressable pixel location. The various combinations of drop density and number of drops yields what we refer to as a set of *native tones*. Halftoning succeeds by generating a high spatial frequency pattern of alternating native tone values that is not well resolved by the human observer at normal viewing distances. Instead, a local spatial average of the texture is perceived.

The three most widely used categories of halftoning methods: iterative methods, screening, and error diffusion can all be adapted for multilevel output devices. For example, Kurasawa and Kotera [1] describe an error-diffusion-like approach that is based on the correlation between adjacent pixels. Bakić et al [2] describe the use of cellular neural networks for multilevel halftoning. Goldschneider et al [3] describe a frame-

work for embedded multilevel error diffusion that supports rendering of a halftone image on several devices with different resolutions.

When the desired tone-value is near a native tone, traditional multilevel halftoning approaches use the native tone of the output device directly. In these areas of the output image, there will be no halftone texture. Consequently, as the gray value of the continuous-tone image to be rendered changes smoothly, the output image transitions between regions with halftone texture and regions with no halftone texture. This may cause an objectionable contouring artifact. To overcome this problem, Yu et al [4] introduce overmodulation implemented via a lookup-table-based approach. Lin and Allebach [5] use a schedule-based framework to control the number of native tones used to render any specific graylevel. Bacca Rodriguez et al [6] implement stochastic, dispersed-dot multilevel halftoning by applying error diffusion to separate channels of the image that has been decomposed according to the range of gray levels. All these approaches use stochastic, dispersed-dot halftone textures. They all do eliminate contouring, but at the expense of an increase in graininess relative to traditional multilevel halftoning. In addition, the characteristics of the halftone texture changes continually as a function of gray level, which further increases the visibility of these textures.

In this paper, we propose a novel approach to multilevel halftoning that is based on the use of periodic, clustered-dot halftone textures. In addition, we develop a framework in which the appearance of the halftone texture is kept as nearly the same as possible across the entire tone scale. Our hypothesis is that the viewer can see through a texture pattern that is consistent throughout the entire image. An additional advantage of our approach is that it is well suited to color halftoning by using different halftone screen angles and frequencies for different colors. These screen angles and frequencies are chosen to yield minimal moiré when printed together. This is in contrast to the difficult-to-control stochastic moiré that results from the use of stochastic textures for each color plane.

*This work was supported by the Hewlett-Packard Company.

2. PRELIMINARIES

We will describe our halftoning processes in terms of the *dot profile function* $p[m, n; a]$, which is the halftone pattern used to represent each level of constant tone $0 \leq a \leq 1$, where level 0 denotes the absorptance of paper only with no colorant; and level 1 denotes the absorptance of the paper printed with the maximum amount of colorant. We assume that $p[m, n; a]$ is periodic with periodicity \mathbf{M} ; and we let Ω denote a single period or unit cell of this pattern, which we refer to as a *microcell*. Each microcell contains $|\Omega| = \det(\mathbf{M})$ pixels. If we denote by $p_0[m, n; a]$ a single period of the dot profile function; so $p_0[m, n; a] \neq 0$ only if $(m, n) \in \Omega$, then we have that

$$p[\mathbf{m}; a] = \sum_{\mathbf{k} \in \mathbb{Z}^2} p_0[\mathbf{m} - \mathbf{M}\mathbf{k}; a]. \quad (1)$$

Here $\mathbf{m} = [m, n]^T$ and \mathbb{Z}^2 denotes the domain of 2-tuples of integers.

If we let $f[m, n]$ denote the continuous-tone original image, then the halftone image $g[m, n]$ may be expressed as

$$g[m, n] = p[m, n; f[m, n]]. \quad (2)$$

Equation (2) describes any halftoning process that is a spatially periodic, point-to-point mapping from the input continuous-tone image to the halftone output. If the dot profile function also satisfies the stacking property, a bi-level halftoning process may also be implemented by thresholding with a screen matrix. For a multilevel halftoning process, quantization, followed by rescaling and thresholding is required. All the halftoning processes to be considered here can be implemented by screening; but we will not discuss this representation further in this paper.

