HALF-TONING USING INK-JET: PART 1. ALGORITHM OF DISCRETIZATION

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Abstract: Main features of ink-jet printers—fixed dot size—overlap of dots on paper—fixed addressability of dots on page—restricting selection of algorithm for half-toning with ink-jet machines. This size of dots is big enough to prevent usage of complete picture of elements ("orthographic" tone fonts) because of high spatial resolution of eye in B/W. Ordered dither methods produce blurred edges and create false textures. Error diffusion algorithm was selected as more superior from the rest of half-toning methods. Main attention was paid to break false textures in reproduction of large areas of the same level by additional pseudo-randomization of thresholds. Fresnel zone plate images were used to study frequency responses of the algorithm and the appropriate balance between randomization and high frequency reproduction was found.

Introduction

The increase in resolution and drop placement accuracy of ink-jet printers during the last decade created a possibility of using these machines as hard copy output devices in image processing systems. Individual addressability of the dots throughout a page together with high spatial frequencies of 'drops' placement (about 300 dots/inch) are the major factors advocating this new application of ink-jet.

However, because of some restrictions in ink-jet printing technology, direct substitution of signals from CRT monitors is impossible: the placement of dots is a binary process and there are no methods known, at present, to modulate the reflectivity of an ink spot on paper. The micro-shape of the spot is far from being round because of the ink-paper interaction. The characteristic size of a spot is usually bigger than the spatial period of the dots. This leads to overlapping of dots which is useful for imaging characters and presents another constraint in the application of an ink-jet as an image recorder.

This research is an exploratory study aimed at "teaching" an ink-jet printer to image continuous tone pictures. Following the tradition we called it half-toning, although a more precise term would be binarization of continuous tones. We selected an algorithmical approach in which a continuous tone image exists as a bit map of micro-densities with known depth, and is used as an input to a program-binarizator. The output of the program is one bit deep map of pixels sent directly to an ink-jet printer. The selection of a concrete binarization algorithm was based on the ability of the human eye to resolve grey levels. We found that the Error Diffusion (ED) algorithm was most suitable for our purpose. It is known that ED performs badly on large areas of the same intensity creating visual tex-

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ture ("snow powl" effect or "herring bone" texture). We succeeded in destroying this texture by a threshold randomization procedure added to ED algorithm. We found that increasing randomization decreased overall resolution of the binarization algorithm but an acceptable balance could be achieved.

Human Eye Resolution

The ability of the human eye to resolve grey levels depends on the spatial frequency. Roetling (1977) reported data, presented as a solid curve at Figure 1.

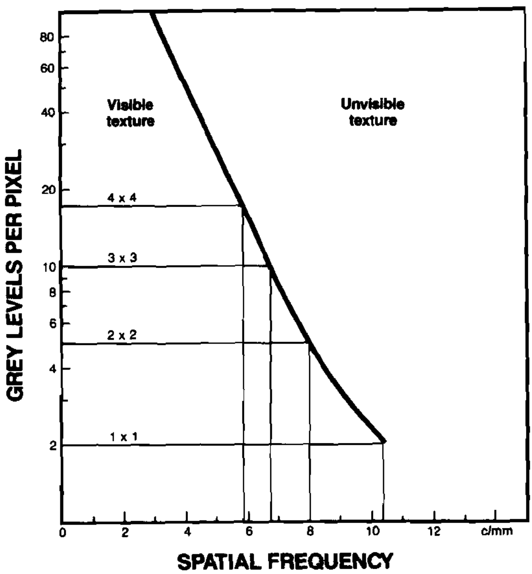

Figure 1. Human eye resolution of grey levels.

The curve can be treated as a borderline between visible and invisible texture of a picture. If, for example, continuous tones of a picture are approximated only by ten levels of grey, the density of such pixels must be about seven per millimeter to create a texture that is invisible for the human eye from normal reading distance. Because of a binary character of the placement of the dots, there must be 9 places for dots in such a pixel. Accepting the matrix 3 × 3 internal structure for a pixel, it is easy to find that the spatial resolution of such a machine must be more than 500 dots/inch. Using these considerations, the data of Figure 1 can be converted to a criterium for selecting an algorithm of binarization, as illustrated in Figure 2.

