Scanner-based Technique to Adjust LED Printbar Uniformity

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Abstract

Electrophotographic printers using light emitting diode (LED) imagers may print images with streaks due to nonuniformity in the light output intensity and spot shape. Typically, each LED intensity is measured and the current adjusted to maintain uniform light output. However, the spot profile from emitter to emitter is different because of the imaging optics and emitter structure variations. The response of the print engine to spot structure can cause a printer to have streaks even though the intensity profile is uniform. We describe a technique that monitors the print uniformity to adjust the LED elements. The test pattern consists of an arrangement of single pixel wide lines arranged in a way that minimizes the sensitivity to printer and measurement noise. Control theory methodology is used to adjust the LED exposures to achieve a uniform profile of line widths and thus full print uniformity. This approach can be used to compensate for other system sources of print nonuniformity.

Introduction

It is difficult to achieve a uniform density output from a printer. The problem is particularly severe for high quality color printers, where subtle changes in shading and uniform fields are perceptible. For example, a 1 mm periodic variation in the optical density with a peak to peak amplitude of only 0.25ΔL can be perceived.[1] This is a variation of only about 0.3%.

An LED imager has advantages of speed, resolution and compactness, but can have a nonuniform response which manifests itself as streaking. Adjustments following the manufacture of the LED print bar to make the intensity profile uniform may no longer give a uniform profile when the LED is incorporated into a printing system. The beam shape may differ from LED to LED within a print bar because of the differences in the optical path. The beam shape change may give rise to a nonuniform printer output. Other subsystems in the printer may also be a source of streaks which could potentially be compensated for by the LED printbar.

Using a printed test pattern to monitor uniformity is a more direct probe. The uniformity can be quantified at the print and the LEDs can be adjusted to give a uniform print. In ref. 2, scanned flat field contones are used to adjust individual LED on times. In ref. 3, scans of different density strips are used to determine the amount to shift the input gray levels to compensate for the LED nonuniformity.

In this paper, we describe an improved technique to maintain uniform prints. Our technique differs in 3 respects from the previous techniques. First, we use a test pattern that allows individual LED outputs to be measured with high sensitivity. Second, we use a control methodology which makes our measurements less sensitive to noise. Third, we generalize our technique so that it still functions for 1200 spi or higher imagers.

Scanner-based Compensation

Previous compensation techniques scan uniform halftones. A constraint of scanning halftones is that LEDs cannot be adjusted on an individual basis. Averaging must be performed over some amount of the halftone cell to eliminate the structure introduced by the halftone.

Individual LED intensities can be monitored with a test pattern sensitive to single LEDs.[4] A portion of the test pattern we use is shown in figure 1. The darkness of the line is proportional to the intensity output of the LED.

Figure 1. Section of test pattern. Bar on the left is for alignment.

The uniformity achievable with a scanner-based technique depends on how precisely each line can be measured. Figure 2(a) shows an magnified view of one of the lines of figure 1. It was scanned on a UMAX Powerlook III flatbed scanner at 1200 spi, the true optical resolution. Figure 2(b) shows a cross section through this line. To extract line width we define a threshold and determine the spacing between the crossing points with linear interpolation.[5] Using this gray level information increases the resolution beyond the scanner resolution.

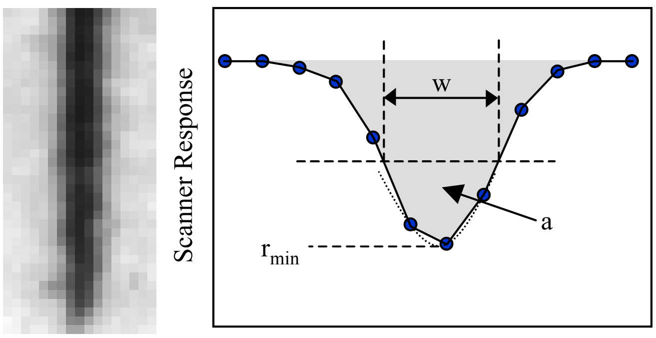

Figure 2. Image of line and cross section. Possible metrics are line width w, minimum response at line center rmin, and area under curve a.

We estimated the measurement precision by scanning a print with many single pixel lines multiple times. The print was moved on scanner platen each time. The standard deviation of each line width measurement was found. The average of these standard deviations could be made as low as 0.47 μm by adjusting the threshold.

In order to measure all the LEDs on a single print, multiple LEDs must be turned on. The single pixel lines must be separated by enough space in a single print so the presence of one line doesn't affect the measurement of another line. We found that a separation of at least 7 pixels at 600 spi is sufficient.

An additional technique to increase the sensitivity is to print multiple repeats of the single pixel line on the page. The LED response is found by averaging these multiple measurements together.