Suppose that our output device can render N native tones $\alpha_j, j = 0, \dots, N - 1$. For convenience, we assume that the native tones are equally spaced at interval $\Delta = 1/(N - 1)$ between 0 and 1. For a bi-level halftoning process, $N = 2$; and each microcell can represent $|\Omega| + 1$ gray levels $0, 1/|\Omega|, 2/|\Omega|, \dots, (|\Omega| - 1)/|\Omega|, 1$, by setting $0, 1, 2, \dots, |\Omega| - 1, |\Omega|$, pixels equal to 1, respectively. As $|\Omega|$ increases for an output device with fixed spatial resolution, the number of realizable gray levels increases; but the halftone texture becomes increasingly visible. Supercell techniques allow one to achieve a greater number of output levels, while still keeping $|\Omega|$ relatively small. All the halftoning methods to be described in this paper will use the supercell method; but due to space limitations, it will not be discussed further. In particular, we will use a variant of the supercell method, known as the hybrid screen [7] that generates high quality stochastic, aperiodic, dispersed-dot textures in the highlights and shadows that transition to periodic, clustered-dot textures in the midtones.

In this paper, we will work with the specific periodicity matrix and microcell shape shown in Fig. 1, along with the

bilevel dot profile function and index matrix that we will use to generate multilevel halftones according to the traditional method. The index matrix shows the order in which pixels in the microcell are changed from value 0 to value 1.

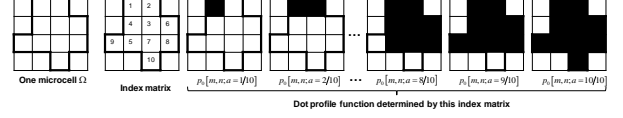


Fig. 1: Microcell Ω for periodicity matrix $\mathbf{M} = \begin{bmatrix} 3 & 1 \\ 1 & -3 \end{bmatrix}$ and $|\Omega| = 10$. An index matrix and bilevel dot profile function are also shown here.

In the traditional approach to multilevel halftoning, we achieve the lowest level of absorptance by setting all the pixels in the microcell to the lowest native tone α_0 . We then follow the sequence given by the index matrix in Fig. 1 to increase the pixel values one-by-one until all the pixels in the microcell have native tone value α_1 . This process is then repeated to transition to the next highest native tone α_2 , and so on, until we reach the point where all the pixels in the microcell have native tone α_{N-1} . In this manner, we can represent $N|\Omega| + 1$ levels of tone, uniformly spaced between 0 and 1.

In the next section, we will describe our new multilevel halftoning approach that is designed to eliminate these contouring artifacts by maintaining a constant halftone texture across the tone scale.

3. MULTILEVEL CLUSTERED-DOT, PERIODIC HALFTONING TO MAINTAIN HALFTONE TEXTURE

Our choice of the prototype halftone texture that we try to maintain across the entire tone scale is based on two criteria: (1) it should be the texture that would be used with a bi-level halftoning process to represent a gray value near $a = 1/2$; and (2) it should have a simple and regular geometric shape.

Figure 2 contains these quantities for the specific periodicity matrix $\mathbf{M} = \begin{bmatrix} 3 & 1 \\ 1 & -3 \end{bmatrix}$ that we will use in this paper to illustrate our new multilevel halftoning algorithm. The prototype halftone texture is shown as having levels α^+ and α^- . For a binary halftoning process, these two levels would be $\alpha^+ = 1$ and $\alpha^- = 0$. Note that our choice of prototype binary texture corresponds to a gray level of 0.4 in absorptance units (Criterion 1) and the region with level α^+ is a 2×2 square (Criterion 2).

In our multilevel halftoning context, α^+ and α^- will be assigned values corresponding to the native tones that can be directly rendered by the output device. According to the prototype halftone texture, we partition the microcell Ω into two subsets Ω^+ and Ω^- , based on whether the pixel value is α^+

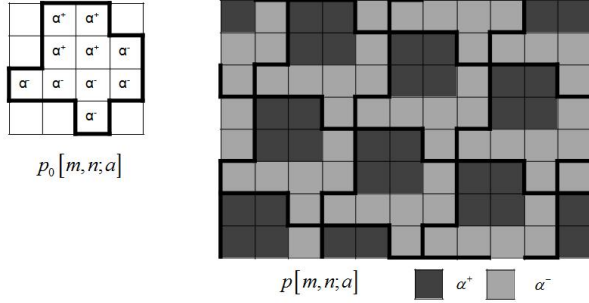


Fig. 2: Prototype microcell $p_0[m, n; a]$ and prototype halftone texture $p[m, n; a]$.

or α^- , respectively. With our multilevel halftoning algorithm, α^+ and α^- will be assigned an increasing sequence of native tone values, as the target gray level a increases from 0 to 1. At certain levels a_j , all the pixels in Ω^+ are assigned the same native tone α^+_{j+1} ; and all the pixels in Ω^- are assigned the same native tone α^-_{j+1} . We refer to these levels as *anchor levels*.

