Graininess of Color Halftones

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Introduction

Graininess describes the subjective perception of noise in an image. The perception has been quantified with metrics to allow quantitative monitoring of graininess. In this paper, we show how a metric for graininess can be transformed into a form more suitable to describe the graininess of clustered dot images. We review different models that explain the toner number fluctuations that give rise to graininess. We propose an extension of the graininess metric to color images. Using the color visual transfer functions, we extract the relative contributions of chroma and luminosity to graininess. We apply the metric to two examples – the relative graininess of the individual color separations, and the graininess of toner blends for use in custom color.

Graininess metrics

A number of different metrics have been proposed to quantify image graininess.[1-4] These metrics differ because psychophysical experiments give slightly different results, and measurement tools improve which allow for a different metric. Here we use the Dooley-Shaw[1] metric of image graininess G, which is given by

$$G = e^{-1.8D} \int \sqrt{W(\omega)} VTF(\omega) d\omega \qquad (1)$$

D is the optical density, *W* is the Weiner spectrum (the Fourier transform power) of the image cross section, and VTF is the visual transfer function of the eye. The average density appears because psychophysical experiments show the eye is more sensitive to density fluctuations at light densities than at darker densities. The Fourier transform is necessary because of the eye's varying sensitivity to different spatial frequencies. The visual transform function quantifies this sensitivity.

Different forms of the graininess metric have been proposed.[2-4] These metrics are also a function of the AC and DC components of the optical density and the visual transform function, but in different ways. Some authors find a different density dependence. Some perform a 2D rather than a 1D integration. Other metrics preprocess the data to remove nonrandom effects such as periodic banding and the halftone screen. Various estimates of the visual transfer function are used. However, in this paper the different metrics don't change anything substantial. As long as a single metric is used for comparisons, any of them is valid. We will continue using the Dooley-Shaw metric, but the techniques can be applied to the other metrics.

Halftone Image Graininess

Image graininess is highest for images at low area coverages, where the halftone dots are isolated. Graininess arises in part from variations in the shape, size, edge roughness, and the scattered toner between the individual halftone dots. Many of the physical processes that give rise to these variations are uncorrelated from dot to dot. The lack of correlation will lead to a frequency independent noise spectrum. $W(\omega)$ can be pulled out of the integral, and eq. (1) just becomes an integral over the visual transfer function.

For uncorrelated dots with a standard deviation in reflectance *r* of σ_r, and an interdot spacing *u*, the Dooley-Shaw metric becomes[5]

$$G = \frac{2.52 e^{-1.8D} u \sigma_r}{r \ln 10} \qquad (2)$$

The factor 2.52 comes from the integral of the visual transfer function. We rewrite eq. (2) in terms of luminosity using $L=116r^{1/3}-16$.

$$G = 4.73\times10^{-5}(L+16)^{1.35}\sigma_L u = C_G \sigma_L u \qquad (3)$$

Eq. (3) will be the form of the graininess metric which will be extended to color.

Models of Toner Number Fluctuations

A simple model of toner deposition can be used to understand the physical sources of image graininess and the roll color plays. One possible model is random sequential adsorption (RSA).[6,7] RSA is most applicable to a xerographic printer that would favor the development of a single monolayer of toner to completion. RSA starts with an empty square which represents a halftone dot. Toners with a circular cross section are deposited in sequence on this square by picking the coordinates of the new toner randomly. If the toner position overlaps a previously deposited toner, it is not allowed to adsorb and a new position is picked. Toner is continued to allow to adsorb until the halftone dot is filled up to the maximum extent possible. The geometrical constraints of the toner positions give a different number of toners per halftone dot which

