The MTF of Printing Systems

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Abstract

Many imaging systems are described by an MTF function. However, MTF is defined rigorously only for linear imaging systems, and the printing process is intrinsically non-linear. However, a spatial attenuation function we call the Printer Transfer Function, PTF, can be defined experimentally, and it behaves much like an MTF. The measurement of the PTF is illustrated for a 300 dpi electrophotographic printer. The PTF is shown to be experimentally independent of the halftone pattern printed, but a scaling factor, r, which is highly dependent on the halftone pattern, is required in order to calculate the noise power spectrum, NPS, of the printed halftone from the NPS of the ideal halftone in the computer.

Introduction

Over the past decade there have been many reports of halftone algorithms designed to incorporate a model of the spatial sensitivity function for human vision, also called the Visual Transfer Function (VTF).[1] The VTF is much like an MTF function for an imaging system and low-pass filters the noise one observes in an image. The visual noise in a halftone can be estimated by measuring the noise power spectrum, NPS, of the halftone and multiplying it by the VTF. Most reports in the literature calculate the NPS directly from the virtual matrices (bit maps) of 0s and 1s in the computer. However, when halftone patterns are printed they do not form perfect matrices of reflectance factors 0s and 1s. Ink reflectance is greater than 0 and paper reflectance is less than 1. More important, the printing process suffers both physical and optical dot gain effects. While many attempts to incorporate so-called "printer models" have been reported,[1] only the effects of dot gain on tone reproduction have been considered. However, the printing process also acts like a low-pass filter, and one would expect the printing process as well as the VTF to have a significant impact on printed halftone noise. This study was undertaken to examine the impact of the printing process on the NPS of halftones. Experimental work involved halftone patterns printed by a 300 dpi electrophotographic printer with black toner onto plain paper.

Experimental

Five halftone types were printed at 300 dpi in this study; clustered dots at 30 LPI; a Linear Pixel Shuffling (LPS) system[2]; a Robert's white noise system[3]; a proprietary error diffusion system; and a Bayer dispersed dot halftone[1]. As shown previously,[2] these systems cover the entire spatial range of NPS for halftones at 300 dpi addressability, and they also cover the entire range of clustering types from maximum (clustered dots) to minimum (Bayer). Noise power spectra were calculated from the virtual matrix of 0s and 1s in the computer before printing. NPS were also determined for the printed halftones by microdensitometric analysis. Microdensitometry was done by capturing video-microscope images of the printed halftones at a field of view of 10.8 mm. The MTF of the video-microscope system was measured and found to have a linear decline from 1.0 at 0 cy/mm to a value of 0.75 at 10 cy/mm. Data was not examined beyond 8 cy/mm, so instrument MTF correction was small and straightforward. The video-microscope was calibrated so pixel values (0 to 255) could be converted pixel by pixel into reflectance values (0 to 1). Thus image matrices (x,y, pixel value) were converted to reflectance matrices (x,y, R), and two-dimensional NPS were calculated. The RMS reflectance deviation, σ, was calculated both for the virtual halftone and for the printed halftone pattern. The NPS were normalized such that the total area under each NPS curve equaled its corresponding σ^2. The NPS of halftones before and after printing were then used to estimate a spatial transfer function we call the Printer Transfer Function, PTF.

Printing Ink on Paper

The NPS functions of the error diffusion system before and after printing are shown in Figure 1 as the log of the radial averaged noise power, Log(W), versus the spatial frequency in cy/mm.

Two features are immediately evident in Figure 1. First, the two curves do not appear to extrapolate to the same value at zero cycles/mm. This was observed for most halftones examined. In general, zero frequency noise estimates are experimentally difficult.

The second prominent feature of Figure 1 is the increased attenuation of noise at higher frequency. This is a low-pass filtering effect we will attribute to a printer transfer function, PTF, we will define subsequently.

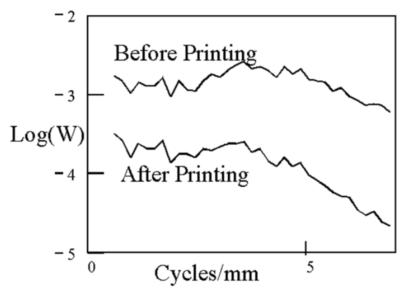

Figure 1: Log of the noise power, W, versus spatial frequency for an Error Diffusion halftone with a nominal dot area fraction of F_n = 0.2 before and after printing.

A decrease in noise power on printing is partially rationalized by the decrease from $\Delta R = R_p - R_i = 1.00$ in the ideal computer halftone to a value much less than 1.00 in the printed halftone. From the Murray-Davie equation, it can be shown easily that the overall RMS granularity, σ, of an ideal halftone with ink reflectance R_i and paper reflectance R_p should be given by equation (1).

$$\sigma^2 = F \cdot (1 - F) \cdot \Delta R^2 \qquad (1)$$

If one calculates σ^2 before and after printing, a decrease in noise power can be estimated. For the virtual halftone the values of R_p and R_i are 1 and 0, so $\Delta R^2 = 1$ and the virtual RMS noise is given by equation (2), where F_n is the nominal dot fraction.

$$\sigma_o^2 = F_n(1-F_n) \qquad (2)$$

In the example of Figure 1, Fn = 0.2, but when the halftone is printed, microdensitometric measurements show Rp = 0.70, Ri = 0.10, and F = 0.3 (a 10% physical dot gain). Equation (3) then estimates the noise power of the printed halftone.

