High Image Quality achieved through High Precision Measurements

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Abstract

The high image quality of recent xerographic and direct marking products are achieved in part by accurately placing marks on the paper to microns precision at substrate speeds of up to 500 mm/sec. Accurate measurement techniques are required to develop products with this capability. Measurements of the positions of marks on paper to sub-micron precision can be achieved by printing and scanning specific test patterns. Even though scanner resolutions are tens of microns, the measurement precision is increased orders of magnitude by using various signal processing techniques and massive statistical averaging on the hundreds of megabytes of information. Examples include (1) measurement and adjustment of an LED bar imager to achieve uniform images, (2) measurement of beam positions and intensities due to imperfections in motor polygon assemblies and multiple beam images, and (3) signal processing techniques to compensate for imperfections in contact image sensors.

Introduction

High quality printed images require that the digital image be reproduced on paper at the desired locations and desired intensity. In a xerographic printer, the exposure device is controlled by the digital image. The light is turned on and off to create a charge pattern on a photoreceptor which is ultimately developed and transferred to paper. Any variation the exposure device has in intensity or spacing can lead to graininess, mottle, or objectionable banding in the printed image.

To determine the exposure subsystem's manufacturing requirements, the relationship between beam uniformity requirements and the print uniformity requirements must be determined. Specifically, a technique that can measure a dot's size and intensity to high precision is needed. Additionally, a technique that can measure these parameters in a printer is even better. Interactions of the exposure subsystem with the rest of the printing system can change the size and shape of the dots.

In this paper, I show how full page images of specially designed test patterns can be used to measure the position and intensity of the imager with an accuracy and precision more than sufficient to observe potential print defects. The high precision is possible because of the massive amount of data that can be collected by the flatbed scanner which enables averaging over random noise. The high accuracy is possible by performing additional processing that calibrates out scanner and print defects. Specifically, I propose a technique which measures imperfection in the scanner pixel to pixel spacing in a simple way. In addition, I describe how a test pattern can be randomized so that noise due to printer nonuniformity is spread throughout the measurement.

I give three applications of how the flatbed scanner measurement technique is used. The first application is the determination of motor polygon assembly (MPA) once around errors in a laser raster optical scanner (ROS) imager. The second application is used to measure the imaging uniformity of an light emitting diode (LED) imager, where I expand on the measurement technique described in an earlier presentation [1]. The third application is the measurement of beam to beam spacing and uniformity variations in a multi-beam laser imager, which are used for high speed and high resolution imaging in recent products [2,3].

Exposure Devices and Banding

A laser ROS writes an image by sweeping one or more beams across a moving photoreceptor belt or drum. To write an image free of banding defects, a number of tight constraints must be met. The photoreceptor must move at a uniform speed. Each facet of the rotating polygon mirror from which the beams are reflected must have the same angle with respect to the axis of rotation and reflectivity. The polygon must not wobble or vibrate as it rotates. For multi-beam lasers, the spacing between beams must be uniform and the intensity of each beam equal.

An alternative exposure device is a light emitting diode (LED) printbar, which consists of a linear array of light emitters perpendicular to the process direction. Each LED must give the same intensity and beam shape or else streaks will be introduced into the prints.

It is possible to monitor the light from these devices so they can be manufactured to meet these tight requirements. However, performance on the bench doesn't always correspond to performance in the printer. There can be system interactions with other subsystems of the printer which change the performance of the exposure device.

There is therefore a need to determine the performance of an exposure device as used in a printer. The need is not just to determine the resulting print quality, but to relate this to the characteristics of the exposure device. Specially designed test patterns and image analysis of prints of these test patterns can give the information needed [4]. This analysis begins with characterizing single pixel lines.

Line Position and Intensity Measurements

Low cost flatbed scanners may have an intrinsic resolution of 600 spi or 42 μm. Changes in the size of dots or lines on the order of 1 μm can cause visible defects. A line width measurement at the scanner resolution is insufficient. The measurement resolution is increased using the gray level information of the scanner.