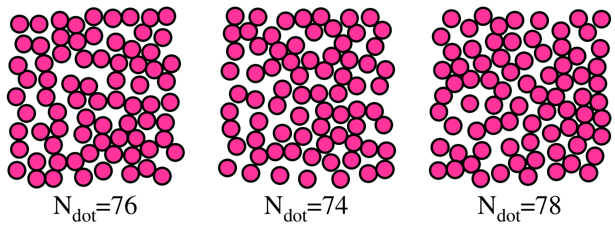

Figure 1 –Different toner arrangements from RSA

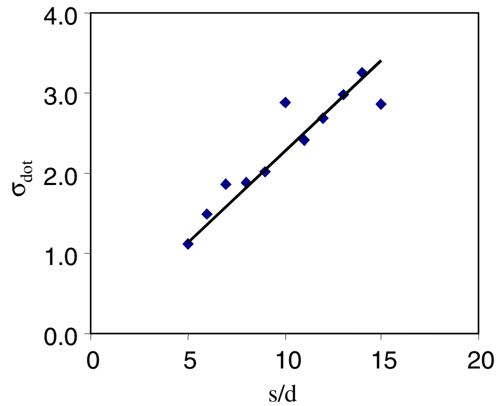

Figure 2 –Toner dot number fluctuations as a function of side to toner diameter ratio.

ultimately leads to image graininess. Three different arrangements of toner on a halftone dot are shown in figure 1. From a simulation of many more of these dots we can relate the toner number fluctuations to the number of toners deposited. The results of this simulation are shown in figure 2 and we use these results later in this paper in the simulations of custom color toner blends.

The relationship between toner number and luminosity is needed to relate the modeled toner number fluctuations to the luminosity or optical density fluctuations that the graininess formula needs. This can be measured experimentally from the measured mass of toner on the paper and the measured luminosity.

Sensitivity to Color Fluctuations

Kane and Cookingham, quoting an early study of Bartleson, state "graininess was found to be structly a function of the achromatic channel of the visual system".[8] However, Sakatani and Itoh, looking closely at psychophysical data meant to get at the color contributions to graininess, find "subjective evaluated levels.improve greatly compared with the case where color noise is not considered".[9] We propose an extension of equation (3) to color space to describe the graininess of color halftones. In support of the latter study, we use measurements of the visual transfer function in color space to infer the parameters that give the relative contributions of the achromatic and chromatic channels to graininess.

Recently, Itoh et al have proposed an extension to their metric of graininess to include color information.[9-13] They write the metric graininess index GI as

$$GI = \sqrt{LN^2 + k \times CN^2} \tag{4}$$

where LN is the lightness noise and CN is the color noise. *k* is a scale factor giving the relative contributions. They define LN in a way similar to Dooley and Shaw, but with a slightly different optical density dependence and a two dimensional integration. Color noise is defined in a slightly different way. The color data is convoluted with rectangular windows and the standard deviation of the image in color space (implicitly assuming a constant noise spectrum) is used to quantify the color noise. The value of k is chosen to match the psychophysical data, but the color data has different "units" so the color contribution cannot straightforwardly be inferred from the magnitude of *k*.

We propose an expression for color graininess specific for clustered dot images by generalizing eq. (3). We replace σ_L with an expression for the variations in color space. The variations are scaled by the constants s_a and s_b. These express the relative sensitivity of noisy variations along the a* and b* to those along the L* axis. Specifically,

$$G = C_G \sqrt{\sigma_L^2 + (s_a \sigma_a)^2 + (s_b \sigma_b)^2} \tag{5}$$

To determine s_a and s_b, we integrate over the visual transfer function for color as we did over the visual transfer function for luminosity.

Color Visual Transfer Function

Hirose inferred the relative visual transfer function along the three color axes.[14] He superimposed noise patterns varying in either chroma or lightness with a specific spatial frequency content on a pictorial image. The appearance of the images were subjectively evaluated with respect to noise by a number of observers. From these experiments, the sensitivity as a function of spatial frequency was found for each the L*, a*, and b* axis. This sensitivity is plotted in figure 3. We use Simpson's rule to perform the numeric integrations, assuming the sensitivity is 0 at 0 frequency for L* variations and equal to the lowest frequency

