Clustered AM/FM Halftoning Algorithm

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Abstract

In this paper, we present a hybrid halftoning algorithm called clustered AM/FM halftoning. It is a generalization of the AM/FM halftoning algorithm developed by the authors earlier. With tone-dependent clustering strength control, the algorithm generates dispersed-dot halftone as error diffusion in highlight area and clustered-dot halftone similar to clustered-dot screen in mid-tone and shadow areas. The transition of the halftone texture is smooth. Moreover, the algorithm shows good Moiré resistence. Therefore, it may be especially suitable for such application as electro-photograpic multi-function printer.

Introduction

Conventional digital halftoning approaches function by modulating either the dot size (amplitude modulation or AM) or the dot density (frequency modulation or FM). AM halftoning algorithms, such as clustered-dot screening [1], have the advantages of low computational load and resist to such electro-photographic (EP) printing artifacts as dot gain and banding. But, it suffers from low spatial resolution and Moiré artifacts. FM halftoning algorithms, such as error diffusion [2, 3], achieve high spatial resolution and is free of Moiré artifacts. But it may lack of the print stability required for EP printing.

Some efforts have been made to combine AM and FM halftoning methods. Error diffusion with output-dependent feedback was proposed in [4]. Its spectrum was characterized as green noise [5]. Eschbach applied a clustered-dot screen as threshold matrix of error diffusion to mimic the halftone texture of the clustered-dot screen[6]. Recently, we developed a hybrid halftoning algorithm named AM/FM halftoning [7], which modulates both the dot size and dot density to produce the best quality halftone at each gray level.

In this paper, we generalize AM/FM halftoning to clustered AM/FM halftoning, which can generate dispersed-dot halftone texture as error diffusion in highlight area and clustered-dot halftone texture similiar to clustered-dot screen in the midtone and shadow areas.

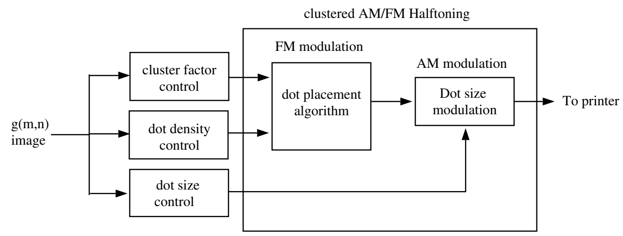

Figure 1: Diagram of the clustered AM/FM halftoning algorithm.

Clustered AM/FM Halftoning Algorithm

Figure 1 illustrates how clustered AM/FM halftoning algorithm functions. Three look-up tables (LUT's) are first used to determine the dot density, dot size and cluster factor at each pixel of gray level $g(m,n)$. The cluster factor $\lambda_{g(m,n)}$ and dot density $\rho_{g(m,n)}$ are then used as the input to a dot placement algorithm, which determines where dots are printed. The size of each printed dot is then independently modulated based on the dot size $\theta_{g(m,n)}$ at that position. The essential attribute of clustered AM/FM halftoning is that it not only modulates both the dot density (i.e. spacing between dots) and the dot size, but also varies the strength of dot-clustering through the cluster factor. If the control factor is turned off everywhere, clustered AM/FM halftoning degenerates to AM/FM halftoning [7].

The dot placement algorithm can be any halftoning method that is capable of producing both dispersed-dot and clustered-dot halftone patterns through parametric control. Examples include the error diffusion with output-dependent feedback developed in [4] and the clustered-dot error diffu-

