

# SCREEN DESIGN FOR PRINTING

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## ABSTRACT

To display or print a continuous tone image on a bi-level device, the image goes through a halftoning process. For best rendition, the halftoning algorithm should adapt to the output device. In this paper, we review printer dot models, and the utilization of printer dot model in generating halftone screens, especially frequency-modulated (FM) screens. We also show the possibility of accurate control over tone reproduction using density measurement data without quantization errors.

## 1. INTRODUCTION

When a continuous tone image is to be rendered on a bi-level device, one of the most common way is to use a screening process to binarize the image. In the digital age, a screen is a dither matrix with elements in the same range as the input continuous tone image. A pixel-wise comparison is performed, and depending on whether the input is larger or smaller than the matrix element, a 0 or 1 will be sent to the output device, which in turn is interpreted as whether or not a dot will be put down.

The way dither matrix elements are arranged determines both the tonal response as well as the pattern of the halftoned image. There is a large variation in dot size and shape among different printing technologies, among different units, and even among different environments surrounding the same unit. It is thus critical to design a dither matrix by taking into account the behavior of the marking device.

## 2. PRINTER DOT AND DOT MODELING

The physical properties of a printer dot depend very much on the printing mechanism. For example, an ink jet produces a dot by ejecting a drop of ink. Since the cartridge is moving at the same time, the dot shape is usually not symmetrical, but rather elongated. Sometimes small satellite drops can be observed as well. An

electrophotographic printer dot is composed of toner particles. The toner particles attach to exposed photoconductor in the development process, and are then transferred to paper and fused. Due to the statistical nature of the processes, a printer dot is usually not round and solid black. Rather, the toner particles are scattered.

Dot models were proposed to design a halftone pattern, and to predict the tonal response of the halftone pattern. Roetling and Holladay proposed a dot model where dots are represented by circles with a uniform distribution of density [5]. When dots overlap, the overlapped area is of the same density as the non-overlapped area. The model has been used in a number of halftoning algorithms, including clustered-dot screening [5], error diffusion [8] [4], model-based halftoning [4], and frequency-modulated (FM) screening [2] [7].

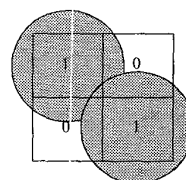


Figure 1: Printer dot model.

Lin and Wiseman proposed a dot model for electrophotographic printers [3]. Printer dots are modeled by using a Gaussian probability function to describe the distribution of toner particles. The probability of having a toner particle at a particular position is determined by the distance  $d$  to the center of the dot:  $p = e^{-\alpha d^2}$ . The parameter  $\alpha$  is an indicator of dot overlap. In the event of a position being influenced by multiple adjacent dots, the presence of a toner particle at that position is the OR event of its presence resulting from each individual dot. The EP model was used to predict the tonal response of several different halftoning algorithms [3]. Flohr, Allebach and Bouman extended

the model to account for toner particle overlap, and implemented it in the direct-binary-search halftoning algorithm [1].

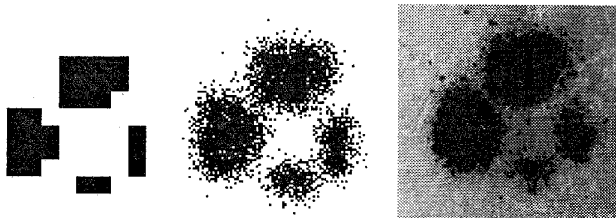


Figure 2: Comparison of simulated dot pattern with actual print samples - left: dot pattern; middle: simulation of EP printer output using the proposed model; right: microscopic image of the actual print sample.

The development of a printer dot model enables better design of halftone screen for printing. In the next section, we discuss this issue in more detail.