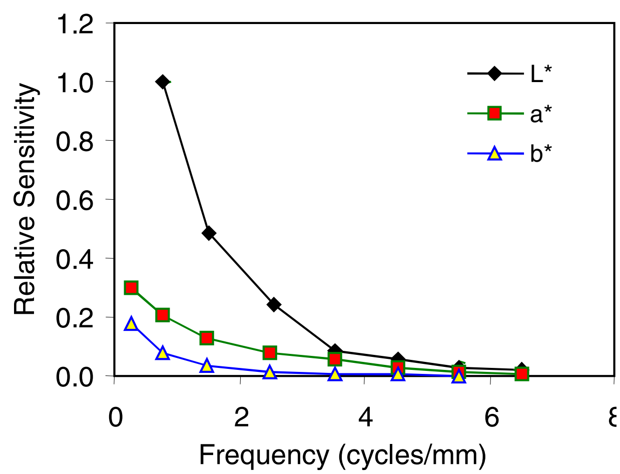

Figure 3 –Hirose VTF. The data is not presented this way in the paper, but inferred from the individual VTF's and the relative peak sensitivities.

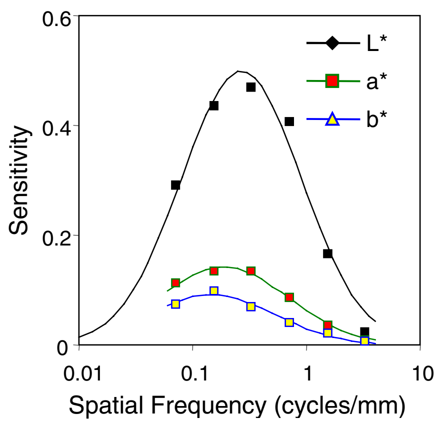

Figure 4 –Klassen-Goodman color visual transfer function

measurement for a* and b* variations. From the integrations, we find s_a=0.34 and s_b=0.11.

Klassen and Goodman performed a psychophysical study on contrast sensitivity as a function of spatial frequency, color, and direction of variation.[15] They found a dependence on spatial frequency and direction of variation, but none on the mean color. We therefore average their results over all colors, translate relative sensitivities to a visual transfer function, and plot the results in figure 4. Performing the numerical integraiton for the Klassen-Goodman study gives s_a=0.24 and s_b=0.12. The parameters are of the same order as determined by Hirose. We use the Klassen-Goodman values in the color graininess formula.

Graininess of Color Separations

The physical source of graininess is the toner number or mass variations on the paper. The color of the toner just affects the perception. For full color printers the development subsystems for each color are usually the same and would contribute in the same way to the mass variation. It is therefore of interest to relate the same mass variation to graininess for different colors. The graininess will vary in a different way for the colors.

We separate out color by expression the graininess formulate in eq. (5) in terms of area coverage fluctuations.

$$G = C_G \sigma_{ac} \sqrt{\left(\frac{\partial L^*}{\partial a_c}\right)^2 + \left(s_a \frac{\partial a^*}{\partial a_c}\right)^2 + \left(s_b \frac{\partial b^*}{\partial a_c}\right)^2} \quad (6)$$

The partial derivatives of eq. (6) can be calculated from a measurement of L*,a*, and b* vs. area coverage (toner reproduction curve, or TRC). These curves were measured for a Docucolor 40 printer and the graininess results for an arbitrary choice of σ_{ac} are plotted in figure 5. One sees that at the low mass densities black has the highest graininess, but for high area coverages, color toner graininess is large.

Graininess of toner blends

Many classes of documents use black plus one or more highlight colors to create the image. Many applications

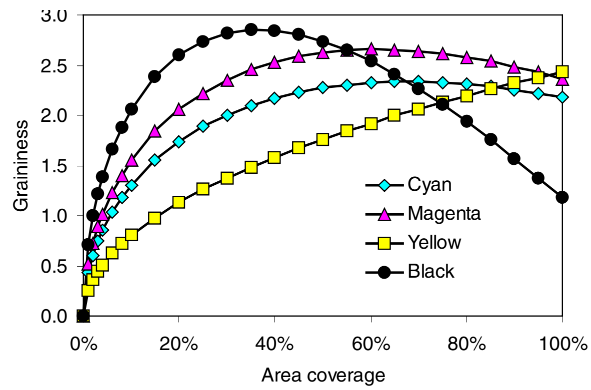

Figure 5 –Graininess for different color separations

require a unique color. In xerography it requires a large investment to design a toner with a unique color. One way to create a large number of colors is to blend two or more toners of different colors.[16]

Some highlight color images contain color sweeps or large regions with less than full area coverage. Each halftone dot therefore contains a small number of each color toner. The statistics of the xerographic process cause the number of toner in each dot to vary. In addition to this variation, the ratio of each color toner will vary between dots. This color variation will be an additional contribution to graininess.