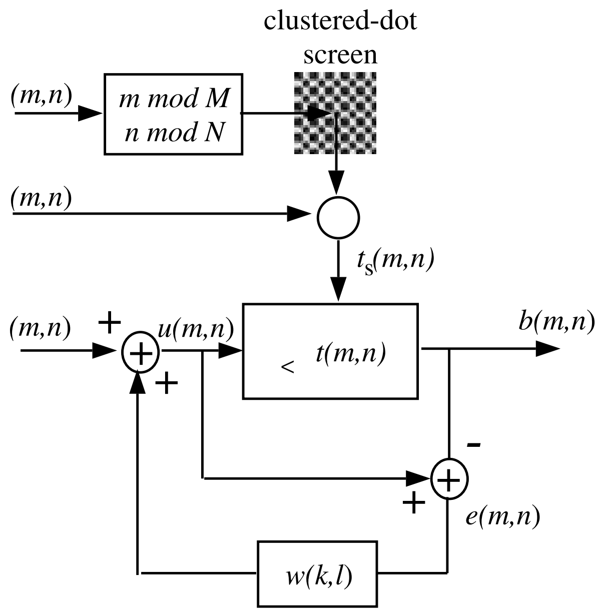

Figure 2: *Diagram of FM modulation in clustered AM/FM algorithm*

sion developed in [6]. In this paper, we select Eschbach's clustered-dot error diffusion algorithm [6]. The dot placement algorithm is shown in Fig. 2. It differs from basic error diffusion by using threshold modulation $t(m,n)$, which is formed by the product of a clustered-dot screen and a weighting function $\lambda(m,n)$.

$$t(m,n) = t_0(m,n) + t_s(m,n) \quad (1)$$
$$t_s(m,n) = \lambda(m,n)s(m \bmod M, n \bmod N) \quad (2)$$

Here, $t_0(m,n)$ is the threshold for the basic error diffusion. When $\lambda_{g(m,n)} = 0$, this algorithm is the basic error diffusion. As λ increases, the resulting halftone texture becomes more like that produced by the clustered-dot screen.

The method to modulate dot size will, in general, depend on the particular printing technology. In this paper, we use pulse width modulation (PWM) as described in [8]. Through modulating the laser beam, PWM controls the pulse width and justification of each pixel. A greater pulse width increases exposure and therefore creates a darker printed pixel. We use the PWM that can produce 64 pulse width levels (0-63) and three justification modes: left, center, or right positions of the pixel grid. The dot size is simply modulating the PWM code at each pixel. So the output PWM code at each pixel is given by

$$PWM(m,n) = \theta_{g(m,n)} b(m,n) \times 63 \quad (3)$$

where $0 \leq \theta_{g(m,n)} \leq 1$ is the desired dot size and $b(m,n)$ is the binary output value 1 or 0 of the error diffusion algorith. Left justification is used for every pixel.

Design of Clustered AMFM Parameters

The cluster factor, dot density and dot size LUT's are critical parameters of the clustered AM/FM halftoning algorithm. These LUT's must be selected to obtain the desired absorptance for each input gray level value $g(m,n)$. This leaves two additional degrees of freedom which may be used to optimize a variety of printing attributes including print quality or print stability.

There are two important quantities to design clustered AM/FM LUT's, output tone level $T(\theta,\rho,\lambda)$ and print distortion $D(\theta,\rho,\lambda)$, at dot size θ, dot density ρ and cluster factor λ. Smaller the print distortion, higher the print quality. The definition of $D(\theta,\rho,\lambda)$ depends on the specific printing application and the printing artifacts we would like to avoid. Our objective is to select the triple (θ,ρ,λ) for each input gray level g which gives the best haftone quality subject to a constraint that the tone $T(\theta,\rho,\lambda)$ is correct.

We use the measurement method developed in [7] to obtain the output tone level $T(\theta,\rho,\lambda)$. Let $A(g)$ be the desired tone curve at gray level g. Since $T(\theta,\rho,\lambda)$ is monotonic with respect to ρ, we have the inverse function of $T(\theta,\rho,\lambda)$ with respect to ρ, denoted as $T^{-1}_{\theta,\lambda}(\cdot)$. Thus, the dot density achieving the desired tone level $A(g)$ is given by

$$R_{\theta,\lambda}(g) \triangleq T^{-1}_{\theta,\lambda}(A(g)) \quad (4)$$

We call this the tone compensation curve for dot size θ and cluster factor λ. The print distortion function to render gray level g can be written as $D(\theta, R_{\theta,\lambda}(g), \lambda)$. We need to select $\theta(g)$ and $\lambda(g)$ to minimize $D(\theta, R_{\theta,\lambda}(g), \lambda)$, $g = 0, 1, \cdots, 255$. Similar to AM/FM halftoning [7], some smoothness constraints on dot size curve $\theta(g)$ and cluster factor curve $\lambda(g)$ are necessary to achieve smooth halftone texture transition.