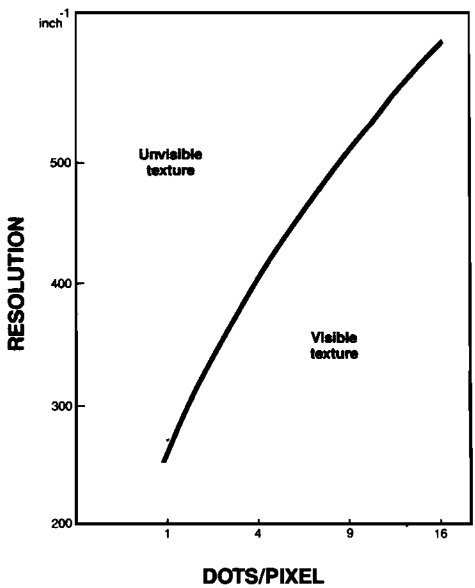

Figure 2. Algorithm selection criterium.

The criterium restricts the selection of a binarization algorithm for ink-jet printers with 300 dots/inch to one with only one dot per pixel. It should be mentioned that neither size nor optical density of an ink spot can be changed. This does not present a problem for binary encoding: instead of using amplitude modulation of a pixel density (different brightness of spot on CRT, different size of dot in conventional half-tone screening, different number of dots/pixel in electronic screenings), the frequency modulation can be used. In such a method, the spatial frequency of the spots will depend on the tone level to be produced, increasing toward high tones. The eye then will integrate the reflectance over a larger-than-spot area creating the feeling of half-toning.

Error Diffusion

Such a method was suggested by Floyd & Steinberg (1976). In this method, the grey levels were simulated in three steps:

a) printing decision based on thresholding;
b) error calculated as a result of printing decision;
c) error propagation to neighbor pixels.

Instead of the actual picture levels I (i,j) (density of the i-th pixel in j-th scan), the method is using corrected levels $I_c(j,j)$ and initially $I_c(i,j) = I(i,j)$. The printing decision for the pixel processed (i,j) is made by comparing the corrected level of the pixel, I_c, with the threshold value T. Binary decision can be expressed as $P(i,j) = 1$ if $I_c(i,j) \geq T$ and $P(i,j) = 0$ if $I_c(i,j) < T$. Because of the binary character of the decision, the error was made for the pixel processed. This error is calculated as a difference between the corrected level and the level actually put on paper:

$$E(i,j) = I_c(i,j) - I_{max}P(i,j). \tag{1}$$

where I_{max}-maximal density of an ink spot, then spreaded to its neighbors so that

$$I_c(i+m, j+m) = I_c(i,j) + E(i,j)W(m,n)/\Sigma_{min} W(min) \tag{2}$$

for $m=-k,...k$; $n=0...k$. Term $W(m,n)$ in the last equation is a matrix or kernel of error diffusion.

Floyd & Steinberg (1976) used k=1 matrix; Schroeder (1969) suggested k=2:

k=1

m:	−1	0	1
n=0	–	#	7
n=1	3	5	1

k=2

m:	−2	−1	0	1	2
n=0	–	–	#	7	5
n=1	3	5	7	5	3
n=2	1	3	5	3	1

In these matrixes, (–) stays for previously and (#) for currently processed pixels. The numbers are at places of pixels for future processing. The direction of this processing is n=0,1,2,...k. In general, usage of larger kernels is desirable because of the bigger area of error accumulation. Kernel k=2 was used in current work.

Error Diffusion With Random Threshold

Value of the threshold T does not influence the reproduction of grey scale. The obvious settings of T to a mid-point of continuous tones suggested by Floyd, Steinberg (1976) permits the resolution of a wide range of grey levels as presented at Figure 3.

However, for some values of grey, the appearance of non-desirable texture is obvious. The effect of this texture increases with increasing area of constant level as shown in Figure 4. Billotet-Hoffmann and Bryngdahl (1983) suggested to combine the advantages of ED with dither methods, so that the value of T was obtained by adding a ring-shaped dither to a constant.

We found that random variations of the level T from pixel to pixel are yet more efficient than dithering the threshold. A pseudo-random generator with uniform distribution was used to set the value of T, selected from a given range each time before pixel processing. The results of Error Diffusion with Random Threshold (EDRT) are presented at Figure 5.