Consider a toner blend consisting of two toners. The number of toners in each dot is described with a binomial distribution. Specifically, if a dot contains $N_1+N_2=N_{dot}$ toners, the probability of having N_1 toners of color 1 and N_2 toners of color 2 is

$$P_{N_1,N_2} = \frac{(N_1+N_2)!}{N_1!N_2!} f^{N_1} (1-f)^{N_2} \quad (7)$$

where f is the fraction of toner 1 in the blend. The standard deviation of the number of toners of both color 1 and color 2 is $\sigma_{fb}=[N_{dot}f(1-f)]^{1/2}$.

To calculate the graininess we need to know the change in color with the number of toners in the dot. This is difficult to model. We measured the color change for solid area images as a function of the blend ratio in a cyan-yellow mixture. Cyan-yellow is an extreme situation because of the luminosity difference. With this measurement and that of the toner reproduction curves, we can estimate the color for any blend ratio and any area coverage by interpolation. We generalize the expression for halftone graininess once again by including the toner blend ratio fluctuations.

$$G = C_G \sqrt{\sum_{i=1}^{3} \left(\frac{\partial X_i}{\partial f_b} \sigma_{f_b} + \frac{\partial X_i}{\partial f_{ac}} \sigma_{ac} \right)^2} \quad (8)$$

X_i is either L*,a*, or b* as i varies between 1 and 3. f_b is the fraction of one of the components in a 2 toner blend, and f_{ac} is the area coverage.

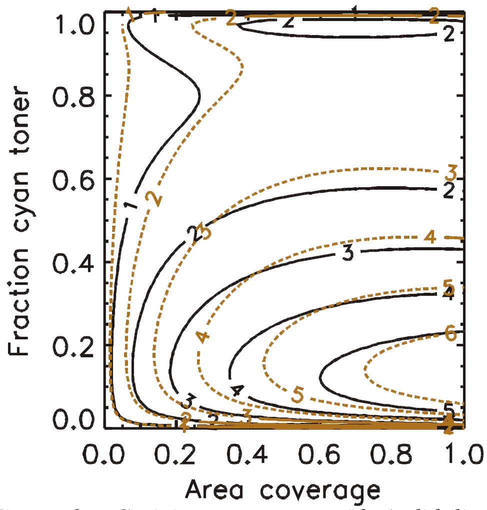

Figure 6 – Graininess contours with (solid line) and without (dotted line) toner number fluctuations.

From the parameters extracted from the TRC and color blend measurements, the graininess is calculated and plotted in figure 6 as a function of area coverage and fraction of cyan toner. The solid lines are the graininess contours assuming no dot size fluctuations, and the dotted lines add fluctuations predicted from RSA.

The graininess of the cyan-yellow custom toner blend can get quite large. At higher area coverages and low concentrations of cyan toner, the graininess can get to be over 6 which would be quite visible and objectionable.

Conclusions

In this paper, we presented a graininess in a form most applicable for cluster dot halftone patterns, which allowed for a straightforward generalization to color. The parameters for the extension to color were evaluated using psychophysical measurements of the color visual transform function. We then applied the new metric to the graininess of single color separations and the graininess of toner blends. Models of the statistics of toner deposition allowed for the relative contributions of color and toner number fluctuations to be extracted.

An important extension would be to be able to link the graininess of each color separation to the perceived graininess of full process color. This extension requires a reasonable model of how overlaid color combine. A model of this sort would allow graininess to be explored over all color space.

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Biography

Howard Mizes received his B.S. degree in Physics from the University of California at Los Angeles in 1983 and a Ph.D. in Applied Physics from Stanford University in 1988. Since 1988 he has worked in the Wilson Center for Research and Technology at Xerox Corporation in Webster, NY. His work has primarily focused on the development process, including toner adhesion, toner transport and image quality issues. He is a member of the IS&T and the American Physical Society. **e-mail: hmizes@crt.xerox.com**