https://doi.org/10.2352/ISSN.2169-4451.2020.36.65

Dynamic Imaging Solution

Chunghui Kuo; Eastman Kodak Company; Rochester, New York, USA 14653

Abstract

The basic economic principle dictates that productivity improvement is one of the main driving forces for raising the living standard of the general public and maximizing companies' profit margin. By replacing analog devices with their digital counterparts, the last digital revolution has made huge contribution in boosting labor productivity annually despite the reduction in averaged working hours. However, the labor productivity growth rate has dropped to the lowest level since the Great Recession in 2008. Recognizing the long-term sustainability challenges of the current economic development, a new societal paradigm has emerged where artificial intelligence and connected devices take over well-defined tasks to achieving economies of scale and empowering people to innovate and create value. Being a form of mass customization manufacturing process, a dynamic imaging solution is proposed in an electrophotographic printing system with computational calibration capability in the spatial and tonal domains when requested, which could serve as an important enabling technology for the vision of autonomous printing.

Introduction

The basic economic principle dictates that productivity improvement is one of the main driving forces for raising the living standard of the general public and maximizing the profit margin of a company. By replacing analog devices with their digital counterparts, the last digital revolution has made pivotal contribution in boosting labor productivity annually from 1980 to 2007 despite the reduction in averaged working hours. However, except from 1980 to 1981, the labor productivity and growth rate has dropped to the lowest level in history during the Great Recession from 2007 to 2016 [1]. Recognizing the long-term sustainability challenges of the current economic development, such as climate change and income inequality, a new societal paradigm, *Society 5.0*, was put forth by the Japanese government at the 2019 World Economic Forum where artificial intelligence, connected devices and other digital transformative technologies will begin to play major roles in guiding well-defined tasks to achieving economies of scale, liberating people from unrelenting pursue of efficiency, and empowering human beings to innovate and create value for the greater society [2, 3].

Being a manufacturing process for mass customization, the aspiration of a *Society 5.0* will most likely lead the digital printing industry to the future of autonomous printing, where each print job is intelligently routed, reproduced, inspected and distributed to each individual recipient at diverse geological locations with optimal efficiency in overall natural resource consumption and minimal human interference while satisfying intelligently determined image quality constraints. This will leave value-creation tasks of generating contents to creative authors who would be free of any concern in the laborious intermediate steps before reaching their target audience. Because of potential imperfections in heterogeneous characteristics, wear-and-tear artifacts on various imaging components in a digital printing press and productivity loss if work stoppage necessary for part replacement, the objective of optimal efficiency during the stage of print job reproduction can be translated into the following technical requirements:

- Accurate fault detection to surgical imaging component replacement and avoid waste.
- Active imaging process optimization with high precision beyond visual acuity to maximize the life expectancy of an imaging component.
- Adaptive calibration to address dynamic nature of imaging process disturbances.

Accurate fault detection is a direct application of intelligent image processing algorithms. However, the decision made by the fault detection system will likely be associated with financial cost and potentially legal contract; hence, the interpretability of the recommendation made by the intelligent fault detection system is essential to ensure its wide acceptance in the printing industry [4]. While important, the topic of accurate fault detection algorithms is outside the scope of this paper.

A *Dynamic Imaging Solution* directly addresses the last two technical requirements: *Active optimization* and *Adaptive calibration*, and has been implemented on the commercial electrophotographic digital printing system of the Eastman Kodak Company [5, 6]. The system is built on the foundation of the computational image formation architecture with dynamic calibration capability in the spatial and tonal domains when requested [7], and it could potentially be an important enabling technology for the vision of autonomous printing.

Dynamic Imaging Solution

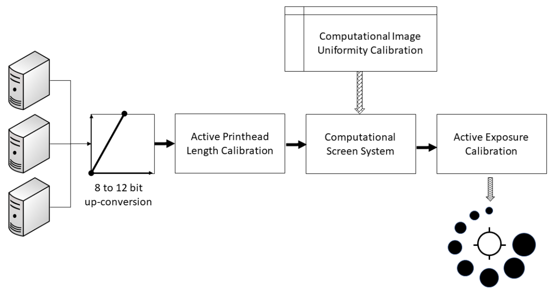

Figure 1. *The flowchart of Dynamic Imaging Solution*

The overall flowchart of the Dynamic Imaging Solution is shown in Figure 1, and it can be divided into two operating spaces: physical space optimization and virtual space compensation. In terms of the calibration capability, the Dynamic Imaging Solution is designed to independently address tone scale nonuniformity via the *Progressive Color Calibration* and geometric distortion via *Active Printhead Length Calibration* in each imaging module.

