Precision Tone Reproduction Curve Measurement Technique for High Image Quality and Halftone Design Applications

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Abstract

We show that an extremely accurate tone reproduction curve (TRC), insensitive to noise in the printer and the media, can be measured using a scanner. In the scanner-based approach, two patterns are written. The first contains as many as 15,000 extremely small patches of the 256 addressable gray levels randomly placed on paper. The random placement averages over the noise and the mean of each patch gives an estimate of the TRC. The second pattern consists of 256 narrow strips with a high spatial frequency modulation between two adjacent gray levels for each strip. The scanner response at the modulation frequency for each strip gives the change in gray level between each halftone. The absolute values of the TRC from the first measurement are adjusted to best agree with the slope measurements, resulting in a highly accurate TRC measurement.

Introduction

A printer's tone reproduction curve (TRC) maps the input gray level to the output gray level (or color, for each color separation of a printer). Producing high quality printed images requires the accurate design and control of the TRC.

The coarse structure of the TRC sets the overall contrast of the image. For example, a printer with a large dot gain will map light gray levels to darker printed areas. A measurement of the TRC provides a means to compensate for dot gain. The gray levels of the digital image can be adjusted so that when they are printed, the desired image contrast is achieved.[1] The ability to measure the TRC also provides a means to control the mapping so it is robust and stable over time.[2]

However, the TRC fine structure is also important. The fine structure depends on the details of the halftone dot. For example, the local TRC slope may be steeper at the gray level where the individual dots begin to touch. This fine structure may have an effect on image quality. Consider, for example, images that contain slowly varying intensity sweeps, or circumstances where it is important to maintain accurate color or gray level control. False contours can appear in images where the jump in adjacent gray levels exceed the objectionability threshold.[3]

Measuring a grid of patches with a spectrophotometer is one approach to determine the TRC.[4] Spectrophotometers are designed to have low measurement noise and to give an accurate color space measurement. Although this approach accurately measures the coarse structure of the TRC, the fine structure is sensitive to noise in the media and the printer.

An alternative approach to measure the TRC is with a scanner. A scanner can rapidly collect an image of calibration patches. However, a scanner does not make an accurate color space measurement. In addition, it introduces an artifact which can cause systematic errors in the measurement. This paper describes image analysis algorithms that can increase the accuracy of a scanner measurement beyond that of a spectrophotometer. This enables the scanner to resolve both the coarse and fine structure of a TRC.

TRC Measured From Large Patches

In this paper we restrict ourselves to a single color separation. If four color separations can be individually monitored, then the behavior of full color sweeps can be predicted.

Banding and streaking (1D macrouniformity[5]) and graininess and mottle (2D macrouniformity failures[6]) are a source of measurement noise in printers. The same calibration patch printed at two different locations at two different times may have a different measured density because of variations across the print. Mottle and graininess adds a random noise to the patch, also causing the sensed density to fluctuate.

In order to provide a reference for the improvement possible with the scanner-based technique, I used large uniform patches to measure the TRC of the black separation with a spectrophotometer. A section of the TRC is shown with the diamonds in figure 1. The structure in this curve depends on the noise level of the printer, but is typical for many commercial printers.

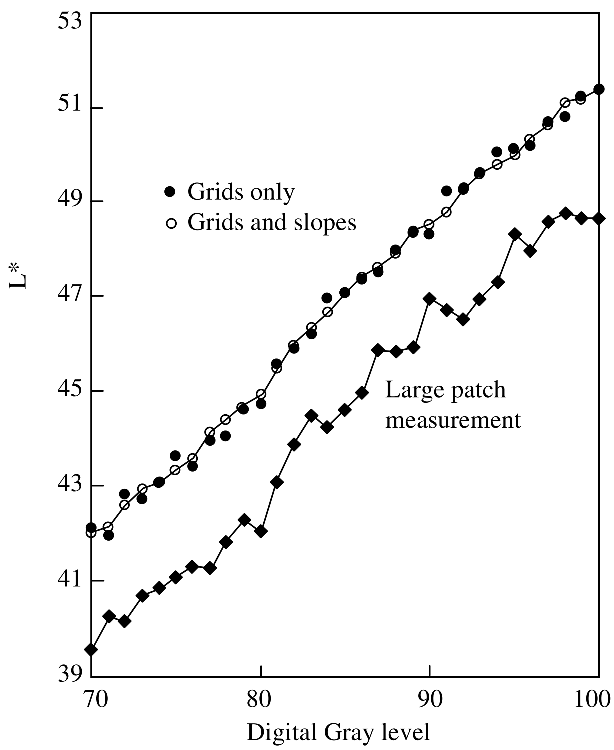

Figure 1. TRC measured in different ways.