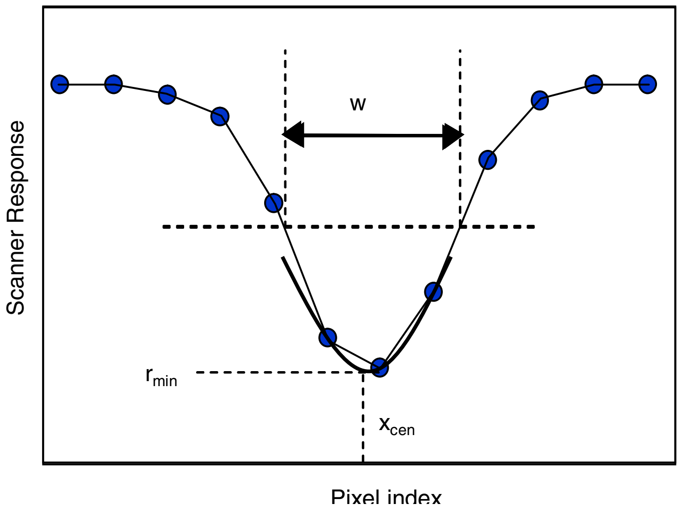

Figure 1. *Line profile and metrics*

A cross section of a single pixel line is plotted in figure 1. A quadratic polynomial is fit through the minimum of the profile and its two neighboring points. The minimum of the fitted quadratic is a measure of the intensity of the line. The position of the minimum is a measure of the center of the line. The resolution of determining the line center is higher than the resolution of the scanner since the gray level information is also used. The resolution of the minimum response is greater than the scanner gray level resolution (typically 256 levels) because each response was averaged over a a pixel column running the length of the line.

For printer performance optimization, the average width of the line written by the laser exposure system at a particular setting is needed. A test pattern can be designed where lines are printed all over a page. The positions and intensities of these thousands of lines can be determined. A full page scan at 600 spi contains approximately 40 MB of information. Orders of magnitude increases in precision are possible with this massive averaging. One can extract information about the exposure subsystems that other noise in the process would hide for individual measurements.

Imperfections in the printing system may cause a small displacement in the cross process direction between different sweeps of the ROS. An example of this offset is shown in figure 2(a). The digital image consists of an array of dashes that are aligned, but the printed image contains an offset.

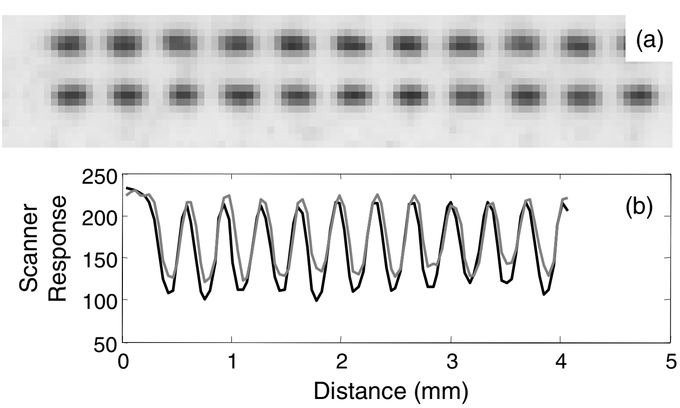

***Figure 2**. Line profile through unaligned sweeps*

One technique to measure the relative displacement is to determine the center of each dash as described above. An alternative is to extract the profile through the center of the dashes, shown in figure 2(b). For small dashes the profile is sinusoidal. The phase is proportional to the dash offset in the horizontal direction. The phase technique gives a higher precision measurement since it uses all the information in the profile rather than the dash minimum.

Random Line Spacing for Robustness

There is a need to determine the characteristics of the exposure subsystem despite the presence of other system noise. Figure 3(a) shows a staggered line pattern used to measure the position and intensity of every single pixel line. The lines are spaced far enough apart in individual rows so that the presence of one line does not effect the measured metrics of another line. The next row consists of the same regularly spaced lines shifted by a single pixel so that all lines can be measured.

If there is banding present in the printer, the print density will vary in the vertical direction. One cannot distinguish if the lines are darker because of the banding or because the exposure subsystem has a variation. Other printer uniformity variations may also be confounded with a line position and intensity measurement.