### 3. DOT MODEL IN FM SCREEN DESIGN

Halftoning algorithms designed for printers can utilize a printer dot model in halftone pattern design and tone reproduction. In screen design, the halftone pattern design and its tonal response can be separated. One of the main concerns in dither matrix design is to achieve a desired tonal response across different media. The tonal response of a dither matrix is determined by the distribution of thresholds. Using density measurement data, it is possible to remap the thresholds to obtain a desired tonal rendition. Equivalently, one can use the measurement data to remap the image to be halftoned. However, this involves an extra table look up operation. An alternative approach to using measurement data is using a printer dot model to predict the tonal response of a dither matrix, and to generate a compensation curve. Rosenberg compared the two approaches [6].

Instead of compensating for dot gain after the dither matrix is generated, one can also incorporate the dot model in the matrix generation process. Roetling and Holladay reported using the round dot model in designing a clustered-dot matrix [5]. The spacings of the dither matrix thresholds and the effect of the position of an additional dot on tonal response are calculated according to the dot model. More recently, a printer model has been used in generating frequency-modulated (FM) screens, and has been shown to produce better halftone patterns as well as better tonal response [2]. Next, we describe this process in more detail.

#### 3.1. Improving Pattern Uniformity

One way of generating a FM screen is to use the void-and-cluster algorithm [9]. The void-and-cluster algorithm designs a halftone matrix by re-distributing dots through locating clusters and voids. The algorithm starts with a white noise pattern at an intermediate gray level. Suppose the 1's in the white noise pattern represent dots, and the 0's in the pattern represent absence of dots. A Gaussian filter is applied to the pattern. The maximum in the filtered output corresponds to a position where dots are most clustered together. The minimum in the filtered output corresponds to a position where dots are most sparse. To make the pattern more uniform, the dot in the center of the cluster is moved to the center of the void. This process is repeated until an equilibrium state is reached. To build up lighter patterns, dots are gradually removed by again identifying where dots are most clustered using the same Gaussian filter. Similarly, to build up darker patterns, dots are gradually added by identifying where dots are most sparse using the Gaussian filter.

This process is very effective at making halftone patterns uniform. However, the algorithm has been designed for the ideal situation, where a rectangular halftone cell is either completely covered or not covered at all. A printer takes as input binary bit patterns, and puts down inked areas on paper. The geometry of a printer dot is usually non-square and larger than the printing grid to ensure unbroken lines. Hence a bit pattern that is uniform in the numerical sense may not be uniform after it is printed on paper. We use the printer dot model in the dither matrix generation process to ensure that printed patterns are uniform.

We apply a printer dot model to the binary bit pattern, and evaluate the uniformity of the modeled pattern. For each bit pattern, the fractional dot coverage area at each pixel is computed according to the amount of dot overlap from its nearest neighbors, and entered into a data array. This array is then filtered by a Gaussian filter. Incorporating a dot model ensures that the voids and clusters are located on a printed pattern instead of on an ideal pattern with square dots. From our experiments, the halftone pattern is more uniform and artifacts are reduced when a printer dot model is used.

#### 3.2. Improving Tonal Response

We can also perform tone compensation in the dither matrix generation process. Consider the example of generating a dither matrix with a linear reflectance. To predict the tone reflectance curve for a dither ma-

trix, we compute the total area covered by toner particles using the dot model for each bit pattern, and then use the Yule-Nielsen equation [11] to compute the reflectance of the pattern. Suppose the fraction of toner covered area is  $a$ , and the reflectance is  $R$ , then  $R$  is related to  $a$  by

$$R = [1 - a(1 - R_s^{\frac{1}{n}})]^n$$

where  $R_s$  is the reflectance of ink, and  $n$  is a parameter determined by internal reflectance.

As dots are added to a halftone pattern, the reflectance of the halftone pattern decreases. Suppose it is desirable to have a uniform decrease in reflectance. This is achieved by gradually adding printer dots until the tone reflectance at the new gray level is  $R_{new} = R_{old} - \Delta R$ , where  $\Delta R$  is a constant. This approach generates a matrix with more effective gray levels than the post compensation approach, *i.e.* remapping matrix thresholds to the tone reflectance curve.

