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Quasi-Center-Weighted PWM Multi-level LED Printhead with Non-linear Exposure Uniformity Correction

Isaac Ajewole and Yee S. Ng
NexPress Solutions LLC
Rochester, New York, USA

Abstract

A Quasi-Center-Weighted PWM exposure scheme (with stretched bit) was created for a Multi-level LED printhead that reduces the exposure time difference between available exposure levels; thereby enabling better non-uniformity correction at very high printing speed. Also this technology still maintains the advantages of centered line with sharper text/graphics and the lower current spike (not all the pixels are turned on or turned off at the same time) of the regular Center-Weighted PWM system at the same time. Working together with a non-linear exposure non-uniformity correction method that obtains non-uniformity correction and gray level simultaneously, this system is shown to produce uniformity of ~ 0.5% throughout the dynamic range of exposure of the multi-level printing system at high speed.

Introduction

LED printhead has been used for many years as an exposure source for electrophotography.[1] There is a certain amount of pixel brightness non-uniformity in the LED writer either due to LED emitters brightness variation or lens transmission non-uniformity that requires exposure correction for higher image quality applications.[2-4] Center-pulse-width modulation has been used on gray level LED writers to achieve high uniformity in multiple level printing.[2-4] Center-pulse-width modulation has the advantage of centered printing line with sharper text/graphics and the lower current spike (not all the pixels are turned on and off at the same time). In order to maintain that advantage at even higher speed, a quasi-centered-weighted PWM method[5] was used together with non-linear exposure non-uniformity correction method that obtains non-uniformity correction and gray levels simultaneously over the whole dynamic range of exposure for gray level printing system. We will be discussing this method and the results thereof in this paper.

Exposure Non-Uniformity Correction

The need for exposure non-uniformity in LED printhead arises because of the inherent emitter brightness variation and/or lens transmission non-uniformity. The exposure energy e_n associated with LED number n is proportional to the product of its intensity i_n and the length of time t_n for which it is turned on i.e.

$$e_n = c i_n t_n \tag{1}$$

where c is the constant of proportionality that depends on the surface area of the LED. For multiple level printing, each LED must be capable of matching the exposure energy E_m for each gray level in order to have a uniformly exposed field. Thus, the on-time $t_n(m)$ for n-th LED and m-th gray level must be chosen such that

$$i_n . t_n(m) = I_{av} . T_m \tag{2}$$

where I_{av} is the average intensity of all the LED's and T_m is the length of time needed to obtain the exposure energy E_m for the m-th gray level. If the number of gray levels is M and all the LED intensities can be accurately quantized to K levels, then it is seen that a total of M.K possibly distinct times must be generated for 100% uniformity. Typically, M is greater than or equal to 16 and K is 256. Thus, a minimum of 4096 possibly distinct times are needed for high quality printing (and more for more gray levels) while an LED printhead and its associated electronics can only generate 64 to 256 distinct times. It is the objective of the Non-Uniformity Correction Algorithm to condense (or quantize) the M.N required times into that number of distinct times (less than 256) which the LED printhead can generate. This quantization must be done in such a way that very low non-uniformity (less than 0.5%) is achieved throughout the whole dynamic range of exposure.

Some of the M.K times described above will overlap. Thus, in practice, the actual number of distinct times needed will be less than MK. Let us arrange all the L distinct times in strictly ascending order. We divide this range into P cells, P being the number of distinct times that the LED printhead can accommodate. The boundaries of these cells are τ_1, τ_2,τ_3,………,τ_{P+1} and all the distinct times $t_n(m)$ within each cell $[\tau_p, \tau_{p+1}]$, p = 1,2,….P are assigned $t_1, t_2, t_3, \ldots, t_P$ respectively. Thus each exposure time from the L distinct exposure times is assigned a value according to the rule

$$t_n(m) \Rightarrow t_p, \text{ if } \tau_p <= t_n(m) < \tau_{p+1} \quad (3)$$

Since the assigned times are not going to be exactly equal to the required exposure times (with the exception of a very few), the LED's will not produce the exact amount of required exposure energy resulting in a certain amount of non-uniformity. We define this resulting non-uniformity, υ within each cell as the maximum deviation of the resulting exposure energy from the required exposure energy (for the gray level that encompasses that cell) normalized by the later i.e.