This problem can be mitigated by randomizing the lines and repeating them multiple times over the page as shown in figure 3(b). Any errors due to print density variations will be distributed throughout the measurement. Any desired accuracy can be obtained by creating enough lines in the test pattern and measuring enough pages.

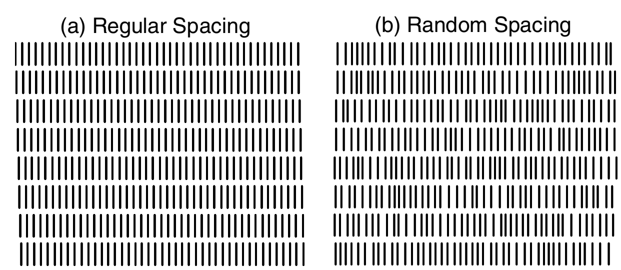

***Figure 3**. Random spacing for robustness against noise.*

Scanner Calibration Improvements

A flatbed scanner's scanning element consists of individual chips with linear arrays of sensing elements butted together to give the desired scanning width. Slight rotations of the individual chips, spacing imperfections between chips, and distortions of light from the lens can result in small distortions in the image.

If the single pixel lines are scanned perpendicular to the sensor bar, then the line profile measurement will be sensitive to these errors. If the lines run parallel to the sensor bar, then the measurement will depend on the motion quality of the sensor bar as it sweeps the test pattern.

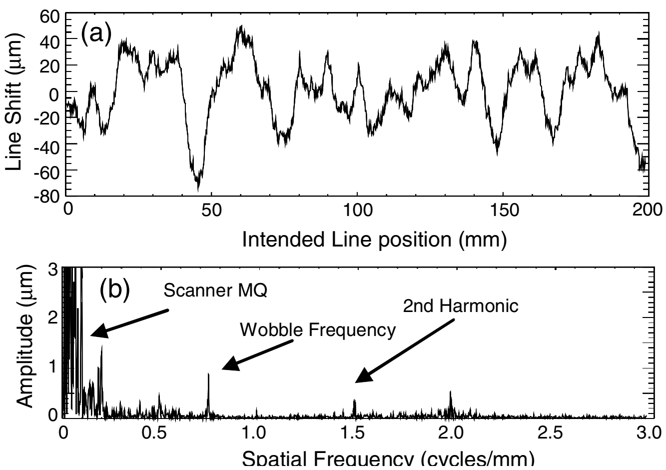

***Figure 4**. Line position measurement example.*

Figure 4 plots the difference between the measured and expected position of a set of regularly spaced lines. There are significant deviations of the lines from their intended positions. The deviations may arise from either poor scanner or printer motion quality [5]. However, the Fourier transform of the deviations shows peaks that correspond to known frequencies of the polygon mirror in the imaging system. In this particular example, the deviation in the line center due to the polygon mirror once around is only 1 µm. Because the true deviation is periodic, it can be extracted from all the measurement noise.

A measurement of the sensor position errors is needed to determine the absolute position of the lines. One technique to measure these errors is to create a test pattern with many rows of dashes that are randomly spaced as in figure 3(b). The test pattern is scanned and the position of every scanned line is determined. From these measurements, the equation

$$\Delta x_{p_{i,j+1}} - \Delta x_{p_{i,j}} = (p_{i,j+1} - p_{i,j}) - (x_{i,j+1} - x_{i,j})$$

is solved, where p_{ij} is the expected position of the j^{th} dash in the i^{th} row, x_{ij} is the measured position of the dash, and Δx are the position errors due to the sensor. By scanning a test pattern with thousands of lines, this becomes an over determined matrix equation which can be solved by standard techniques. Any true spacing errors in the printed test pattern average out, giving an accurate measurement of sensor position errors. Figure 5 plots one example for a low cost 600 spi bar.

Wobble Measurement Example

Figure 6 shows a test pattern of regularly spaced single pixel lines. Each line was written with one sweep of the laser ROS.