$$\sigma_p^2 = F(1-F)(R_p-R_i)^2 \qquad (3)$$

We define a noise attenuation ratio $r = \sigma_o^2/\sigma_p^2$ and then define a shift, S, in log noise power.

$$S = -log(r) \qquad (4)$$

From measured values of R_p, R_i, and F, a log-noise shift of S = 0.33 (r = 0.47) is calculated for the system in Figure 1. However, as shown in Figure (1), total noise power is attenuated more as the spatial frequency increases. Thus S = 0.33 is an estimate of the shift in noise power only at the zero frequency intercept of Figure 1, and indeed it is only a lower limit estimate based on the assumption of a perfect bimodal distribution of reflectance, R_p and R_i. Experimentally, the zero frequency shift in Figure 1 is closer to S = 0.65. Real halftones have reflectance histograms that show significant amounts of spread around the mean values of R_p and R_i. This tends to decrease the estimated value of σ_p^2 and thus to increase the value of S. This coupled with higher attenuation at higher frequency makes zero frequency noise difficult to estimate theoretically as well as experimentally.

The Printer Spatial Transfer Function

As shown in Figure 1, noise is attenuated more at high frequencies than at low frequencies. Prediction of this effect a-priori requires full knowledge and quantitative understanding of the printing mechanism and is beyond the scope of the current work. The alternative is to measure the effect experimentally. This was done comparing the spectrum of the printed halftone, $NPS_p(\omega)$, to that of the virtual halftone, $NTS_o(\omega)$, as shown in equation (5). Figure 2 shows the results for the error diffusion system of Figure 1, with the ratio r adjusted so the data extrapolates through PTF=1 at zero cycles/mm.

$$PTF(\omega) = \frac{NPS_p(\omega)}{r \cdot NPS_o(\omega)} \qquad (5)$$

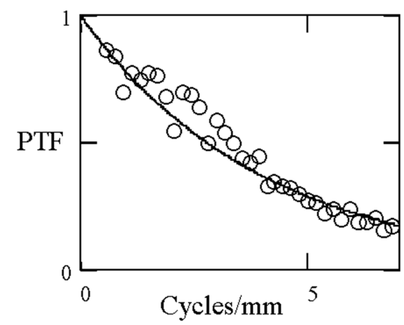

Figure (2): PTF for error diffusion system.

The solid line shown in Figure (2) is the exponential model shown in equation (6).

$$PTF = e^{-k \cdot \omega} \qquad (6)$$

The value of k = 0.25 in units of mm^{-1} was selected to best fit the data.

The approximation behind this analysis and the definition of equation (5) is the assumption that a printer acts as a linear system. The justification for this approximation is based on experimental observations of the five halftone systems examined in this project. Using equation (5), best fit values of r and k were obtained for the five halftone systems in this study. The result was a wide variation in r but nearly constant values of k, within experimental error. Thus the value of k, and therefore the PTF function characteristic of the printing process, appear to be independent of the halftone process within experimental error. The ratio r, on the other hand, is a factor associated with tone reproduction and dot gain effects well known to be closely dependant on the halftone algorithm.

Conclusion

The results of this work suggests that the printer transfer function of equation (5) may provide a useful method for characterizing the noise propagation properties of printing systems independent of the halftone algorithm employed. However the shift factor, r, is not independent of the halftone pattern, so a tone reproduction analysis by microdensitometry is essential to a full calibration of a printing system. Once tone reproduction analysis provides the r characteristic of a halftone algorithm, noise power of the printed halftone, NPS_p can be estimated by equation (7).

$$NPS_p = NPS_o \cdot r \cdot PTF \tag{7}$$

It is important to point out that the PTF function is not an MTF function, although it seems to behave very like one. The printer is intrinsically a non-linear system with two spread functions active in the printing process. One of the spread functions at work mechanistically is the physical spread of colorant mass, often called physical dot gain. This point spread function, PSF, describes the point distribution of colorant in the system. Colorant mass is not linearly related to reflectance, R, or transmittance, T. The other spread function in the system is the optical spread function of light in the paper, and light is linear in R and T. Thus the optical PSF (optical dot gain) is always non-linear relative to the colorant mass PSF (physical dot gain), so they can not be convolved to estimate the overall system PSF. The practical manifestation of this is that although the PTF function suggested in this report may be useful in estimating noise power changes that result from the printing process, it can not simultaneously be used to estimate tone reproduction characteristics of the printer.

References

1. "Recent Progress in Digital Halftoning II", Chapter 1, R. Eschbach, Ed. IS&T monograph, p. 199 (1999), and references contained therein.
2. J. Arney, P. Anderson, K. Ayer, and P. Mehta, "Linear Pixel Shuffling (II): An Experimental Analysis of Tone and Spatial Characteristics", NIP-16, Vancover, BC, October 2000.
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Biography

Jonathan Arney is an associate professor at the Center for Imaging Science at Rochester Institute of Technology. His research interests include physical and optical characteristics of colorants on substrates, with particular emphasis in halftone systems. He serves as faculty advisor for the Student Chapter of IS&T and as a council member for the Rochester Chapter of IS&T. Jonathan received the IS&T Journal Award (Science) in 1990, the IS&T Service Award in 1995, and in 1996 he received the Raymond C. Bowman Award for contributions to education in the fields of Photographic and Imaging Science.