TRC Measured From Scanned Patches

A scanner is an alternative measurement system for the TRC. For single color separations, collecting the whole wavelength spectrum to determine CIELAB color is not necessary. A scanner can rapidly collect the reflectivity of a series of calibration patches. The scanner can be calibrated to CIELAB color by measuring both the scanner response and the spectrophotometer response to the same patches.

Although the scanner can collect data rapidly, it also has a source of measurement noise. The internal illumination depends on multiple reflections internal to the scanner. Some of these multiple reflections come from neighboring regions on the test pattern. Therefore, the measured patch reflection may depend the surrounding gray level of neighboring patches. This artifact is known as the integrating cavity effect.[7]

This error caused by the integrating cavity effect can be minimized by using the high resolution measurement capability of the scanner. Typically, in color calibration, large patches are used and noise is minimized by averaging over the patch. With a scanner, the patches can be shrunk down to an extremely small size. Each small patch can be printed randomly over different area of the print. Thus, the averaging can be distributed over the page.

A section of a possible test pattern is shown in figure 2. The side of the original patch is 0.05 inches, which gives a halftone cell of 30 by 30 pixels at 600 spi. The patch densities are randomized to spread the noise from image structure over all the gray levels. The image is surrounded by fiducial arks. These fiducial marks are used to align the image and to identify the locations of the patches across the entire image.

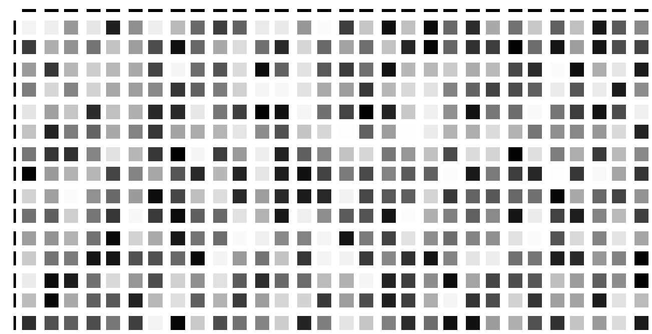

Figure 2. Section of grids pattern

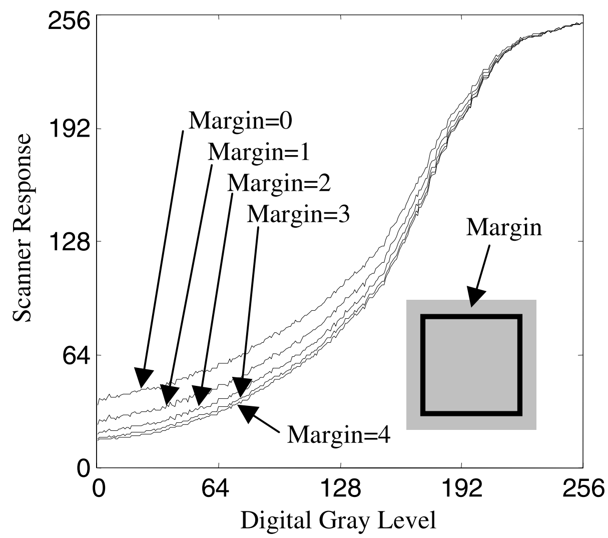

Figure 3. Margin effect

Distributing the patches over the page also makes the TRC measurement insensitive to print noise. For example, if a printer has a light streak in the center of the page, the response to all patches printed in the region of this streak will be underestimated. However, if the patches are small and distributed over the image, the light patches will effect all gray levels a smaller amount and won't distort the TRC.

To obtain the lowest measurement noise when there are within page variations, the patches should be made as small as possible. But there is a limit to their size. When the patches become too small, not enough of the halftone brick is sampled to infer the gray level. Also, the perimeter to area ratio becomes larger and edge effects dominate.