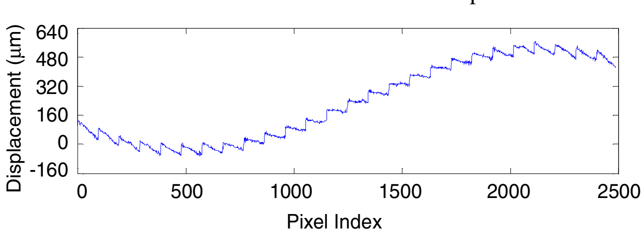

***Figure 5**. Contact Image Sensor spatial pixel calibration.*

The facet of the polygon used to write each line is known from the test pattern. The line centers were measured as described earlier. The thick line plots the difference between the measured and expected position of the facet. The accuracy of this measurement is increased over a single line center measurement because the line center from each facet is measured multiple times. The thin line gives an indication of the measurement noise, which was determined by removing the correlation between the facets. One sees from the figure that submicron accuracy can be obtained.

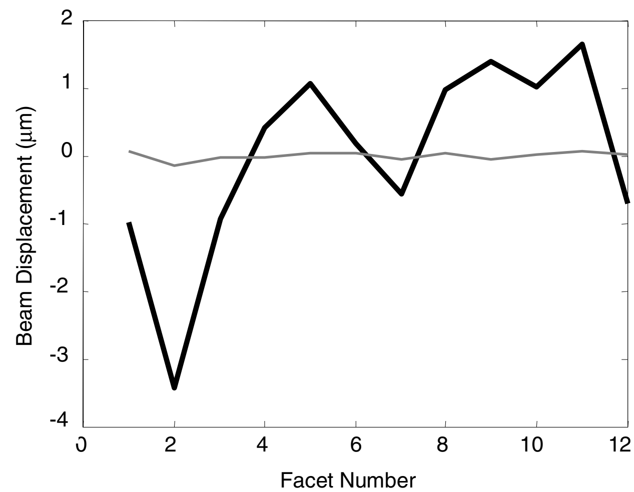

***Figure 6**. High Accuracy ROS wobble measurement on print.*

LED Uniformity adjustment example

LED printbars, which consist of a linear array of emitters, provide a compact way to expose a latent image. However, due to variations from element to element in the design, the intensity and shape of the spot can vary from LED to LED. If this device was used to make prints without adjustment, a large amount of streaking would result. In order to compensate for these effects, the capability to individually adjust the intensity of each LED is provided. One can measure the intensity of the light optically and make adjustments so that a uniform exposure is obtained across the printbar.

However, a uniform spot intensity may not result in a uniform print in the printer. The development, transfer, and fusing of the latent image depends on the shape of the spot and the spot may be different in different printers.

Making the LED intensity adjustments to force single pixel line widths to be uniform will result in a more uniform print. Figure 7 shows a profile of single line widths before (gray line) and after (black line) a series of adjustments to obtain uniformity.

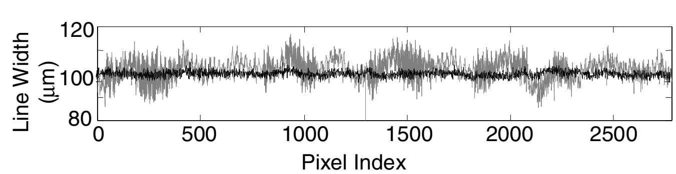

***Figure 7**. Uniformity adjustment for LED imager.*

Alignment of a VCSEL imager

The writing speed of laser ROS imagers are limited by the number of facets and maximum rotation velocity of the polygon. The writing speed can be increased by simultaneously imaging with multiple beams. One way to create multiple beams is using a vertical cavity surface emitting laser (VCSEL). An 2D array of beams is emitted from the device. They can be collimated and swept simultaneously across the photoreceptor with each rotation of a facet. VCSEL ROS's have been recently introduced in high speed digital imaging products.

Writing banding defect free images requires a uniform swath of beams. If there is a variation in light intensity, high frequency banding can be introduced at the period and harmonics of the width of the scanning swath. Similar high frequency banding can occur if the spacing between beams is unequal. Also, the beams must be uniformly aligned in the cross process direction in order to write straight lines and also prevent banding.