Progressive Color Calibration

Macro tonal nonuniformity is one of the primary imaging artifacts in a digital printing press, of which characteristics often exhibit different local tonal variation attributes from diverse imaging sources, especially for a electrophotographic printing system with multiple imaging subsystems including charging, writing, developing, cleaning etc. Thus, it is necessary for a macro nonuniformity correction system to not only be sufficiently flexible to minimizing local tonal variations but also robust against over-compensation and erroneous compensation.

The working principle of the *Progressive Color Calibration* is similar to the noise cancellation algorithm, where unwanted disturbance can be either actively removed through destructive interference or digitally filtered from the contaminated digitized signal. Each approach has its own advantages and disadvantages. On one hand, active noise cancellation system is only controlled by a small number of hardware parameters, which usually leads to a robust parameter estimation algorithm. However, only the noise with the same characteristics as the physical counter-signal generator can be satisfactorily eliminated. On the other hand, while the digital filtering approach is more flexible in modeling local tone scale deviations, the range of nonuniformity correction function needs to satisfy two boundary conditions at 0% and 100% and avoid adverse effect of potential signal overfitting.

The *Progressive Color Calibration* is composed of two concatenated operations, active exposure calibration and computational uniformity calibration, where the active exposure calibration readjusts the internal hardware/firmware parameters of the digital printhead and the computational uniformity calibration modifies the local image rendition in 12-bit tonal space. Let

$$F_a(\omega, v_c) = p_c \tag{1}$$

be the active exposure calibration function mapping from the input code value v_c to output exposure level p_c with the printhead control parameter vector ω, and

$$F_c(\kappa, v_c) = t_c \tag{2}$$

be the computational uniformity calibration function mapping from the input code value v_c to the rendered tone scale t_c via controlling vector κ. The exposure characteristics of the proposed dynamic imaging solution can be represented by the composite function $F_a \circ F_c = F_a(\omega, F_c(\kappa, v_c)) = p_c$. Thus, the perceived local tonal nonuniformity at the image location (x, y) can be attributed to local exposure variation $\partial p_c(x, y)$, and the objective of the *Progressive Color Calibration* system is to find the solution for the following optimization problem:

$$\min_{\kappa,\omega} \|F_c'(\kappa, v_c|x,y) F_a'(\omega, \hat{v}_c|x,y) - \partial p_c(x,y)\|, \tag{3}$$

which can be solve progressively via a backpropagation process similar to that of the neural network.

Active Exposure Calibration

The basic algorithm for active exposure calibration can be found in the article published previously [8], and its implementation is further extended to utilizing the internal LED driver chip current/voltage adjustment capabilities [9].

Computational Uniformity Calibration

The computational uniformity calibration consists of two functional modules, tone-level correction module and position correction module, as shown in Figure 2.

A computational image non-uniformity calibration architecture is proposed based on the computational screen algorithm using a grayscale LED printhead [7]. The current implementation adopts a 12-bit computational operation in terms of tone scale resolution, which is capable of rendering over 4000 gradations in each halftone dot. Note that the computational screen algorithm does not require to have a specific tonal resolution, which will allow for a quick upgrade path to even higher tonal resolutions through firmware upgrade. Let the reproduced image $I(x,y,v) = I_o(x,y,v) + \Delta(x,y,v)$, where $I_o(x,y,v)$ is the ideal intended image and $\Delta(x,y,v)$ represents the color nonuniformity across the entire imaging area. We can first discretize $\Delta(x,y,v)$ in terms of finest spatial and tonal resolution and construct a 3-dimensional tensor Δ_{ijk}, where i represents image cross-track direction, j represents the image in-track direction and k represents the tonal level. We can apply decompose

$$\Delta_{ijk} = \sum_{s=1}^{n} i_s \circ j_s \circ k_s + \varepsilon, \tag{4}$$

where i_s, j_s, k_s are 1D feature vectors along the cross-track, intrack and tonal gradation axis respectively, ε represents the random noise, $\circ$ is outer vector product and n is the rank of Δ_{ijk}. Since j_s is primarily caused by imperfect motion of a roller rotation which can usually be adjusted mechanically during the press initial setup process, we can assume that it is a constant vector with value being 1 and results in the following simplified decomposition:

$$\Delta_{ik} \sim \sum_{s=1}^{n} i_s \circ k_s. \tag{5}$$

We propose a computational image uniformity calibration system by expanding the standard computational screen algorithm to compensate the estimated Δ_{ijk}, using the relationship above:

1. Print a test target with multiple tone scale and flat field.
2. Estimate the nonuniformity and decompose as a summation of rank-1 vector multiplication. The current implementation allows up to 3 terms.
3. $k_s(x)$ is the cross-track nonuniformity feature vector and store in the memory
4. $i_s(v)$ is is the delta tone scale LUT stored in the memory, of which tonal resolution is raised from standard 8-bit accuracy to operating 12-bit accuracy
5. The final image value $I_o(x,y,v)$ is first raised to the operating 12-bit code value space and sent to the computational screening module is as follows:

$$I(x,y,v) = I_o(x,y,v) - \sum_{s=1}^{3} i_s(v) \times k_s(x). \tag{6}$$

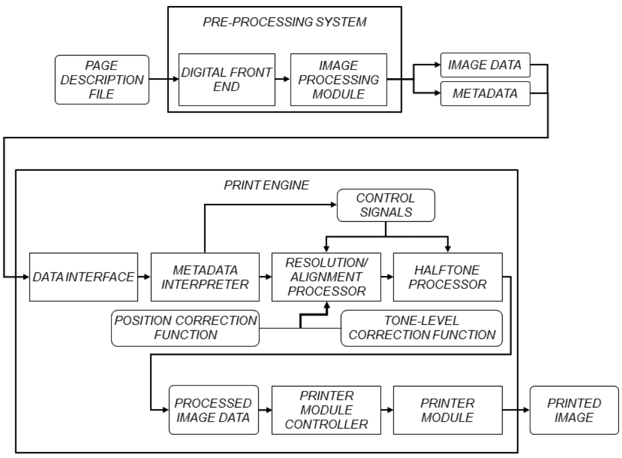

Figure 2. *The flowchart of Computational Calibration Solution*

Active Printhead Length Calibration

One of the critical requirements for a multi-color image formation system is the capability to satisfy color-to-color image registration specification, which can be decomposed into two perpendicular directions: one is parallel to the printhead, V_p, and the other is perpendicular to the printhead, V_q. In general, V_p can be attributed to inconsistent printhead length among different color modules, and V_q is caused by fixed offset and/or variable mechanical motion in time domain. We will focus on the registration error caused by V_p, which is usually addressed by first tightening the printhead manufacturing tolerance and grouping printheads with nearly identical length together to be assembled in a digital printing system. One major drawback of this approach is that it inevitably increases the overall manufacturing as well as logistic cost. We will propose an active printhead length calibration algorithm and the associated implementation architecture in this paper with the benefit of reducing overall production cost of each digital printing press and actively minimizing the inherent printhead hardware variability.

Considering all possible causes for spatial deformation along a digital printhead, it is insufficient to assume that the printhead length variation is only limited to linear expansion or contraction. Furthermore, any final image data manipulation to compensate for local spatial deformation can not cause any perceivable halftone structure artifact, and the proposed algorithm should not result in perceivable image content difference except optimized performance in color-to-color registration, such as quality degradation of fine line and text structures

1. The input image data is in 600dpi resolution and the ideal printhead resolution is in 1200dpi.
2. A test target with a series of fiducial marks is printed on a selected planar substrate via an intended digital printhead with no active length adjustment.
3. The error signal $e(x)$ between the measured fiducial mark locations and their ideal position is estimated
4. A smoothing spline functional is adopted to fit $e(x)$ and remove excessive measurement noise. The denoised error signal is denoted as $s(x)$.
5. Adopt a delta modulation scheme to encode $s(x)$ in a constant increment step size, which is 0.5 under the current input/output configuration.
6. The location of every step jump is stored as a table in a series of predefined memory addresses.
7. Each image pixel index is first compared with the stored table:
    - If current index is not listed in the table, the image pixel is duplicated once and continue to the next image pixel.
    - If current index is listed in the table with the signed bit being 1, the image pixel is duplicated twice and continue to the next image pixel.
    - If current index is listed in the table with the signed but being 0, the image pixel is not duplicated and move directly to the next image pixel.
8. The overall positional bias among each printhead is also computed and send to the image pixel offset register.

