From 8-bit to 4K: A Leading Computational Image Formation Architecture for Digital Printing Technology

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Abstract

As printing technology continues to evolve, the next technical challenges will most likely arise from fully automated digital print production and high-precision digital fabrication, where the printing press needs to detect faults in the printing process, automatically recover without human intervention, and construct images and/or three-dimensional objects beyond the capability of human perception. In this paper, we introduce a computational image formation algorithm of which tonal resolution at each pixel is elevated from the current technology standard of 8-bit to a class-leading 12-bit, i.e., 4K tonal resolution. Combined with a 1200-dpi high spatial resolution adaptive LED printhead, we will demonstrate that the proposed image formation algorithm can effectively address technological challenges for the future of image formation and digital fabrication technologies.

Introduction

A traditional digital halftone screen set is designed based on constraints such as printhead tonal resolution (i.e., 2-level/pixel, 4-level/pixel, etc.), image tonal resolution (binary, multilevel or grayscale), printhead inherent spatial resolution (600 dpi, 1200 dpi, etc) and intended screen frequency/angles [1]. The nal halftone screen design is implemented as a look-up table (LUT) halftone tile on the targeted digital print engine for each corresponding color and has a one-to-one mapping relationship with the output of the Digital Front End (DFE). There are several advantages with this traditional halftone screen implementation process, such as:

- Complicated and computational expensive algorithms can be adopted to optimize every level in a digital halftone screen, as no real-time computational requirement is imposed in this imaging architecture.
- The computational speed of the halftoning process on an image is greatly reduced with customized ASIC design.

While the traditional digital halftoning process provides sufficient power and flexibility for the existing digital printing technologies, the ever-increasing demand for higher image quality and robust printing process has created new challenges and opportunities for the future of digital halftoning technology, such as true fidelity at or even beyond normal vision capability, color consistency in short and long run and ultimately workerless print production. Recent research has shown that reading from paper results in deeper comprehension of the target content [2, 3, 4]. While the technological advantage of digitized information will continue to accelerate, paper is still a preferred medium when deep understanding and appreciation of the subject matter is needed. Just like all manufacturing industries, a scalable fully automated printing process with minimal human intervention will significantly reduce the cost in labor and transportation and provides sustainable growth in a mass customization market. A workerless printing process requires two essential capabilities: active sensing mechanisms for fault detection and automatic defect recovery. Since the root cause of an imaging defect is sometimes unknown and its magnitude lies in a continuous domain, it is necessary for the adopted artifact recovery technology to provide control precision beyond visual sensitivity so as to satisfactorily nullify the detected artifact. Moreover, as the printing technologies continue to evolve into three-dimensional surface/functional manufacturing technologies for the future, the quality requirement is no longer determined by human perception capability but by the functionality requirement.

In this paper, we will introduce a computational image formation architecture composed of two primary imaging modules: the computational screening module and the adaptive LED exposure system. In the computational screening module, the tonal resolution at each pixel is elevated from the current industry standard of 8-bit to a class-leading 12-bit, i.e. 4K tonal resolution. Combined with a 1200-dpi high spatial resolution adaptive LED printhead, we will demonstrate that the proposed image formation architecture can effectively address technological challenges for the future of image formation and digital fabrication technologies.

Computational Image Formation Architecture

Eight-bit imaging is related to the psychophysical study in terms of just-noticeable grayscale difference using two color patches in juxtaposition [5]. However, the visual discernibility increases when the area of the color patch increases, which, in turn, creates new demand for tonal resolution beyond the current 8-bit coding scheme as the size of printed output continues to increase. The commercial digital camera industry has recognized the need for higher image quality and adopted various RAW formats with 12-bit to 14-bit encoding. As explained previously, the ability to physically render color gradation beyond 8-bit tonal resolution will also provide a high-precision control mechanism and pave the way to a fully automated print production with minimal human intervention. It is important to note that the tonal resolution and spatial resolution is inversely related to each other for a digital halftoning process. Consequently, the combined printhead's properties of tonal and spatial resolution will impose the highest quality achievable for the corresponding image formation system. Furthermore, since the current halftone LUT structure controls halftone dot growth pattern at each 8-bit code value, the size of the LUT will increase linearly with respect to the intended tonal resolution. Let's assume the number of gray levels achievable by the adopted digital printhead at each printed pixel is L and the targeted number of printed image tone scales rendered by each halftone dot is D. The minimal number of printed pixels needed to comprise this halftone dot is D/L. If the spatial resolution of the digital printhead is K, the highest isotropic amplitude-modulated screen frequency is

$$F_h = K\sqrt{L/D}. \quad (1)$$

Similar to the technical challenge that semiconductor chip manufacturers encounter when shrinking the chip footprint to reduce power consumption and improve computational efficiency, further raising a digital printhead spatial resolution K has become an increasingly expensive proposition. Thus, researchers have devised the following techniques to improve the perceived image quality:

- Decrease D by the principle of halftone dithering to create perception of smooth color gradation [6, 7].
- Increase L by designing multilevel digital printheads [8].

Therefore, this ensures that any halftone design with a screen frequency lower than F_h has achievable color gradation will have the intended tone scale specification. For example, a digital printhead with 1200-dpi spatial resolution, 8-bit tonal resolution at each imaging pixel, and 4K tone scale gradation at each halftone dot can support an up to 300-lpi amplitude-modulated halftone screen frequency.

Computational screening module

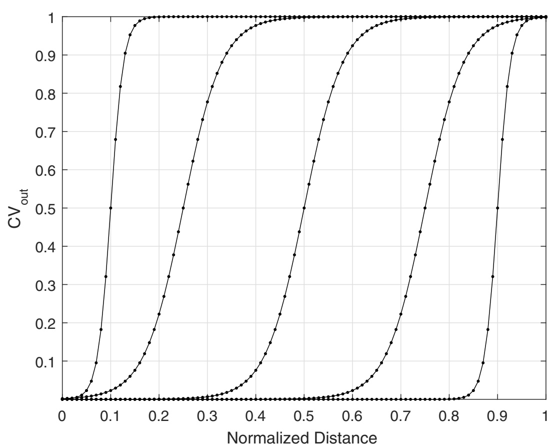

Figure 1. *Computational halftone dot formation*

The traditional digital halftone screening algorithm adopts a two-dimensional tile design through proper LUT implementation. While this can be very effective, the digital printhead technology improvement in higher spatial and tonal resolution has now made possible a real-time computational screening implementation without tiling constraints. The computational screening module provides three main advantages:

- The halftone screen frequency and angle is only limited by the computational precision of the fixed-point operation. This will significantly broaden the domain of allowable halftone screens.
- The final formation of halftone dots is derived by a sigmoid function with a center point moving between 0 and 1 as shown in Figure 1. Thus, the achievable number of tonal resolution is only determined by the same fixed-point computational precision.
- The entire computational screening algorithm is a pointwise operation and can be sped up via a pipelined processing implementation.

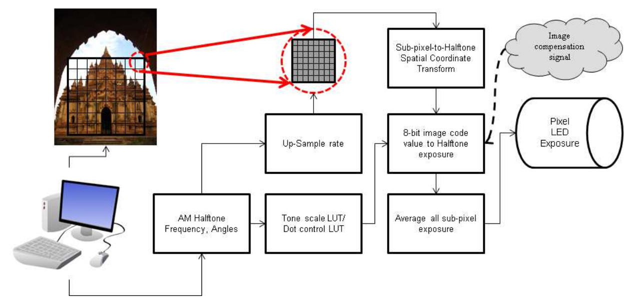

Figure 2. *Computational Screening Flowchart*

The flowchart of the proposed computational screening algorithm is shown in Figure 2 [9]. The key process steps are as follows:

1. Convert the intended AM halftone frequency and screen angle into two coordinate basis V for the halftone domain.
2. Define the intended tone scale for the associated halftone screen.
3. Upsample each image pixel p to $\{p_{ij}|i = 1\cdots n_1, j = 1\cdots_n 2\}$ and transform each subpixel to the halftone domain via V.
4. Compute the distance to the closest halftone dot and normalize between 0 and 1.
5. Compute the halftone code value for each subpixel based on the halftone dot formation function 1 and the input image code value, which can be modified to compensate for potential static or dynamic image nonuniformaity artifact.
6. Compute the image pixel code value associated with the intended halftone screen by averaging all subpixels.

Figure 3 illustrates the 8-bit tone scale of each computed halftone dot evolution. The numerical precision of the fixed-point computational module is 12-bit, which corresponds to over 4K levels of achievable color gradation.