To monitor the full set of LEDs on a print bar requires writing multiple rows of single pixel wide lines. Each row prints out a different set of LEDs. One approach is to stagger the set of LEDs printed, for example, printing LEDs 1,9,17,… in the first row, LEDs 2,10,18,… in the second row, and so on. However, this staggering is not robust against averaging to compensate process direction banding. A better technique is to randomize the LEDs in each test pattern row. We pick a random set of LEDs to print in each row, with the constraint that the lines can't be too close to each other. This approach ensures that all rows are coupled to all other rows.

The line profile can be processed to a single number that correlates with the intensity of the LED. The objective of this processing is not to give a physically meaningful metric, but to get a metric of the highest precision that correlates with the LED intensity. The interpolated line width is one choice, but the threshold crossing can be chosen arbitrarily to increase the sensitivity. The integrated area under the line is another choice. A third choice may be the interpolated minimum reflectance at the center of the line. All of these metrics are illustrated in figure 2.

We have written an image analysis algorithm that takes as input the scanned test pattern and returns a metric corresponding to the exposure of the individual LEDs. Using a key of the ordering of the test pattern lines, the algorithm automatically performs the ordering and the averaging of the multiple line repeats. It is robust against print defects that might typically appear in a print. It is also robust against process direction banding by forcing the average of each row of test pattern lines to be equal.

Control Algorithm

We use a control methodology to ensure a precise measurement in the presence of measurement and printer noise. A flowchart is shown in figure 3. The line width w_i^k of LED i is given by

$$w_i^k = g_i u_i^k + h_i + v_i^k$$

where u_i^k is the LED exposure setpoint, g_i^k is the sensitivity, h_i^k is an offset, v_i^k is the measurement noise, and k is the iteration. We measure the sensitivity by setting half of the LED's high and half of them low and generating a print. The high and low LED's are switched and another print is generating. The average line width of one print is offset and forced to match the other to compensate for printer tone reproduction curve (TRC) drift. The sensitivity is proportional to the line width difference between each line in the two prints.

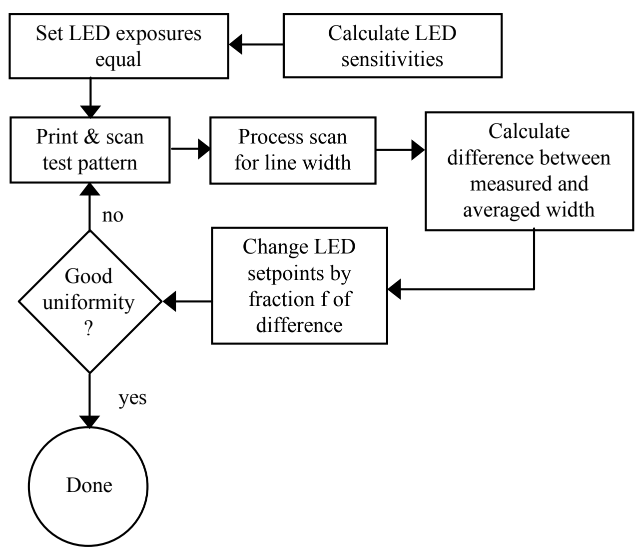

Figure 3. Flowchart of compensation procedure

The next step is to set all the LED exposures equal at halfway between the minimum and maximum set point. Doing this helps ensure that the set points will not clip if a large change is required to balance the LED's. In the third step, the test pattern is printed and scanned. In the fourth step, we process the image to extract the line width corresponding to each LED. We computer the correction setpoints using an integral control law

$$u_i^{k+1} = u_i^k - \frac{f(w_i^k - < w^k >)}{g_0}$$

where $<w^k>$ is the average line width at iteration k and g_0 is the average sensitivity of all LEDs. Controlling to the average line width for a particular page ensures that this LED balancing algorithm is independent of drift in the TRC.

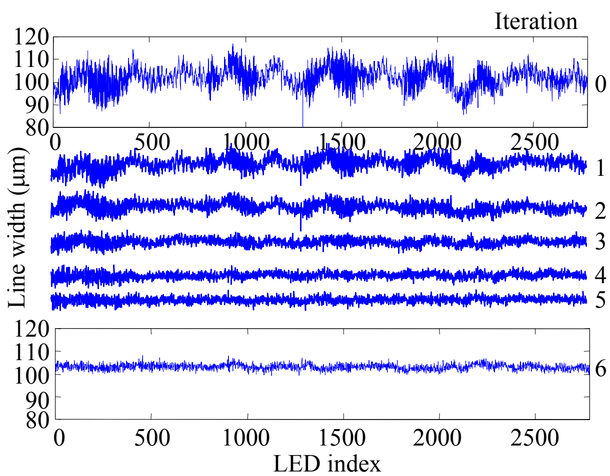

Figure 4. Line width uniformity

The stability and accuracy of the control loop is achieved by the best choice of f. The control loop is stable if $0<f<2g_0/g_{max}$. The performance of the optimization is gauged by the speed of the response and the sensitivity to the measurement noise.