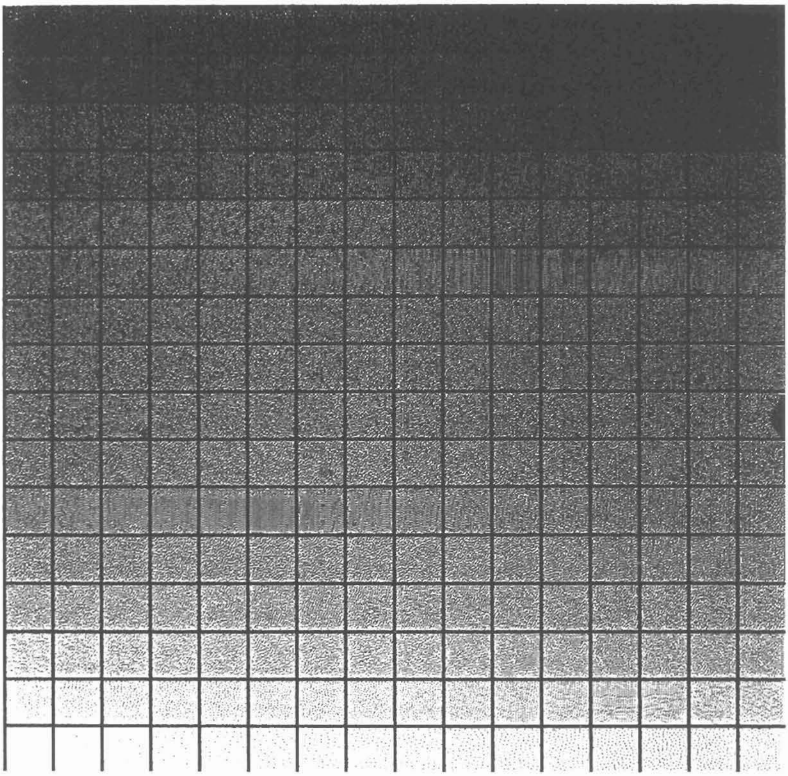

Figure 3. Resolution of 256 grey levels by ED.

To illustrate the resolution of EDRT method, we used a Fresnel zone plate as a target. The radius of the n-th zone can be expressed as

$$R = A\sqrt{n}, \tag{3}$$

where A - constant, equal to the radius of the first zone. The spatial frequency of the appearance of zones is, by definition,

$$f = \frac{1}{2}\frac{dn}{dR}. \tag{4}$$

Differentiating (3) it leads to

$$f = \frac{R}{A^2}. \tag{5}$$

In other words, the spatial frequency of the Fresnel zones is strictly proportional to the radius.

Being scanned the zone plate will create a complex image of Morie patterns (secondary rings) as a result of beats of the scanning frequency and the spatial frequencies of the plate. The quality of an image system can be judged by its ability to reproduce these secondary rings. Equation (5) permits the calculation of the upper cut-off frequencies directly from the image processed.

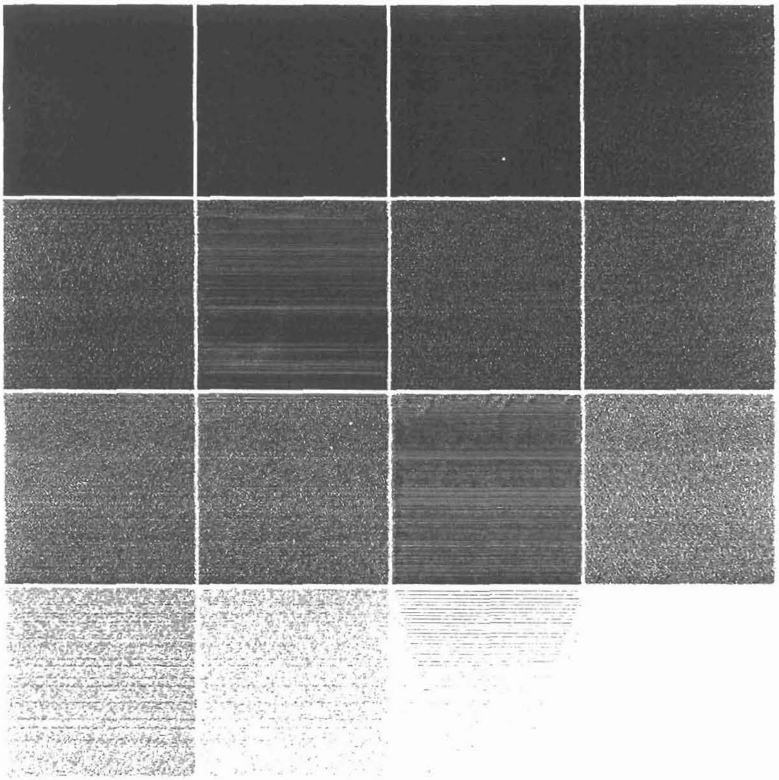

Figure 4. Texture appearance on large areas, ED algorithm.