We will consider two cases: (1) at the j -th anchor level, $\alpha^+_{j+1} = \alpha^+_j$ and $\alpha^-_{j+1} = \alpha^-_j$, $0 \leq j < N - 1$; and (2) at the j -th anchor level, $\alpha^+_{j+1} = \alpha^-_j$ and $\alpha^-_{j+1} = \alpha^+_j$, $0 < j < N - 1$. In the first case, the tone values in the regions Ω^+ and Ω^- differ by one native tone level; and the average tone is $\alpha_{\text{avg}} = (\alpha^+_{j+1} + \alpha^-_j)/2$. In the second case, they differ by two native tone levels; and the average tone is $\alpha_{\text{avg}} = \alpha^-_j$. Hence, we refer to these two cases as *one-level-contrast multilevel halftoning* and *two-level-contrast multilevel halftoning*, respectively. We similarly refer to the traditional multilevel halftoning approach described at the end of Sec. 2, as *zero-level-contrast multilevel halftoning*.

As the target gray level increases from the j -th anchor level to the $j + 1$ -st anchor level, the native tones are increased according to a sequence given by the dot growth order in the microcell. The sequence is chosen so that the increments in native tone alternate between Ω^+ and Ω^- . This helps to maintain the prototype halftone texture. Figure 3 illustrates this process for one-level-contrast multilevel halftoning. At the anchor levels, the gray values in Ω^+ and Ω^- only differ by one native tone. Thus, at certain target gray levels between two adjacent anchor levels, pixels in Ω^+ and Ω^- that are spatially adjacent to each other may have the same gray value. In this case, the shape of the texture boundary between Ω^+ and Ω^- will be distorted from what it is for the anchor levels; and the prototype halftone texture will not be exactly maintained.

For the two-level-contrast multilevel halftone, the situation is similar. However, at the anchor levels, the gray values in Ω^+ and Ω^- differ by two native tones. Thus, at target gray levels between two adjacent anchor levels, pixels in Ω^+ and Ω^- that are spatially adjacent to each other will never have the same gray value. This assures better fidelity to the pro-

otype halftone texture, but at the expense of greater texture contrast that will make the texture be more visible overall.

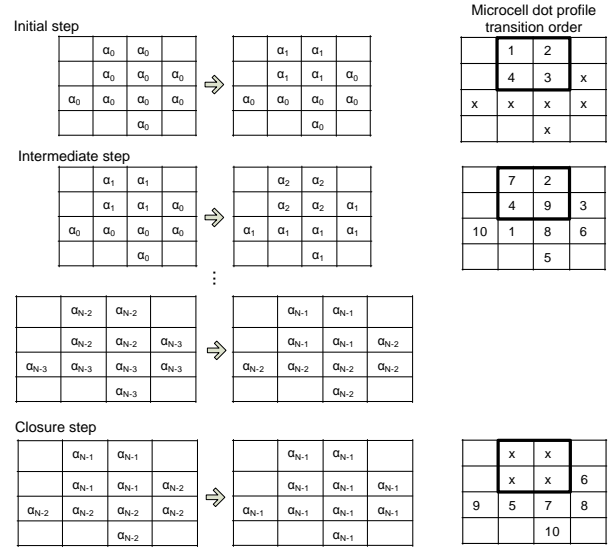


Fig. 3: Three steps to realize one-level-contrast multilevel halftoning.

4. OPTIMIZING THE DOT PROFILE TRANSITION ORDER

In the previous section, we described a process whereby the native tone values are alternately incremented within the regions Ω^+ and Ω^- to maintain the form of the prototype halftone texture, as specified for example, by the index matrix illustrated in Fig. 3. We also discussed, in general terms, the tradeoff between maintaining constancy of the texture shape and minimizing overall texture visibility. However, we have not so far provided any quantitative basis for achieving these two goals.