To verify the accuracy of the modeling, we tested the algorithm on a laser printer and an inkjet printer. Using a microscope with a ruler, the dot diameter of the laser printer is determined to be  $135\mu m$ , and the dot diameter of the inkjet printer is  $160\mu m$ . The ink reflectance for the laser printer is 0.035 (density of solid black is 1.45), and the ink reflectance for the inkjet printer is 0.041 (density of solid black is 1.39). A scanner was used to measure the surface reflectance, since it was shown in a study by Walowit that scanner output is linear with respect to reflectance [10]. Figure 3 (upper) shows the measured scanner output for halftoned gray test patches printed on an inkjet printer. The solid line shows the printer response to a dither matrix with equal number of dots per level. The dotted line shows the result of modeling. It was found that the parameter  $n$  of 1.65 fits the linear curve best. Figure 3 (lower) shows the measured scanner output for halftoned gray test patches printed on a laser printer. The parameter  $n$  used in the model is 3.0. It is observed that the model does not fit the linear curve as well as in the inkjet printer case. This observation is consistent with one of our previous studies [3]. The cause of the disagreement is the dot-to-dot interaction, which seems to play a much more important role in laser printers than in inkjet printers.

In summary, the advantages of incorporating a dot model in the FM screen generation process are two fold: it reduces the quantization error in remapping an existing dither matrix, and it improves halftone pattern uniformity. However, for devices with dot-dot interactions, the tonal response prediction may not be very accurate. The deviation can be further corrected by recomputing threshold distribution from measurement

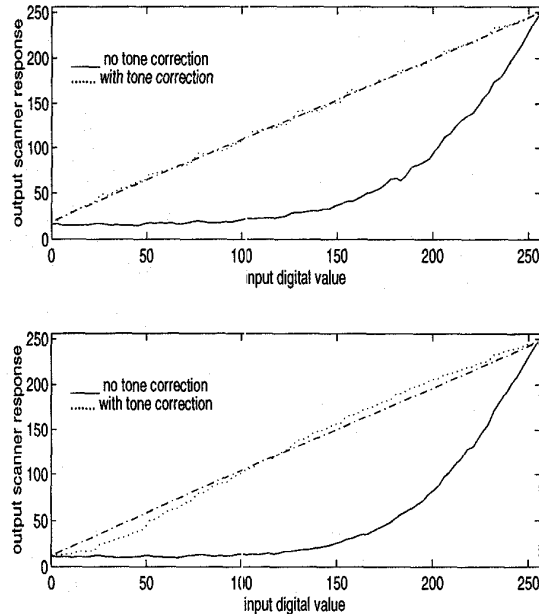


Figure 3: Dither matrix tonal response of an inkjet printer (upper) and a laser printer (lower).

data.

#### 4. ACCURATE TONAL RESPONSE CONTROL VIA MEASUREMENT

In the previous section, the calibration is performed by modeling the printer dots and predicting the tonal response during the dither matrix generation process. This process preserves the number of gray levels of the matrix. It works well for some printers, for example, ink jet printers. However, the model-based tonal response prediction for laser printers is not as accurate. The tonal response of the calibrated dither matrix has small deviations from the desired one. Unfortunately, the method does not provide means for further adjustment.

More accurate control of tonal response can be achieved by adjusting the cumulative histogram of the FM screen according to measurement data. This has the advantage of eliminating quantization errors. Let us define cumulative histogram as the number of printer dots in a halftone pattern as a function of gray level. Then any matrix generation algorithm can easily be modified to generate a dither matrix with any valid cumulative histogram. A valid histogram is a non-decreasing function of gray level with 0 as the smallest value and maximum

number of dots possible in a matrix as the largest value.

Figure 4 shows the printer response  $f_o(x)$  to an original matrix, and the desired response  $f_d(x)$ , as a function of gray value  $x$ . To change the threshold values in the original matrix so that the new matrix will have the desired tonal response, we do the following. For each threshold value  $a$ , we find the response of the original matrix,  $f_o(a)$ . Then we find the new threshold value  $b$  on the desired response curve so that  $f_d(b) = f_o(a)$ . The new threshold value therefore is  $b = f_d^{-1}[f_o(a)]$ . The mapping is illustrated graphically in Fig. 4. When the desired response is linear, the new threshold value is simply  $b = f_o(a)$ . Equivalently, we can map the input image data  $x$  according to  $f_o^{-1}[f_d(x)]$ .