The reproduction of the Fresnel zone plate by EDRT is shown in Figure 6. The increase in the range of randomality for threshold T degraded the resolution of secondary rings. We selected the range that still permitted the reproduction of the rings which corresponded to a half of the Nyquist frequency.

Conclusions

Error diffusion is the most suitable method for half-toning using ink-jet.

Randomizing the threshold in error diffusion permits the destruction of false textures in reproduction of large areas.

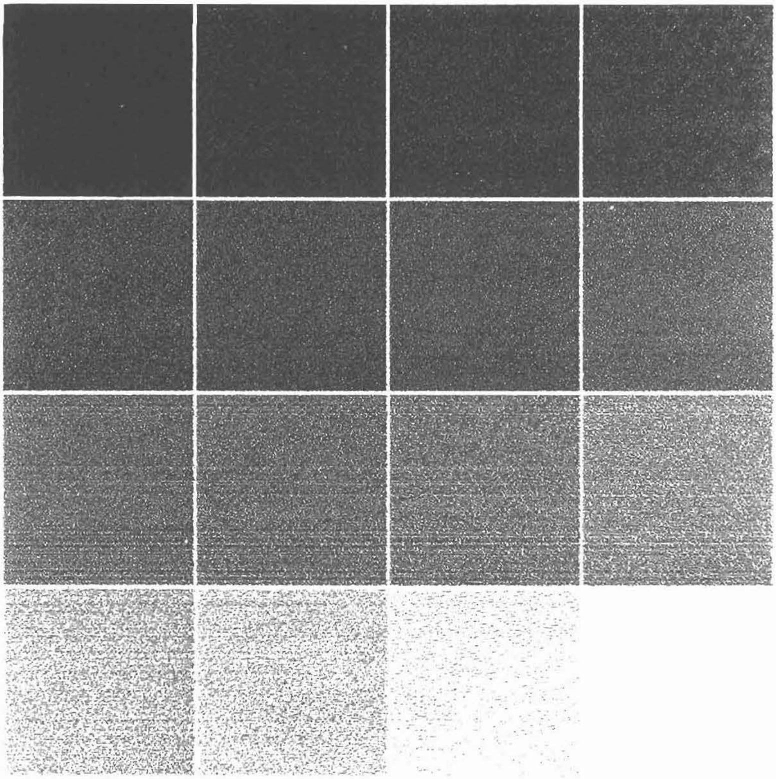

Figure 5. Large areas reproduced by EDRT algorithm.

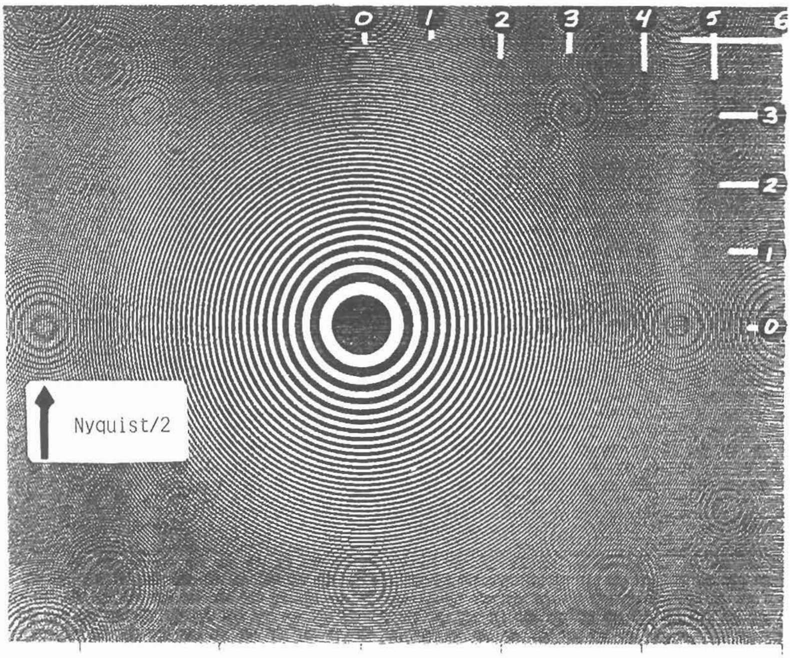

Figure 6. Scan of Fresnel zone plate, reproduced by EDRT.

Acknowledgements

The authors are indebted to L. Nevil Davy, Eastman Kodak, for his suggestion to use the Fresnel zone plate as a target to determine the resolution of ink-jet half-toning, and for his help in scanning the target.

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