Since no suitable print distortion metric is available, our current approach has been to select the best values of $\lambda(g)$ and $\theta(g)$ by visually inspecting a set of ramp print samples. Let $(\theta^{(i)}, \lambda^{(j)})$ represents a set of sampled parameter pair values. For each pair $(\theta^{(i)}, \lambda^{(j)})$, we print a gray level ramp halftoned by using clustered AM/FM halftoning with parameters $(\theta^{(i)}, R_{\theta^{(i)},\lambda^{(j)}}(g), \lambda^{(j)})$. Our subjective evaluation is based on the following set of objectives. In the highlight regions, the dominant halftone artifacts are visible isolated dots. Therefore, it is generally desirable to use smaller dot size in these regions. Moreover, $\lambda = 0$ is preferred for highlight regions in order to retain the "blue noise" dispersed-dot distribution. For the midtone and shadow areas, print stability artifacts, such as banding, becomes more dominant. Thus, we prefer larger λ values to generate larger dot clusters which are more stable for EP printing. However, if λ value is too large, it can compromise the Moiré resistance and spatial resolution of the algorithm. Therefore, a tradeoff must be made. To further enhance the stable formation of dot clusters, we apply the following rule to dot size selection: if the cluster factor $\lambda > 0$, we set the dot size to be the maximum possible pulse width. Finally, it is essential for the dot size, dot density and cluster factor curves to vary smoothly in order to avoid contouring artifacts when rendering slowly varying image regions. Once the values of $\theta(g)$ and $\lambda(g)$ for sixteen sampled gray levels are selected, cubic spline interpolation is used to generate the dot size curve θ_g and the cluster factor curve λ_g for $0 \leq g \leq 255$. Finally, the dot density curve is computed as $\rho_g = R_{\theta_g,\lambda_g}(g)$.

Experimental Results

The 1-row serpentine tone-dependent error diffusion (TDED) developed in [9] is selected as the basic error diffusion algorithm in the experiments. The diamond shape clustered-dot screen applied in the threshold modulation has 18 thresholds and 45 degree orientation. The screen is scaled to the full gray range and the mean of the resulting screen is subtracted to yield the final set of threshold matrix values.

A HP4000 LaserJet printer modified to allow pulse width modulation is selected as the target printer. The printer resolution is 600dpi. The sampled (θ, λ) used to generate the tone-compensated ramps for visual inspection are (0.44, 0.0), (0.55, 0.0), (0.67, 0.0), (0.78, 0.0), (0.89, 0.0), (0.89, 0.2), (0.89, 0.4), (0.89, 0.6), (0.89, 0.8), (0.89, 1.0). The corresponding pulse widths are 28, 35, 42, 49 and 56. We observe that pulse width 56 can produce full black because of dot gain. The $\gamma = 1.5$ power curve is chosen as $A(g)$. We assume $g = 0$ is white and $g = 255$ is black.

Figure 3, Figure 4 and Figure 5 show the subjectively optimized dot size, dot density and cluster factor curves. Small dot sizes and zero cluster factor are chosen in the highlight area to avoid visible isolated dots and keep the 'blue noise' halftone texture. In the midtone area, maximum dot size and large cluster factor are applied to generate stable dot cluster at more regular position, in order to reduce such print stability artifacts as banding and enhance the smoothness of halftone texture. We limit the cluster factor to a maximum value of $\lambda = 0.8$ because we have found this to produce a good tradeoff between print stability and Moiré resistance. In darker shadow areas, banding and graininess in texture become less visible again. Therefore, we use a smaller value of λ to enhance the Moiré resistance and text edge rendering.

To show the image quality of the actual print-outs generated by clustered AM/FM halftoning, we scan some real print-outs at 1200dpi scan resolution and present them at 300dpi. (i.e. $4\times$ magnification). Figure 6 shows a ramp. Please see the electronic version of this paper for better image quality of this figure, if possible. Overall, the algorithm produces pleasing halftone textures. And the halftone texture transits smoothly without contouring. In the highlights and shadows, it produces smooth dispersed dot patterns without visible dots. In the midtone regions, It has a regular halftone texture similar to the clustered dot screen. In practice, this regular halftone texture tends to be less grainy and more banding-resistant than the purely stochastic dot patterns of error diffusion. At the same time, it still retains much of the Moiré resistance. Next, we halftone a scan image including 120 and 140 line per inch frequency bars, english texts and a picture. The scan of the print-out of the halftone result is shown in Figure 7. As we see, it shows high spatial resolution. No Moiré artifact is visible. The text edge achieves sharp rendering due to the smaller value of cluster factor λ in the highlight and shadow areas. The image is rendered smoothly without contouring artifact in the slow-varing areas, such as the sky. More regular clustered-dot formation in the mid-tone area enhances the EP print stability, which makes it less vulnerable to such artifacts as banding.