If $v_i=0$, then the closed loop response Δu_k to an initial condition Δu_0 is given by $\Delta u_i^k=(1-fg_i/g_0)^k\Delta u_0$. So, provided that $|1-fg_i/g_0|<1$, the number of iterations $k_{2\%}$ needed to achieve $|\Delta u_i^k/\Delta u_i^0|<0.02$ is $k_{2\%}=\log(0.02)/\log(|1-fg_i/g_0|)$. Therefore, the speed of response is determined by $|1-fg_i/g_0|$, the smaller this value the faster the response.

Assuming a stable closed-loop and a random zero-mean measurement noise with standard deviation σ_v, the standard deviation of the line width σ_w is given by $\sigma_w=N_G\sigma_v$, where N_G is the noise gain (specifically, the H2 norm of the discrete-time closed-loop map from v_i to Δw_i) and is computed as $N_G = 1/(1 - (fg_i/g_o)/2)^{0.5}$. The standard deviation of the actual linewidth Δw_i^{true} is thus given by $\sigma_w^{true} = ((N_G^2-1)^{0.5})\sigma_v$.

Experimental Results

Figure 4 shows the improvement in line width for a scanner-based uniformity operation. The sensitivity of line width to exposure setting was g_i=0.96 µm. We ran the normalization for 6 iterations with a gain factor f=0.5.

The uniformity improvement can be seen more clearly by plotting the standard deviation of all the measured line widths as a function of iteration as shown in figure 5. The initial standard deviation is above 5 µm. The measurement noise for our choice of threshold, exposure, and repeat of the line widths is 1.06 µm. We find that after each iteration, the measured noise level becomes twice as close to the 1.06 µm level as it previously was, as expected for a gain of f=0.5. Our choice to stop at the 6th iteration looks justified as the noise level has reached its lower limit.

Figure 6 plots the Fourier transform of the line width s for the scanner-based optimization. Also shown in this figure is the Fourier transform of the line widths following a uniformity adjustment based on a direct measurement of the LED intensities. The direct intensity measurement contains two large peaks at 1.09 cycles/mm and 2.18 cycles/mm. This is the frequency and the harmonic of the focusing lens repeat distance. These two peaks are completely absent in the scanner based normalization.

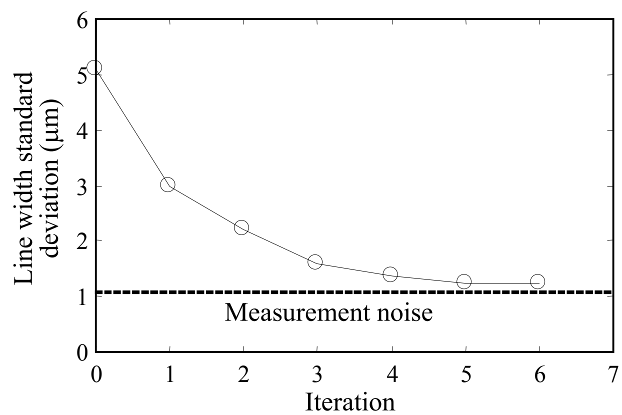

Figure 5. Decrease of noise metric

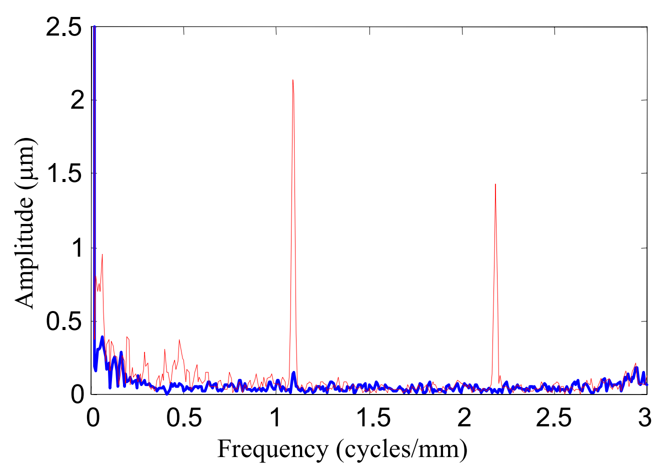

Figure 6. Frequency spectrum of line width uniformity. Thin line before, thick line after.

The low frequency (<0.5 cycles/mm) noise, presumably due to the other xerographic subsystems, is also lower for the scanner-based normalization. The scanner-based normalization doesn't differentiate between noise coming from the LED and noise coming from the xerography. It will adjust LED intensities to eliminate both.