$$\upsilon = max_{m,n} \mid I_{av}.T_m - i_n t_p \mid / I_{av}.T_m \quad (4)$$

Note that the maximum in Equation (4) is taken over all the LED's (or over all the cells) and that in general, $t_n(m)$ does not equal t_p. By writing i_n as $I_{av}.T_m \; / \; t_n(m)$ (from Equation (2)), we can re-write Equation (4) as

$$\upsilon = max_{m,n} \mid 1 - t_p / t_n(m) \mid \quad (5)$$

It is obvious from Equation (5) that the exposure times at the extreme ends of each cell determines the maximum in this Equation and we can therefore write

$$\upsilon = (t_p - \tau_p)/ \tau_p = (\tau_{p+1} - t_p)/ \tau_{p+1} \quad (6)$$

Given υ, we can re-write Equation (6) as

$$t_p = (1 + \upsilon)\tau_p \quad (7)$$

$$\tau_{p+1} = t_p /(1 - \upsilon) = \tau_p(1 + \upsilon)/(1 - \upsilon) \quad (8)$$

Equations (7) and (8) can be used recursively to generate the t_p's and τ_p's for a given non-uniformity υ, with t_1 as the first time to be calculated since τ_1 is known. Starting with a given value of υ, one computes all the t_p's and τ_p's needed to achieve that level of υ. If more than P t_p's are needed, then this value of υ can not be achieved with the printhead in question and the value of υ must be increased and the process repeated until exactly P t_p's can be found. If fewer than P t_p's are needed, then the value of υ must be decreased and the process repeated until exactly P t_p's can be found. In this manner, one obtains the optimum υ for the printhead. This approach can be used not just for a constant non-uniformity across the whole exposure range but also for functions of non-uniformity. One needs only to parameterize the function and the variation will be done with respect to one of the parameters. In this way one can assign lower non-uniformity to certain portions of the exposure range and higher non-uniformity to others.

Whether or not one can achieve a certain non-uniformity for a certain portion of the exposure range depends on how close the t_p's can be: the closer the t_p's can be, the lower the non-uniformity that can be achieved for that region. The hardware (clock pulse generator, comparator etc) that is needed to generate these exposure times puts a lower bound on the difference between two adjacent times.[2-4] Center-pulse-width modulation has been previously used to generate these times. This method has the advantage of printing centered lines with sharp text and graphics and lower current spike. However, both edges of the pulse have to be symmetrically adjusted to produce the times, with the result that the closest difference between two exposure levels is two exposure clock pulses. This puts a lower bound on the level of non-uniformity that is achievable with this method. The Quasi-center-weighted method improves upon the Center-pulse-width approach by alternating exposure level changes at the commencement of the exposure and termination of exposure, thereby reducing the difference between two exposure levels by at least half. This makes it possible to obtain better uniformity with the approach discussed herein.

If d is the minimum difference between two adjacent times by the hardware, then we must have

$$t_{P+1} - t_P >= d$$

$$\text{i.e.} \quad \tau_{p+1} - \tau_p >= d/(1 + \upsilon) \Longrightarrow \tau_p >= (d/2\upsilon)(1 - \upsilon)/(1 + \upsilon) \quad (9)$$

Thus, the effect of the hardware constraint is to force a lower bound υ_{min} on the non-uniformity achievable as a function of gray level number or time. In summary, one must solve Equations (7) and (8) in conjunction with the constraint

$$\tau_{p+1} - \tau_p >= d/(1 + \upsilon) \quad (10)$$

In the region where this constraint is not normally satisfied, we force τ_{p+1} to be equal to $\tau_p + d/(1 + \upsilon)$ and accept the resulting non-uniformity imposed by the hardware constraint. This constraint hits the lower end of the exposure range particularly severely since this is the region where the required LED exposure times are closest i.e. $\tau_{p+1} - \tau_p$ are smallest. This is therefore the region in which the advantage of the Quasi-center-weighted method manifests itself most strongly.