Experimental Result

The *dynamic imaging solution*, including printhead hardware and software application, has been successfully deployed for commercial usage. Readers interested in the implementation and experimental result of active exposure calibration can find relevant information from previous publications [8]. Figure 3 illustrates extracted feature vectors, i_s and k_s, for $s = 1,2$. The first feature vector combination $\{i_1, k_1\}$ isolates the nonuniformity component with a unimodal characteristics and the second feature vector combination, $\{i_2, k_2\}$, encompasses the residual bimodal nonuniformity component, where boundary conditions of being zero at both ends of the digital domain are strictly enforced.

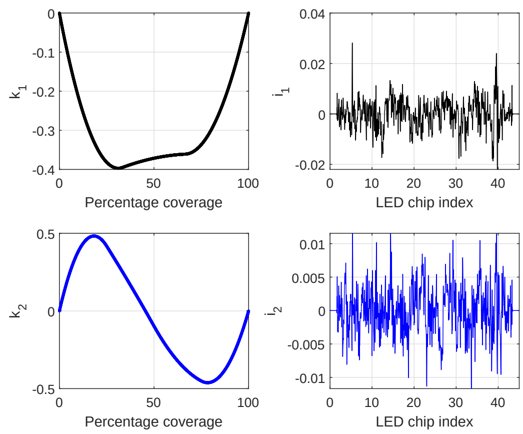

Figure 3. *Estimated feature vectors i_s and k_s, $s = 1,2$*

Sequential system optimization via the backpropagation algorithm of the *Progressive Color Calibration* is shown in Figure 4 and Figure 5. Figure 4 represents a nominal case with above average performance at the default setting, but unacceptable nonuniformity artifact can be seen at the top graph in Figure 5. While a print provider might still be able to tolerate the image quality degradation in the first scenario, there is no doubt that imaging component replacement is necessary to return the printing press to the satisfactory state, which results in labor/material cost and productivity loss. Thus, the image quality improvement shown in Figure 4 and 5 demonstrates that the *Progressive Color Calibration* provides an effective and economical alternative to satisfactorily restore the system performance with minimal working knowledge of the complicated digital printing press.

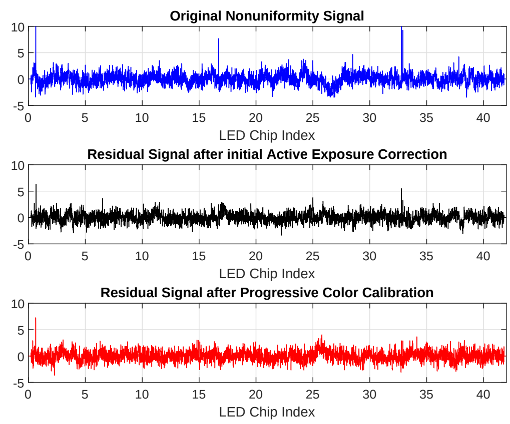

Figure 4. *Progressive Color Calibration - Nominal case*

A nominal and extreme example of active printhead adjustment can be found in Figure 6 and Figure 7. Adopting the piecewise constant functional for overall printhead length approximation not only minimizes the influence of measurement error but also provides a highly efficient coding scheme. The active length adjustment is performed before the computational screening module to avoid any halftone structure perturbation.

Conclusion and Future Works

The *Dynamic Imaging Solution* is described in this paper, which includes the *Progressive Color Calibration* addressing automatic tonal nonuniformity optimization and the *Active Printhead Length Calibration* to allow plug-and-match across all printheads. Nominal and extreme scenarios were presented to show the effectiveness and wide latitude of the *Dynamic Imaging Solution* in minimizing overall cost while maximizing productivity without prerequisite of deep understanding of the associated digital printing process. We believe that this technology will play an important role in realizing the ultimate objective of autonomous printing and on-demand digital fabrication.