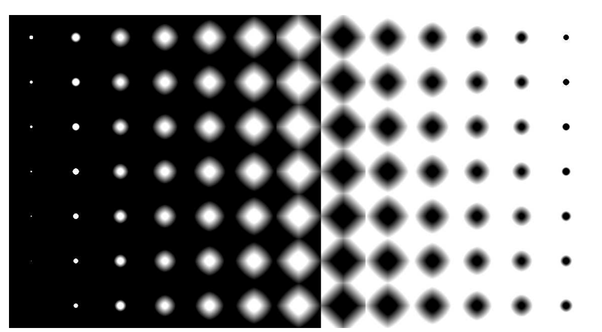

Figure 3. *Computational Halftone Dot Gradation*

Adaptive LED exposure system

As shown in Equation 1, $\sqrt{L}$ is linearly correlated with F_h, which not only enables a digital printing press to incorporate an AM halftone screen set with higher spatial frequencies within the associated physical imaging process capability but also provides instantaneous local tone scale adjustment without interrupting the printing operation. It is analogous to the computer industry embracing the multicore CPU architecture when the technical challenges of microelectronics manufacturing process of continuing to shrink in size becomes increasingly daunting.

LED printhead technologies have been shown to produce 8-bit tonal resolution at each image pixel[11]. A 1200 dpi multilevel LED exposure subsystem is developed to further enhance the electrophotographic imaging process with the capability of adaptively compensating nonuniformity artifacts along the process direction [10]. We first denote that φ_0 and φ_1 be the predetermined nonlinear functionals spanning nonuniformity signal subspace in the time domain. Let the estimated nonuniformity signal on a printing press as δT_{x_0} be presented as follows:

$$\delta T_{x_i} = [\delta t_{x_i}(u_1)\ \ \delta t_{x_i}(u_2) \cdots \delta t_{x_i}(u_m)]'. \tag{2}$$

The discrete vector bases of φ_0 and φ_1 at the corresponding gray scale levels $\{u_i, i = 1, \cdots, m\}$:

$$\begin{aligned} V_0 &= [\varphi_0(u_1)\ \ \varphi_0(u_2) \cdots \varphi_0(u_m)]' \\ V_1 &= [\varphi_1(u_1)\ \ \varphi_1(u_2) \cdots \varphi_1(u_m)]'. \end{aligned} \tag{3}$$

The adaptive LED exposure algorithm for active nonuniformity calibration can be mathematically described by the following optimization problem:

$$\min_{\alpha_0, \alpha_1} \| \delta T_{x_i} + [V_0\ \ V_1] \begin{bmatrix} \alpha_0 \\ \alpha_1 \end{bmatrix} \|^2 \tag{4}$$

$$subject\ \ to\ \ [V_0\ \ V_1] \begin{bmatrix} \alpha_0 \\ \alpha_1 + 1 \end{bmatrix} \geq 0 \tag{5}$$

where α_1 adjusts the overall power at pixel x and α_0 shapes the associated exposure contrast [10]. The nonuniformity signal is first decomposed into the low spatial frequency component and the high-frequency component via a Spline-fitting algorithm with a predefined knot sequence. The correction coefficient for each component is computed independently. Because the low-frequency component is more susceptible to normal fluctuations of a printing process, a discount factor is first multiplied to the correction coefficient of the low-frequency component before merging with that of the high-frequency component.

Experiment results

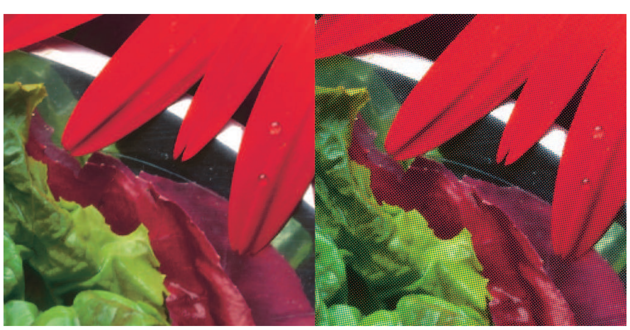

Figure 4. *Side-by-Side Comparison between the input and the computational screen module output*

Figure 4 shows the side-by-side comparison between the standard 8-bit contone image and the halftoned image processed the proposed computational screening algorithm and it demonstrates that the proposed computational imaging architecture can properly render images with standard 8-bit coding scheme. In addition, Figure 5 and Figure 6 enlarge a $10.8mm \times 7.6mm$ section of a textile image to illustrate the algorithm's capability to reproduce high frequency image detail.