A series of random single pixel dashes using a test pattern similar to that shown in figure 3(b) were printed and the centers determined. The relative spacing between neighboring beams of the VCSEL ROS was determined by averaging the individual centers corresponding to each beam. Figure 8 plots the relative spacing between neighboring beams for a VCSEL ROS with a 1200 spi (21 µm) nominal beam spacing. The figure overlays 4 repeat measurements from 4 prints in sequence. One observes that the measurement noise is much lower than the determination of the beam to beam spacing. The variation between the individual beam spacing is likely due to spot shape variation, characteristics of the optics, and geometry of the VCSEL array.

Figure 9 plots the beam intensity determine from the same test pattern. The repeat measurements show that the relative beam to beam intensity can be monitored with a standard deviation of 0.13%, much lower than the natural beam to beam variation. These accurate measurements of beam spacing and beam power variations can be used to monitor conditions that may lead to high frequency banding in prints.

Two examples of using this measurement technique to align the VCSEL ROS are shown in figures 10 and 11. Figure 10 plots the relative beam spacing for 3 different conditions of the VCSEL ROS. The gray lines show a unoptimized adjustment, while the

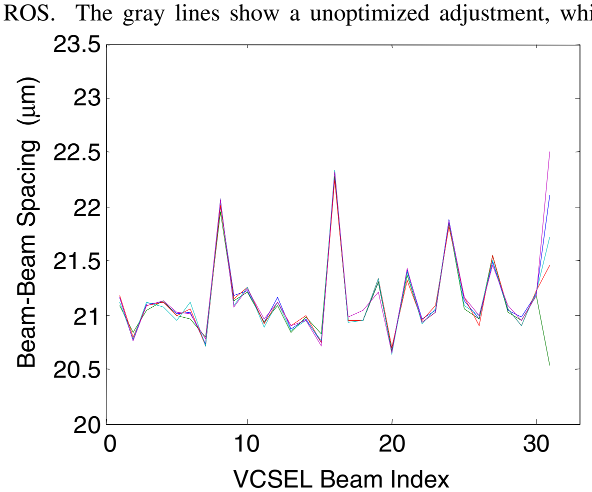

***Figure 8**. Relative spacing between VCSEL beams*

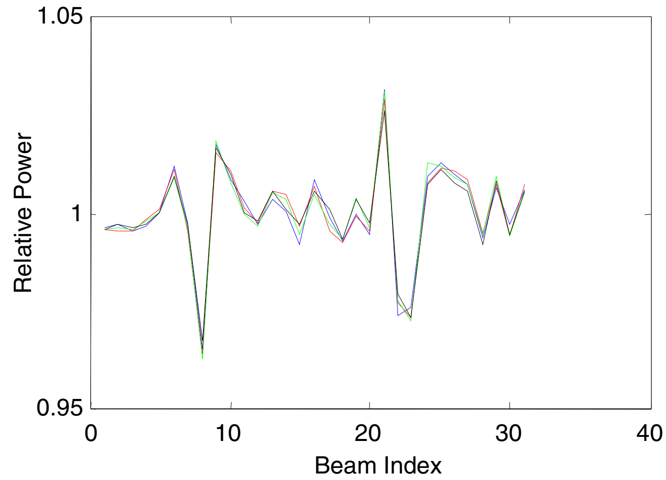

***Figure 9**. Relative Power between VCSEL beams*

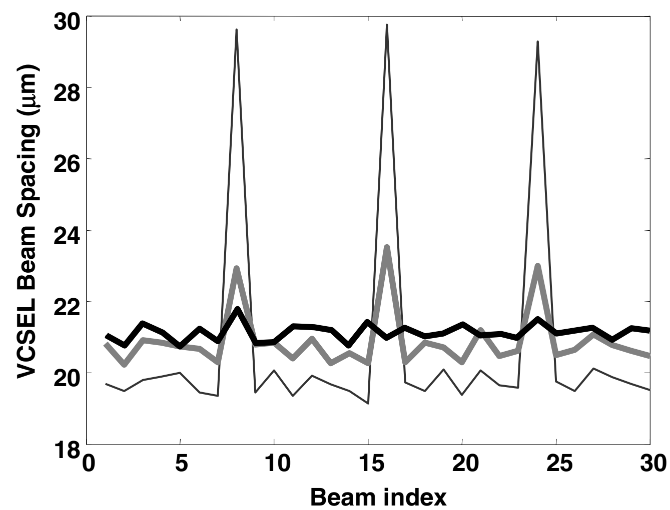

***Figure 10**. Process direction alighment of VCSEL beams*

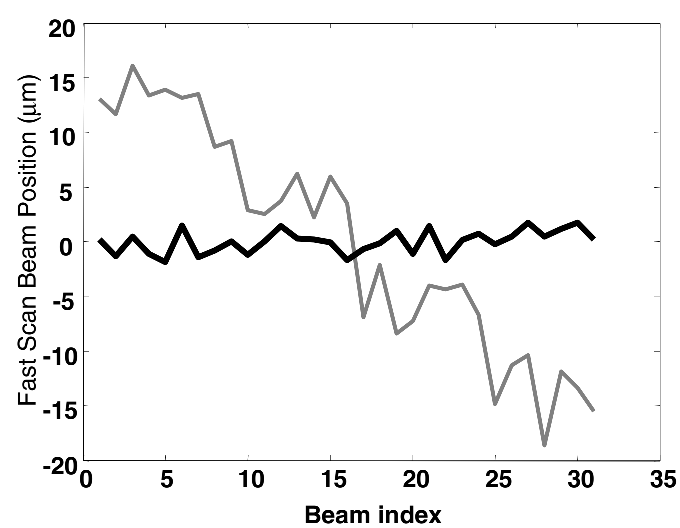

***Figure 11**. Cross Process Direction of VCSEL beams*

black line shows a good adjustment. One sees that for the poor adjustments, there is an increased spacing between every 8^{th} beam, which is due to the transition from one row to the other row in the 2D VCSEL chip. By adjusting the angle of the chip, the row error can be eliminated.

Another example is optimization of the timing adjustment of the parallel beams. Since the beams are emitted from a 2D array and reformed into a parallel swatch of beams, they are not all aligned in the cross process direction as they sweep across the photoreceptor. Differential timing delays must be added to each beam to force the beams to turn on and off at the correct cross process position. A test pattern of single pixel