The edges of the patch are lighter than the center because of more light entering the paper at the boundaries. For large patches this effect is negligible and not measured, but for small patches the edge effect may shift the measurement. Figure 3 shows the measured TRC as a function of the number of pixels end from the edge that are used in patch averaging. The figure shows the measured patch density darkens and then levels off when pixels far enough in from the edge are used. Monitoring the edge effect confirms that the measured small patch density is representative of large patches.

The result of using 15,000 small patches gives an improvement in the measurement noise shown by the solid circles in figure 1. The TRC is shifted because it was measured at a different time.

TRC Slope Measurement

Even though the noise in the measurement of each gray level has been reduced, the noise level is still high to make fine judgments about halftone dot design. For example, there are regions where a halftone with one additional pixel turned on in the halftone brick is measured to be lighter. This noise can be reduced by specifically designing a test pattern to address this issue. I call this the slopes test pattern.

Figure 4 shows a section of the test pattern to measure the slope of the TRC. The test pattern consists of 256 narrow strips, one corresponding to each gray level. The strip is not a uniform gray. Instead, strip i alternates between gray level i and gray level i+1 in 20 pixel wide segments. I choose 20 pixels so as to be large enough to sample the full halftone brick, but small enough so that many repeats occur along the halftone strip. In the test pattern shown, the strips are 1110 pixels long, giving 28 repeats of the alternation.

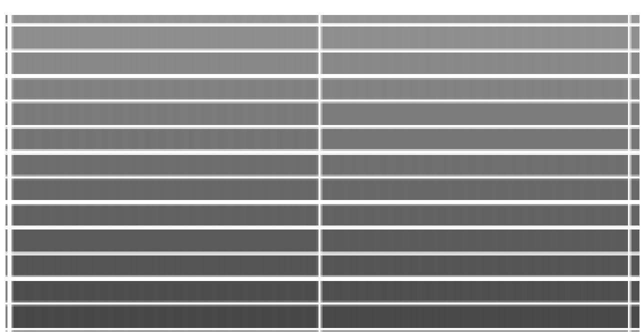

Figure 4. Slopes test pattern

When the strip is scanned, there will be noise due to the inherent streaking of the printer and the quantized response of the scanner. However, there will be a signal at the frequency that the gray level variation was introduced. This signal is not clearly measured in the profile across a strip (figure 5), but shows up strongly in the Fourier transform of the profile (figure 6). The amplitude of the signal is a measure of the difference between two adjacent gray levels. The average of the noise in the vicinity of the peak is subtracted to get the true values of the gray level difference.

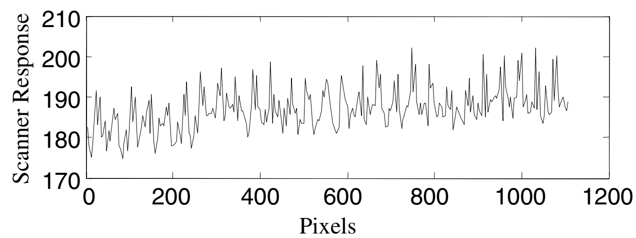

Figure 5. Profile across slopes pattern strip.

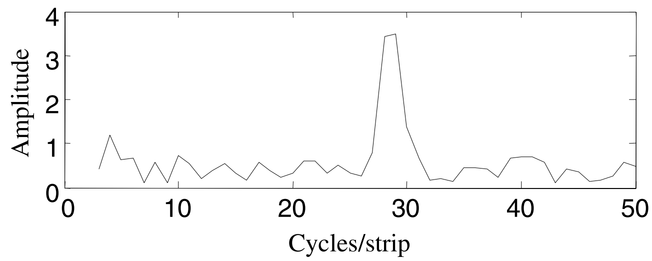

Figure 6. Fourier transform of strip profile

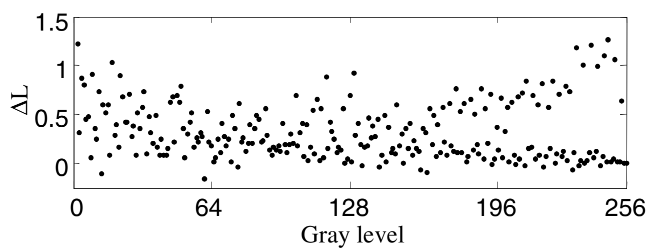

Figure 7. Local TRC slopes

The Fourier transform is an inefficient way of getting the amplitude of a signal at a known frequency. Instead, one can use techniques of digital signal process to extract this amplitude.[8] Specifically, I calculate the integral of a square wave at the strip frequency multiplied by the strip profile. I maximize the signal by adjust the square wave phase.