Conclusions

In this paper, we proposed a new hybrid halftoning algorithm, clustered AM/FM halftoning. With explicit clustering strength control, the algorithm is capable to maintain 'blue noise' halftone in the highlight area and generate halftone texture similar to clustered-dot screen in the midtone and shadow areas. The transition among different halftone texture is smooth. The combination of good detail rendition, stability, and resistance to Moiré make it particularly suitable for scan-to-print applications of electrophotographic printing.

Acknowledgement

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Biography

Zhen He received his B.S. degree in 1994 and M.S degree in 1997, both in Measurement and Instrumentation Engineering from Zhejiang University, P. R. China. He received his Ph.D. degree in Electrical Engineering from Purdue University, West Lafayette, in 2002. He has been working for the Office Group of Xerox Corporation as an imaging scientist since then. His research interests include digital printing, color imaging and electronic imaging related algorithm development. His research has resulted in multiple patents and been commercialized into the multi-function printer products. He is a member of IS&T and IEEE.

Charles A. Bouman received a B.S.E.E. degree from the University of Pennsylvania in 1981, and a MS degree in electrical engineering from the University of California at Berkeley in 1982. From 1982 to 1985, he was a staff member in the Analog Device Technology Group at MIT, Lincoln Laboratory. In 1987 and 1989, he received MA and Ph.D. degrees in electrical engineering from Princeton University. In 1989, he joined the faculty of Purdue University where he holds the rank of Professor with a primary appointment in the School of Electrical and Computer Engineering and a secondary appointment in the Department of Biomedical Engineering. His research focuses on the use of statistical image models, multiscale techniques, and fast algorithms in applications including multiscale image segmentation, tomographic image reconstruction, image printing and rendering, and document segmentation and compression. He is a Fellow of the IEEE, a Fellow of the American Institute for Medical and Biomedical Engineering (AIMBE), a member of the SPIE and IS&T professional societies.