The minimum achievable non-uniformity υ_{min} can be derived from Equation (9) in terms of the separations of adjacent LED exposure times as

$$\upsilon_{min} = (d - (\tau_{p+1} - \tau_p))/ (\tau_{p+1} - \tau_p) \quad (11)$$

or, in terms of the actual LED exposure times as

$$\upsilon_{min} = ((4\tau_p^2 + d^2 + 12d\tau_p)^{1/2} - (d + 2\tau_p))/4\tau_p \quad (12)$$

The non-uniformity parameter discussed so far measures the maximum deviation of exposure energy from its average. One can describe this as a peak-to-peak kind of criterion. Another useful measure of uniformity is the signal-to-noise ratio (SNR) which is defined as the ratio of the average of the exposure energy to its standard deviation. The peak-to-peak criterion does not address the question of how many LED's have a particular non-uniformity or what the range of non-uniformity distribution is. The SNR measure, on the other hand , is a more global measure and more statistically significant since it takes the distribution of the non-uniformity into account. As a check, we always compute both measures.

Functional Variation of Non-uniformity Across The Exposure Range

Two of the most important considerations in the development of this algorithm are the levels of uniformity achievable as a function of the gray levels and the computational times required to obtain these levels. The algorithm is an iterative process: starting with an initial desirable functional form for the levels of non-uniformity across the gray levels, we change this functional form iteratively with respect to a parameter of the function and compute the number of levels required to achieve the corresponding uniformity levels, stopping when this number equals the target value. The form of the function chosen is therefore very important.

We have found that the most useful and practical functional form is the linear function whereby the non-uniformity increases linearly from a minimum value at the low end of the gray scale to a maximum value at the high end. Iteration of this form can be done in any of the following ways:

Method A:

Increasing the non-uniformity at the high end of the gray scale while holding that of the low end at the minimum value dictated by the hardware configuration (see Equation (11)). This approach necessitates the re-computation of the slope at each iteration step. This is illustrated in Figure 1 below.

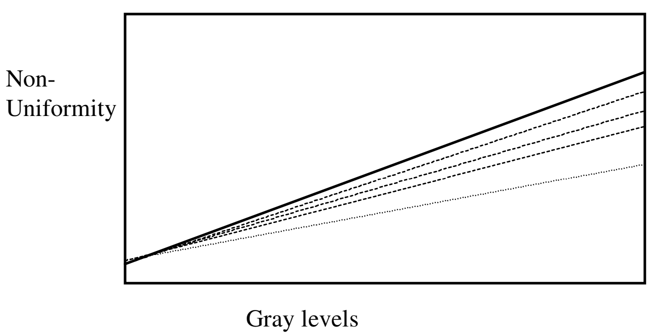

Figure 1

Method B:

Increasing the non-uniformity at each gray scale in such a way as to hold the ratio of maximum to minimum non-uniformity constant at a given initial desirable value. This also requires the re-computation of the slope at each iteration step. It is shown in Figure 2.

Method C

Increasing the non-uniformity at each gray level by the same amount, thereby holding the slope constant at a given initial value. This is illustrated in Figure 4.