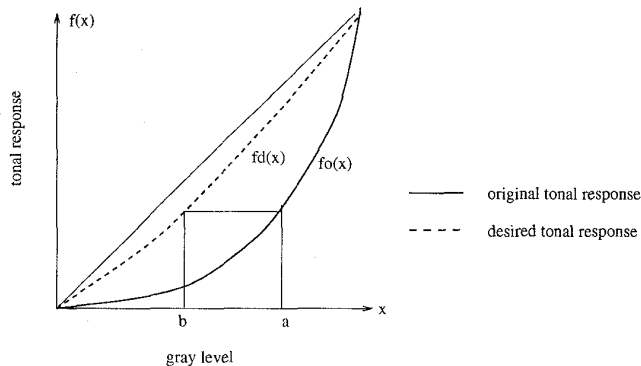


Figure 4: Direct mapping from the original to the desired tonal response curve

Suppose the cumulative histogram of the original matrix is  $c(x)$ , then the cumulative histogram of the new matrix should be  $c(f_o^{-1}[f_d(x)])$ . If the histogram of the original matrix is uniform, *i.e.*  $c(x) = x$ , then the new cumulative histogram is proportional to the input mapping function.

## 5. CONCLUSIONS

This paper reviewed two printer dot models and described their application in screen design, with emphasis on FM screens. A printer dot model improves a FM screen in both the printed pattern uniformity and the tonal response. However, it is difficult to achieve precise tonal control with the dot models. By adjusting the cumulative histogram of a FM screen according to density measurement data, more accurate tonal control can be achieved.

## 6. REFERENCES

- [1] T. J. Flohr and J. P. Allebach. Halftoning via direct binary search with a stochastic dot model. In *Proc. IS&T Third Technical Symposium on Prepress, proofing, and printing*, Chicago, IL, Oct. 1993.
- [2] Q. Lin. Improving halftone uniformity and tonal response. In *IS&T Tenth Congress on Advances in Non-Impact Printing Technologies*, pages 377-380, New Orleans, Louisiana, Oct. 1994.
- [3] Q. Lin and Jeanne Wiseman. Impact of electrophotographic printer dot modeling on halftone image quality. In *SID International Symposium Digest of Technical Papers*, volume 24, pages 147-150, Seattle, Washington, May 1993.
- [4] T. N. Pappas and D. L. Neuhoff. Model-based halftoning. In *IS&T/SPIE Symposium on Electronic Imaging: Science and Technology*, San Jose, CA, Feb. 1991.
- [5] P. G. Roetling and T. M. Holladay. Tone reproduction and screen design for pictorial electrographic printing. *Journal of Applied Photographic Engineering*, 5(4):179-182, 1979.
- [6] C. J. Rosenberg. Measurement based verification of an electrophotographic printer dot model for halftone algorithm tone correction. In *IS&T Eighth Congress on Advances in Non-Impact Printing Technologies*, Williamsburg, VA, Oct. 1992.
- [7] M. A. Schulze and T. N. Pappas. Blue noise and model-based halftoning. In *IS&T/SPIE Symposium on Electronic Imaging: Science and Technology*, San Jose, CA, Feb. 1994.
- [8] R. L. Stevenson and G. R. Arce. Binary display of hexagonally sampled continuous-tone images. *Journal of the Optical Society of America A*, 2(7):1009-1013, 1985.
- [9] R. Ulichney. The void-and-cluster method for dither array generation. In *IS&T/SPIE 1993 International Symposium on Electronic Imaging: Science and Technology*, San Jose, CA, 1993.
- [10] E. Walowit. Quantitative image quality analysis for desktop color scanners and printers. In *IS&T/SPIE 1994 International Symposium on Electronic Imaging: Science and Technology*, San Jose, CA, 1994.
- [11] J. A. C. Yule and W. J. Nielsen. The penetration of light into paper and its effect on halftone reproduction. *TAGA Proc.*, 3:65-76, 1951.