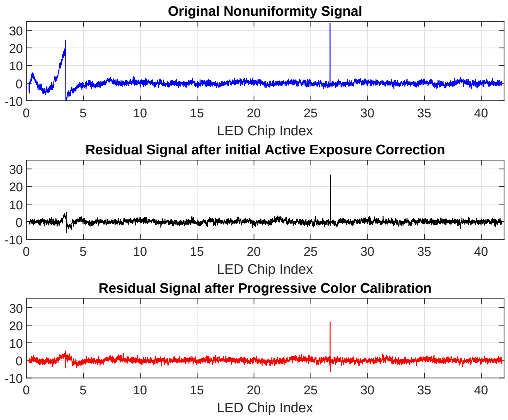

Figure 5. *Progressive Color Calibration - Extreme case*

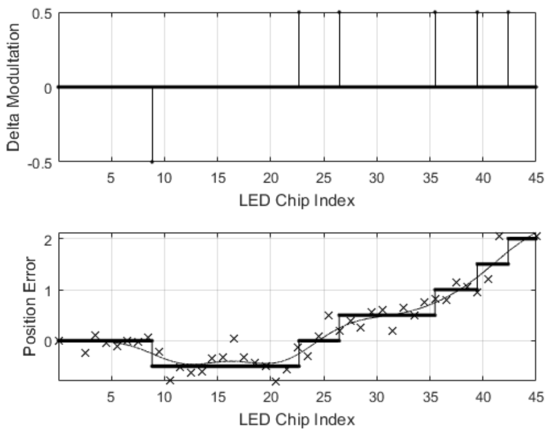

Figure 6. *Nominal printhead length active adjustment*

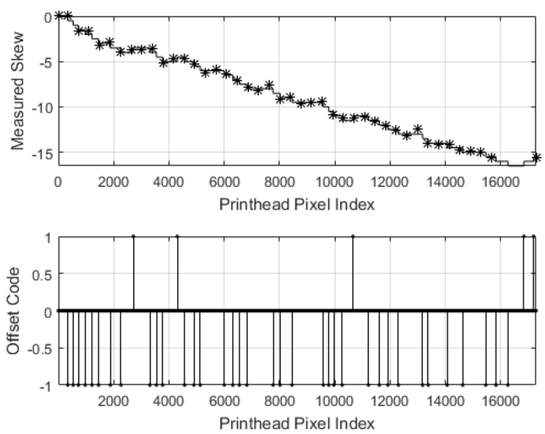

Figure 7. *Extreme printhead length active adjustment*

References

[1] Prodcutivity, Beyond The Numbers, US Bureau of Labor Statistics, Vol 6, No 2, January 2017.

[2] Y. Shiroshi, K. Uchiyama and N. Suzuki, Society 5.0: For Human Security and Well-Being, IEEE Computer, Vol 51, No 7, pg.91-95, 2018.

[3] "Modern society has reached its limits, Society 5.0 will liberate us", https://www.weforum.org/agenda/2019/01/modern-society-has-reached-its-limits-society-5-0-will-liberate-us/, World Economic Forum, Davo, 2019

[4] Dimitris Bertsimas and Jack Dunn, Machine Learning under a Modern Optimization Lens, Dyanmic Ideas LLC, 2019

[5] Chung-Hui Kuo, David Brent and Stacy Munechika, Computating array of high-resolution halftone pixel values by addressing halftone dot function and averaging values to determine value at printing resolution, US Patent 9,565,337, USPTO, February 7, 2017.

[6] Chung-Hui Kuo, David Brent, Frederick Altrieth, Stacy Munechika, Richard Allen, Print engine with print-mode-dependent pulse timing functions, US Patent 10,192,150, USPTO, January 29, 2019.

[7] Chunghui Kuo, From 8-bit to 4K: A leading computational image formation architecture to digital printing technology, NIP&Digital Fabrication, Vol 2017, No 1, pg. 9-12, November 2017.

[8] C. Kuo, "Active digital press optimization," 2014 IEEE Global Conference on Signal and Information Processing (GlobalSIP), Atlanta, GA, 2014, pp. 669-673, doi: 10.1109/GlobalSIP.2014.7032202

[9] Chung-Hui Kuo, Stacy Munechika and Frederick Altrieth, Adaptive printhead calibration process, US Patent 10,126,696, USPTO, November 13, 2018.

Author Biography

Chunghui Kuo is a senior scientist at Eastman Kodak Company. He received his Ph.D. in Electrical and Computer Engineering from the University of Minnesota and joined Kodak in 2001. His research interest is in image processing, image quality, blind signal separation and classification, and neural network applied in signal processing. He is a Distinguished Inventor and IP coordinator at the Eastman Kodak Company, the Editor-in-Chief at the Journal of Imaging Science and Technology, a senior member of the IEEE Signal Processing Society and a member of IS&T.