In this section, we define two metrics – one for granularity, and one for structure dissimilarity to the desired prototype texture pattern – as the basis for quantitatively achieving these two goals. The manner for minimizing the granularity metric is outlined in Fig. 4 for the one-level-contrast multilevel halftoning framework. For a given index matrix, and for each level of the resulting dot profile function, we calculate the difference $e_G[m, n; i]$ between the i -th microcell halftone pattern and its mean, filter it with a human visual system point spread function, compute its RMS value, and then average that over the R levels of the dot profile function. Since the dot profile transition order is the same between any two adjacent anchor levels, we only need consider one pair of native tones, shown as (α_0, α_1) and (α_1, α_2) in Fig. 3. Since there are only $4! \times 6!$ possible orderings of the indices in the two regions Ω^+ and Ω^- , we can perform an exhaustive search to find the one that

minimizes the granularity metric.

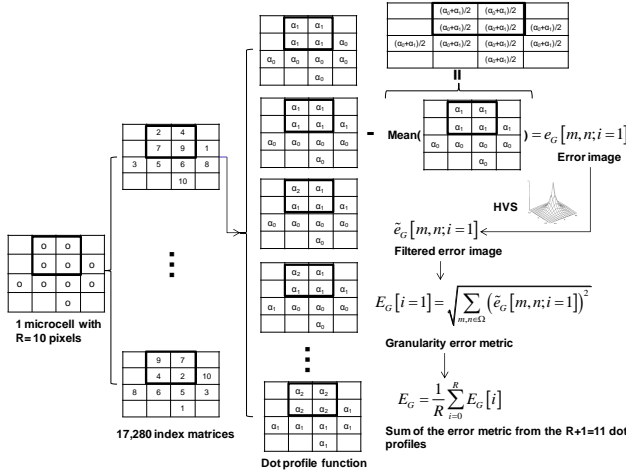


Fig. 4: Framework for finding dot profile transition order that minimizes the granularity metric.

Figure 5 shows how the dissimilarity metric is calculated. Here, we take as our error $e_S[m, n; i]$, and substitute it for the error $e_G[m, n; i]$ in Fig. 3.

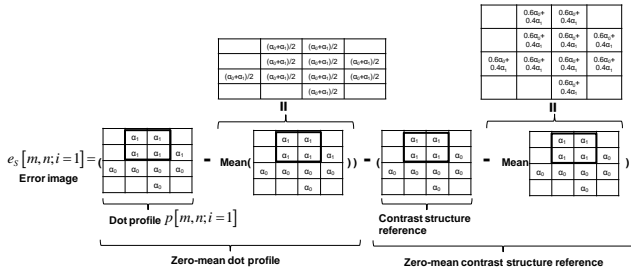


Fig. 5: Calculation of structure dissimilarity metric.

5. EXPERIMENTAL RESULTS

In this section, we illustrate the application of our new halftoning algorithm to the rendering of natural images. Fig. 6 compares a small section of the Kodak Photo CD sampler image of the woman with a red hat halftoned using the 4-native tone multilevel hybrid screen with the traditional zero-level-contrast framework, and our new one- and two-level-contrast frameworks, in which the dot growth order has been optimized using only the granularity metric. We can see that the zero-level-contrast approach results in large areas of contouring artifacts on the woman’s eyelid, nose, and forehead. This contouring is almost entirely eliminated in the one-level-contrast image, and is completely eliminated in the two-level-contrast image. As expected, the one-level-contrast

image is smoother than the two-level contrast image; whereas the two-level contrast image has more consistent texture than the one-level-contrast image. The results shown in Fig. 6 are typical of what we have observed with other natural images.

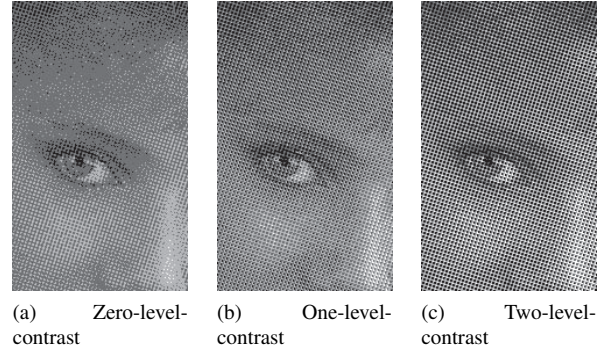


Fig. 6: Comparison of three different levels of contrast for multilevel halftoning of natural image content with 4 native tones

6. REFERENCES

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