Figure 7 plots the slope as a function of gray level. For the halftone pattern analyzed in this plot, there are only 160 independent gray levels possible. Having 256 digital gray levels means that some levels are redundant, that is, different digital gray levels print out the same halftone. At the lighter gray levels, the slope jumps between large numbers and numbers near zero. The near zero slopes measurements are the redundant gray levels.

Combining Slopes and Grids Measurement

The measurement of the average scanner reflectance from the grids test pattern and from the slopes test pattern can be combined to give a highly accurate measurement of the TRC. This combination is made by performing a least squares fit of a TRC simultaneously to the grid pattern and the slope pattern measurement.

First, the slopes must be scaled. Because of the noises present in the numerical analysis of the slopes pattern, the true slope may be underestimated. The sum of all the slopes should equal the difference between the lightest and darkest solid. If this is not the case, the measured slopes are scaled so that these two quantities are forced to match.

After the slopes are adjusted, I solve for the TRC by minimizing the quantity

$$S = w_r \sum_{i=1}^{N} (r_i - t_i)^2 + w_\Delta \sum_{i=1}^{N-1} \left[(t_{i+1} - t_i)^2 - \Delta r_{i,i+1} \right]^2$$

where r_i are the measured patch reflectivities from the grid pattern, $\Delta r_{i,i+1}$ are the measured slopes, and t_i are the true levels of the TRC. w_r and w_Δ are relative weights given to the contribution of the grid and slopes pattern. The choice for these values depends on the application of determining the TRC accurately. If w_r is given more weight than w_Δ then the absolute value of the TRC will be better matched, while if w_Δ is given more weight than w_r, the slope of the TRC will be better matched.

The minimum of S can be solved analytically. The derivative of S with respect to the t_i's are

$$\frac{\partial S}{\partial t_1} = 2w_r(r_1 - t_1) - 2w_\Delta(t_2 - t_1 - \Delta r_{12})$$

$$\frac{\partial S}{\partial t_i} = 2w_r(r_i - t_i) + 2w_\Delta(t_i - t_{i-1} - \Delta r_{i-1,i}) - 2w_\Delta(t_{i+1} - t_i - \Delta r_{i,i+1})$$

$$\frac{\partial S}{\partial t_N} = 2w_r(r_N - t_N) + 2w_\Delta(t_N - t_{N-1} - \Delta r_{N-1,N})$$

Setting the derivatives equal to zero gives a linear set of equations that can be written as a matrix equation.

$$\begin{pmatrix} w_r + w_\Delta & -w_\Delta & 0 & \cdots & 0 \\ -w_\Delta & w_r + 2w_\Delta & -w_\Delta & & 0 \\ 0 & -w_\Delta & w_r + 2w_\Delta & & \vdots \\ \vdots & & & \ddots & -w_\Delta \\ 0 & 0 & \cdots & -w_\Delta & w_r + w_\Delta \end{pmatrix} \begin{pmatrix} t_1 \\ t_2 \\ t_3 \\ \vdots \\ t_N \end{pmatrix} = \begin{pmatrix} w_r r_1 - w_\Delta \Delta r_{12} \\ w_r r_2 - w_\Delta(\Delta r_{12} - \Delta r_{23}) \\ w_r r_3 - w_\Delta(\Delta r_{23} - \Delta r_{34}) \\ \vdots \\ w_r r_N - w_\Delta \Delta r_{N-1,N} \end{pmatrix}$$

From this matrix equation, one can solve for the t's and thus the best fitted TRC.

A TRC calculated by performing this least squares fit is shown with the open circles in figure 1. The relative weighting of the TRC from the grids pattern and the slopes pattern was adjusted to best keep the TRC monotonic while maintaining its absolute value near that determined from the grids pattern.

Conclusions

In this paper, I described a technique that uses the capability of the scanner to collect a massive amount of information to measure the TRC extremely accurately. Some applications of this technique include studying the nuances of halftone dot design and the susceptibility of a printer to artificial contours that appear in color sweeps. The test patterns described here represent a large improvement over using large patches. Further improvements in the sensitivity can be made by optimizing the patch size, locations on the test pattern, strip sizes in the slopes pattern, the spatial period of the toggled levels, and other things.

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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**