Figure 5. *Cropped input image*

Figure 6. *Cropped screened image*

More importantly, we would like to show the technological advantage of the proposed computational imaging architecture beyond 8-bit tonal resolution. Two types of artificial perturbation signals are added to a flat field image before going through the computational screening module: the first is a linear perturbation in double precision and 8-bit precision and the other contains two different sine wave signals in double precision with different frequencies. The simulation results are presented in Figure 7 and Figure 8. The deficiency of the 8-bit coding is exposed as the ”staircase” artifact which is perceivable by most human observers. The maximal error of the reproduced sine wave image signals and the input sine wave signals is slightly over $0.06 \approx 1/2^4$ where 4 is the extra bit depth from 8-bit to 12-bit. This proves that the computational imaging architecture is capable to reproduce image in 4K tonal resolution in each halftone dot area.

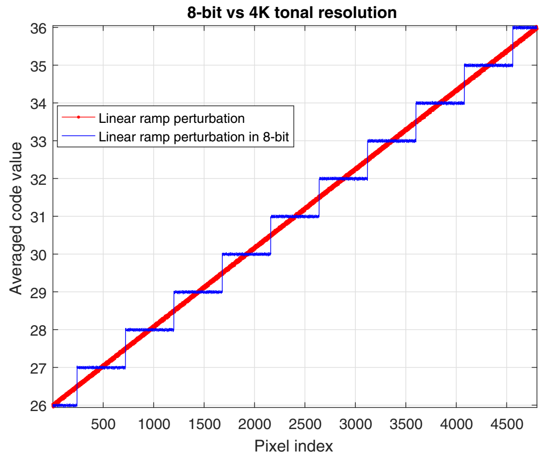

Figure 7. *Ramp reproduction comparison between normal 8-bit and 4K tonal resolution*

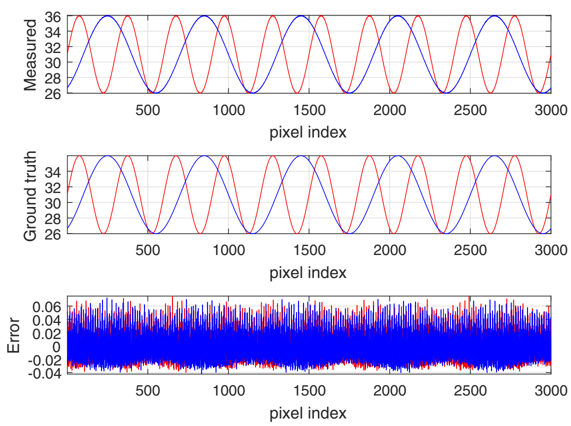

Figure 8. *Sine wave reproduction comparison between 4K tonal resolution and double-precision*

One immediate application for 4K tonal resolution capability is for image nonuniformity correction, which is illustrated in Figure 9. The scanned profiles before applying image correction in double precision clearly show that the front side is much lighter than the rear and the proposed computational algorithm successfully minimizes the magnitude of nonuniformity artifact without introducing perceivable quantized staircase discontinuities, which could occur if the correction module operates in the standard 8-bit coding space as illustrated in Figure 7.

Conclusion and future works

A leading computational imaging architecture is composed of a 1200-dpi adaptive LED exposure printhead and a computational screening module that fully utilize the gray-scale exposure capability of the LED printhead and significantly enhance its tonal resolution from standard 8-bit to 4K. The extra tonal resolution allows this new architecture to play a significant role in pursuing the ultimate goal of workerless print production as well as finding new applications for the future of digital fabrication.

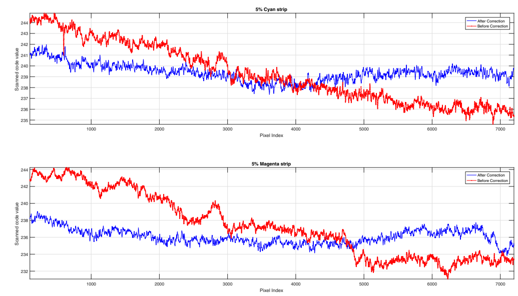

Figure 9. *Image uniformity correction application*

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Author Biography

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