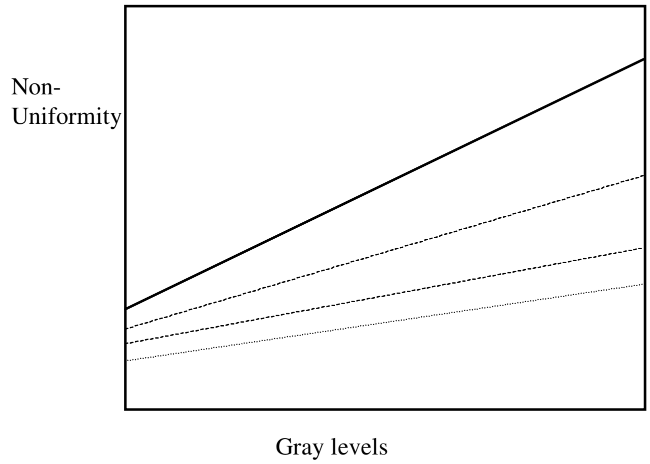

Figure 2

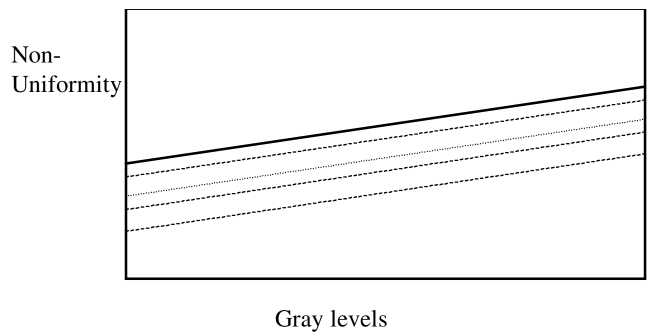

Figure 3

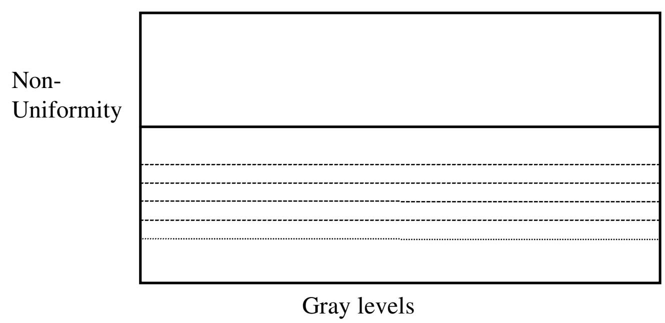

Figure 4

Method D:

This is a special case of C with the slope set equal to zero (i.e. constant non-uniformity). There is only one incremental step for the whole gray level range, in contrast to one for every gray level in C.

Methods A and B have comparable computational times which are longer than C or D. Method D , as will be expected is the fastest. The levels of non-uniformity resulting from all these methods are within the range of acceptability (< 0.8%). Method C pushes the non-uniformity towards the higher gray levels while Method D strives for a constant non-uniformity for all gray levels. Thus Method D may produce may produce slightly higher non-uniformity at the low end than Method C but this is compensated for by lower non-uniformity at the high end of the gray scale. In practice, higher non-uniformity is more acceptable at the high end than at the low end.

Results

In the following Figures, we show typical performance obtainable using Methods C and D for various number of gray levels and quantization levels. Figure 5 shows the performance from using Method C for 16 gray levels (plus white) and 6- and 8-bit quantization levels.

Figure 6 shows the signal-to-noise ratio equivalent of Figure 5.