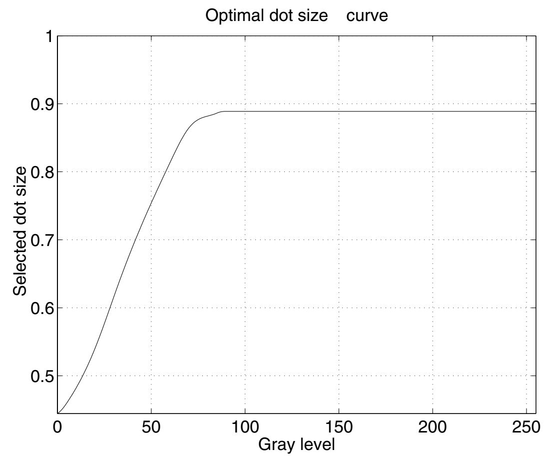

Figure 3: *Optimal dot size curve for clustered AM/FM halftoning*

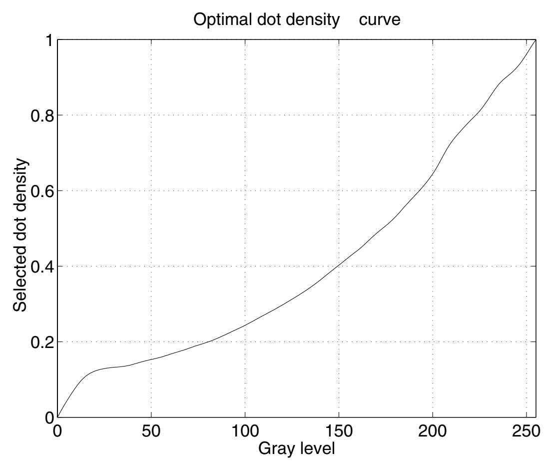

Figure 4: *Optimal dot density curve for clustered AM/FM halftoning*

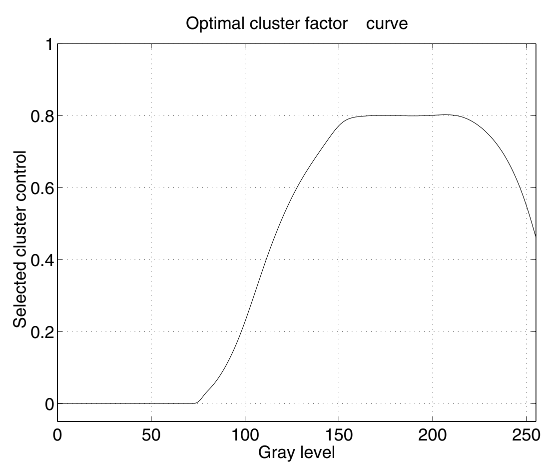

Figure 5: *Optimal cluster factor curve for clustered AM/FM halftoning*

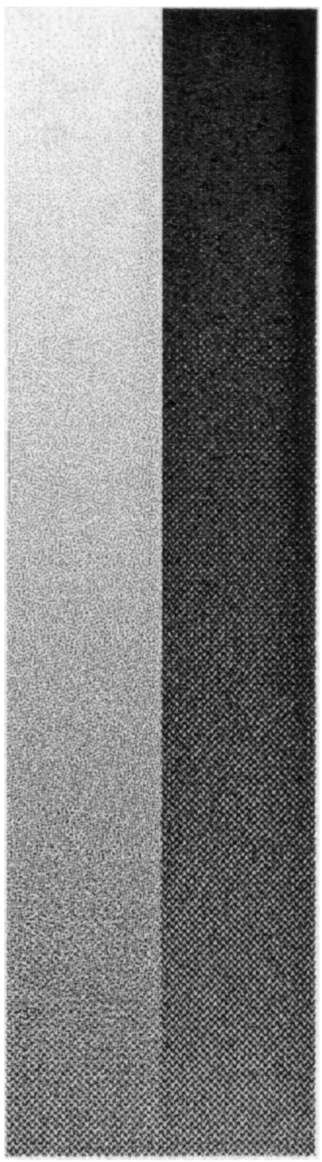

Figure 6: *A ramp print-out of clustered AM/FM halftoning*

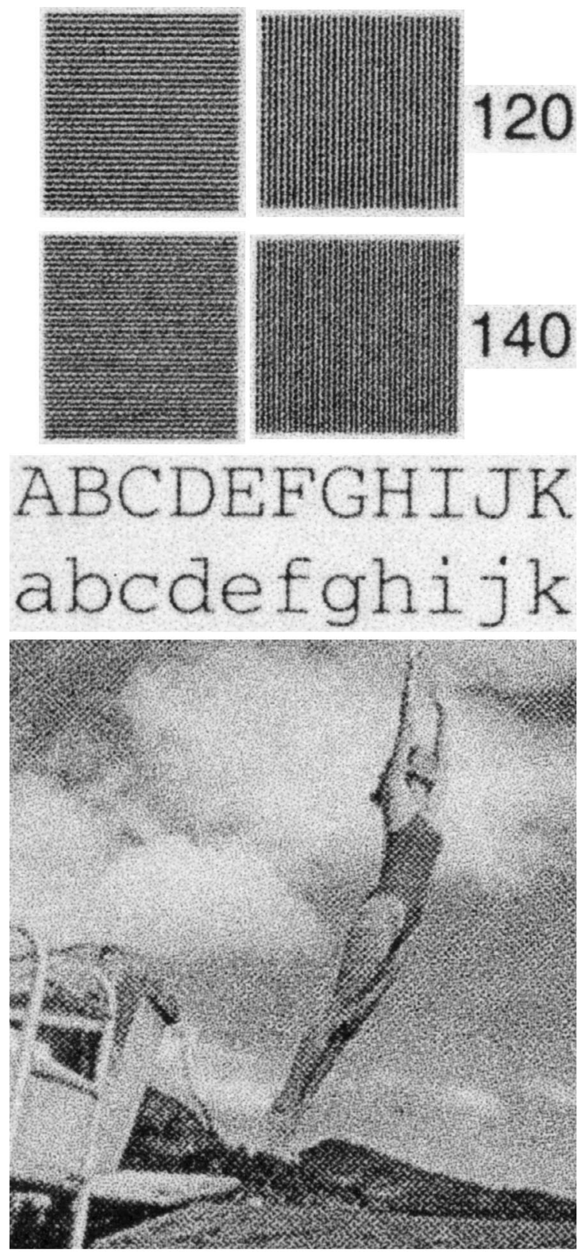

Figure 7: *Rendering of a scanned image using clustered AM/FM halftoning*