Higher Resolution Imagers

1200 spi and higher LED imagers have been developed for higher image quality. The higher resolution imagers give more flexibility for halftone design, but single pixel lines may not print out. The scanner-based uniformity technique as described above would not work.

However, this technique can be modified. Instead of printing single pixel wide lines, double pixel wide lines can be printed. However, this alone is not enough to balance the LED. If double pixel wide lines only are printed, there is an odd/even instability. Making all the odd LEDs bright and all the even LED's dim would give double pixel lines of all the same width, yet would lead to a distorted image.

Adding triple pixel wide lines to the test pattern solves the instability problem. One approach is to group the LEDs by three. Let us label them A,B, and C. The test pattern would then consist of 3 combinations: AB, BC, and ABC. The presence of the ABC combination in the test pattern breaks the instability. If there was an alternating bright/dim pattern, some of the ABC combinations would have 2 dims and a bright, and others would have two brights and a dim, leading to different line widths.

The printed double pixel line width will be a function of exposure. For small changes about the desired uniform exposure, the line width change should be linear with an exposure increase. The sensitivity coefficient should be the same for the left pixel and the right pixel because of symmetry. Therefore, we write the change $\Delta w_{i,i+1}$ in the double pixel line width as $\Delta w_{i,i+1}=s_2(\Delta e_i+\Delta e_{i+1})$, where Δe_i is the exposure change of LED i and s_2 is the sensitivity.

The triple pixel line width is also linear for small changes in exposure. However, the sensitivity is different for changes in the middle pixel compared to changes in the edge pixel. We therefore write $\Delta w_{i-1,i+1}=s_3\Delta e_{i-1}+s_m\Delta e_i+s_3\Delta e_{i+1}$.

These two equations lead to a set of linear equations that can be combined into a matrix equation

$$\begin{pmatrix} s_2 & s_2 & & & & & \\ & s_2 & s_2 & & & & \\ & & \ddots & & & & \\ & & & & s_2 & s_2 & \\ s_3 & s_m & s_3 & & & & \\ & s_3 & s_m & s_3 & & & \\ & & \ddots & & & & \\ & & & & s_3 & s_m & s_3 \end{pmatrix} \begin{pmatrix} \Delta e_1 \\ \Delta e_2 \\ \Delta e_3 \\ \\ \vdots \\ \\ \Delta e_{N-1} \\ \Delta e_N \end{pmatrix} = \begin{pmatrix} \Delta w_{12} \\ \Delta w_{23} \\ \vdots \\ \Delta w_{N-1,N} \\ \Delta w_{13} \\ \Delta w_{24} \\ \vdots \\ \Delta w_{N-2,N} \end{pmatrix}$$

We simulated the compensation algorithm using a typical set of parameters. The open circles in figure 7 show the relative exposure for 100 LEDs on a 1200 spi imager that has a uncorrected standard deviation in the exposure profile of 10%. We simulated the standard deviation of the line width measurement error to be 2 μm, f=0.25, and sensitivities of s_2=36, s_3=30, and s_m=10 μm. The exposure uniformity achieved after the line widths uniformity reached the measurement error is shown by the solid circles in figure 7.

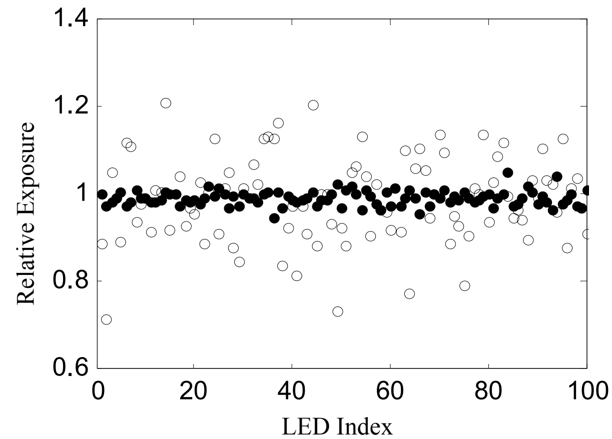

Figure 7. Improvement in exposure uniformity using double and triple wide lines as a measure. Open circles - before correction, closed circles - after correction

Conclusion

Monitoring the uniformity of the final print gives a direct way to calibrate an LED print bar. Artifacts arising from the imager, such as variations in the spot shape due to the optics, are compensated for. In this paper, we present techniques that increase the quality of the compensation with respect to noise. A precise measurement of the LED intensity can be measured with a test pattern with multiple repeats over single pixel wide lines. We described a control methodology that will give a good compensation in the presence of measurement noise. For higher resolution images, where single pixel lines do not print, simulations show that it is possible to make achieve uniformity by printing multiple pixel wide lines.

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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