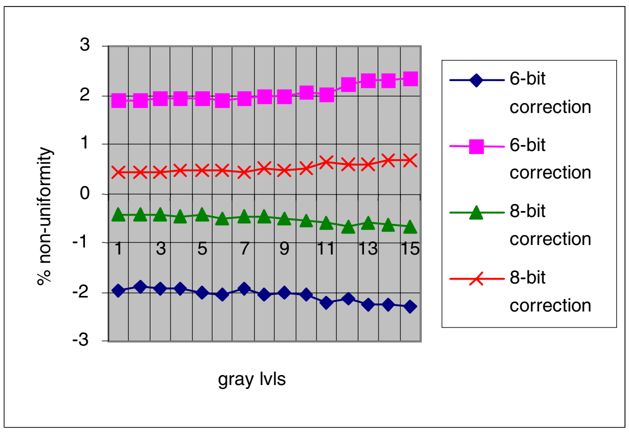

Figure 5: % Non-uniformity vs Gray lvls: Method C, 16 gray lvls

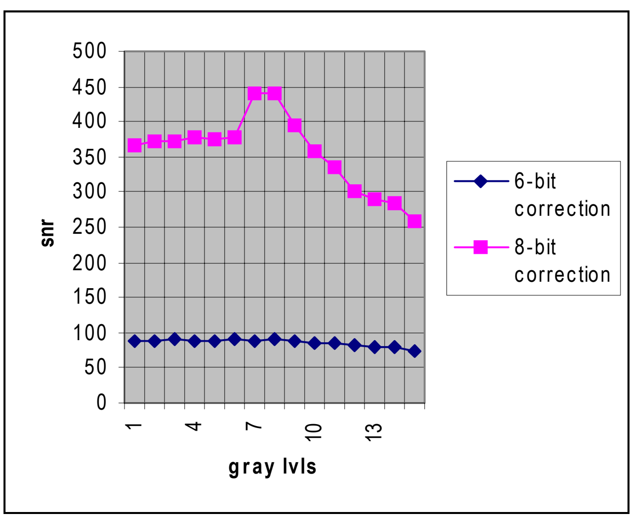

Figure 6: % Non-uniformity vs Gray lvls: Method C, 16 gray lvls

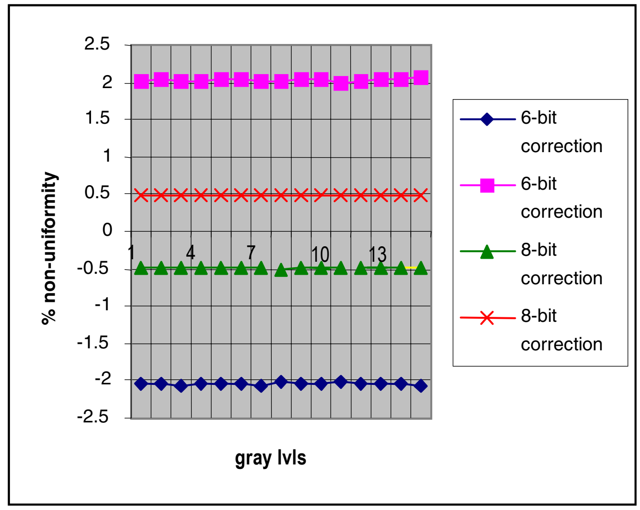

Figure 7: % Non-uniformity vs Gray lvls: Method D, 15 gray lvls

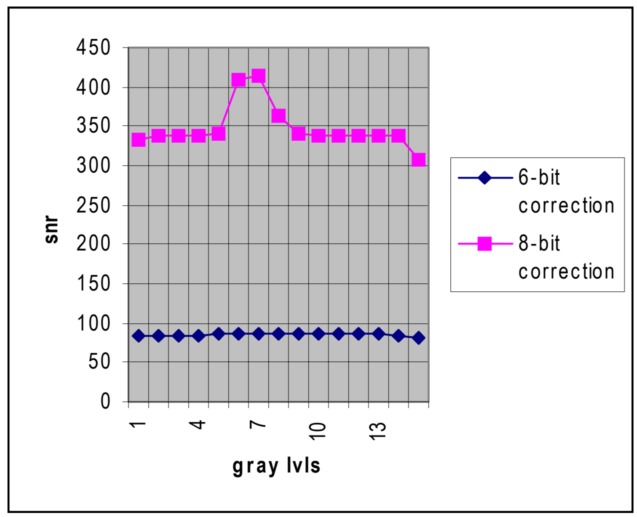

Figure 8: % snr vs Gray lvls: Method D, 15 gray lvls

Figures 7 and 8 above represent respectively the peak-to-peak non-uniformity and signal-to-noise ratio obtained using Method D on 16 gray levels with 6- and 8-bit quantization levels. We see from Figures 5-8 that there is a significant improvement for 16 gray levels both in peak-to-peak non-uniformity and snr by going from 6 bits of correction levels to 8 bits across the entire exposure range. One goes from a peak-to-peak non-uniformity of about +-2% for 6 bits to +-0.5% for 8 bits. The improvement in actual uniform filed prints is also quite significant.

An important question one would like to answer is how much flexibility in terms of number of gray levels is afforded by 8 bits of correction and how much does one gain for each of these levels. In order to answer these questions, we obtain the non-uniformity obtained for varying number of gray levels using 8 bits of correction.