dashed lines similar to those shown in figure 2(a) was designed and printed. The dashes fill the entire page, so all the beams of the VCSEL ROS are monitored and massive averaging is used to reduce the noise. The relative spacing between each beam was found using the technique described earlier in this paper. The diagonal line plotted in figure 11 shows the relative offset between each beam for which the timing delays are not optimized. This offset will lead to jagged lines and other artifacts. After the timing adjustment, the beams could be aligned to within a couple microns.

Conclusions

Accurate positioning is required of the exposure system to write images free of banding and other artifacts. Flatbed scanners provide a means to collect massive amounts of data, where statistical averaging can provide precise measurements despite the presence of noise. These measurements can be made when the exposure system is integrated with the printer so that system interactions are measured directly.

Although the examples given in this paper refer to optical imaging, the same measurement concepts can be applied to direct marking. A direct marking print ejects drops of ink on a substrate just as a xerographic print “ejects” spots of light on a photoreceptor. The same type of banding defects may arise for imperfect placement of the drops on paper. Similar measurements to those described in this paper can be used to optimize the adjustment of direct marking print heads.

Acknowledgements

Joe Sheflin of Xerox Corporation took and analyzed the alignment measurements of figure 10 and performed the alignment of figure 11.

References

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Author Biography

Howard Mizes received his BS degree in Physics from the University of California at Los Angeles in 1983, and his Ph.D. degree in Applied Physics from Stanford University in 1988. Since 1988, he has been with Research and Technology at Xerox Corporation, where he is a Principal Scientist. Dr. Mizes' research has been primarily focused on understanding and controlling the process physics of xerographic printing, and quantifying and improving the resulting image quality. He has worked in the areas of charge transport and contact charging, particle adhesion measurements and modeling, and experimental probes of the xerographic development process. His image quality work has focused on improving the spatial uniformity of the printed page. e-mail: hmizes@xeroxlabs.com