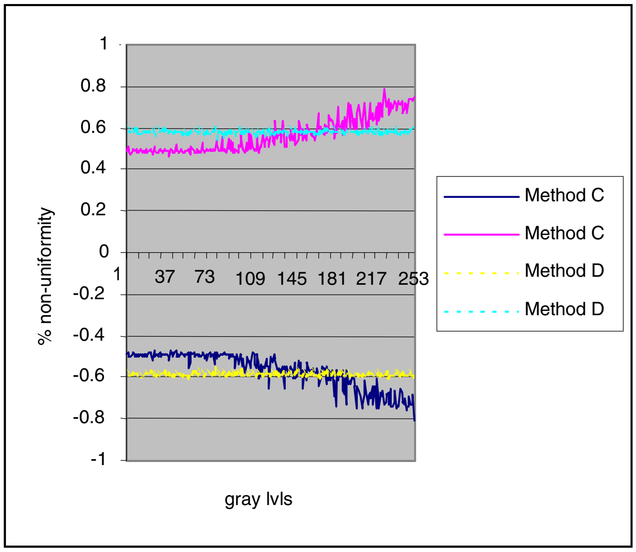

Figure 9. % Non-uniformity: 256 gray lvls, 8-bit correction

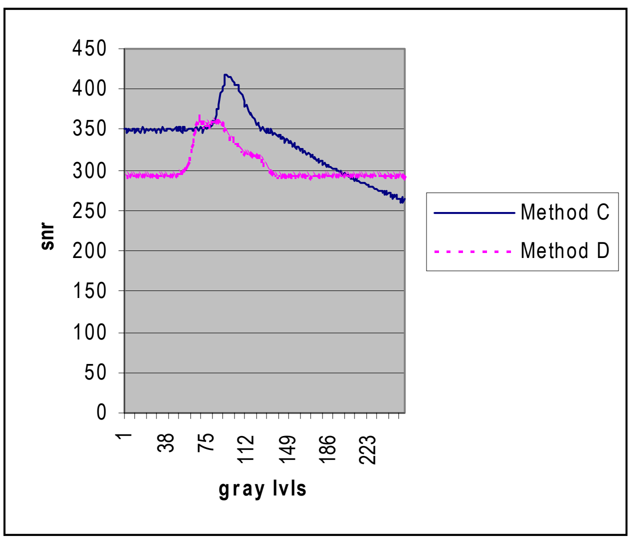

Figure 10. snr vs gray lvls: 256 gray lvls, 8-bit correction

Figures 9 and 10 above show respectively the peak-to-peak and snr obtained for 256 gray levels using 8-bit correction and Methods C and D. Figure 11 shows the average (across all gray levels) of the peak-to-peak non-uniformity as a function of number of gray levels. One sees from this Figure that non-uniformity of less than 0.6% can be achieved using 8-bit correction.

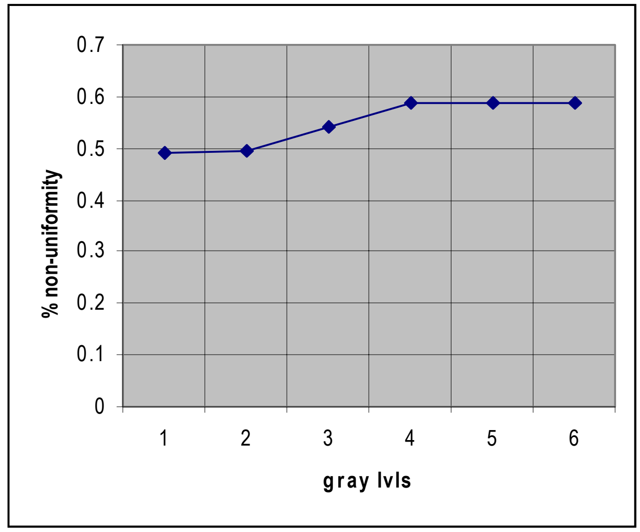

Figure 11: % non-uniformity vs # of gray levels

Conclusion

We have presented in this paper a non-linear exposure uniformity correction method that uses center-weighted PWM system to generate the clocks. This combination makes it possible to have as many as 256 levels of correction thereby providing the possibility of also having as many as 256 gray levels. Non-uniformity of ~0.5% is achievable with this system throughout the dynamic range of exposure of the printing system. The algorithm is very robust and efficient and it is possible assign different levels of uniformity to different sections of the exposure range.

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Biography

Isaac Ajewole was born in Nigeria and moved to the United States for College. He got his BS in Electrical Engineering from Purdue University and after a year of working for a an electrical control company, he went to do graduate work in Electrical Engineering at the University of Rochester NY where he got his MS and PhD. He has worked for Eastman Kodak Company since then in varied roles as a Research Scientist and Senior Research Scientist. His interests are in image processing, general algorithm development and software development. He is currently working for NexPress Solutions LLC in Rochester NY. Isaac Ajewole holds several patents and has published several papers in the fields of Image Processing and Algorithm Development