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Optimized Image Rendition with White Colorant in a Digital Electrophotographic Printing Process

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Abstract

The rapid advances in the display and mobile communication technologies have profoundly challenged the traditional analog high-speed printing press as well as the still-evolving digital printing technology in delivering information to consumers. While the mobile technologies are very efficient to provide instantaneous feed of current affairs to consumers, printing on varieties of substrates beyond plain paper is still irreplaceable to marketing, packaging and additive manufacturing in the real world applications. When printing on nonwhite substrates such as glass and metallics, white colorant is often required along with the other primary colors to properly reproduce the intended color. In this paper, we will introduce a digital color control algorithm that enable white printing capability while satisfying the constraints of simultaneously achieving optimal image quality and minimal total cost of consumption.

Introduction

The rapid advances in the display and mobile communication technologies, such as smart phones and virtual/augumented reality headsets, has profoundly challenged the traditional analog high-speed printing press as well as the still-evolving digital printing technology in delivering information to consumers. While the mobile technologies are very efficient in providing an instantaneous feed of current affairs to a broad audience with little marginal cost, printing on varieties of substrates besides paper is still vital to fulfill the need for marketing, packaging and on-demand manufacturing in the real world. With the advent of digital printing technology that enables mass customization, the demand for short-run and high image quality applications, for example, photobook and digital packaging, has risen considerably in recent years. When printing on non-white substrates, such as transparent and metallic material, white colorant is almost always required along with the traditional cyan, magenta, yellow and black primary colorants to properly reproduce the intended color. One of the critical components in digital packaging is the ability to precisely deposit various amounts of white colorant on flexible substrates with a nonwhite background, to achieve correct color appearance. In this paper, we will propose an optimized color rendition algorithm with a predefined color channel sequence using the new *KODAK NEXPRESS White Dry Ink* on the *Kodak NexPress* digital press. While the selected imaging formation is an electrophotographic printing process, the proposed algorithm can be easily extended to other printing processes such as drop-on-demand and continuous inkjet technologies.

In conventional printing, white colorant is usually deposited uniformly first on the top surface of the intended substrate before the other primary colors to provide white opaque backing and ensure proper color rendition. The same constraint continues to persist to the color management workflow in the digital printing technology, where the color definition of the corresponding media white point plays a significant role in color interpretation as described in the latest *International Color Consortium*(ICC) profile specification [1, 2]. As a result, this constraint will impose the printing sequence of white colorant to be either at the beginning or at the end of the colorant deposition process, depending on the intended printing architecture. Secondly, since some primary colors, such as black, usually exhibit similar opacity as the white colorant, it is possible to reduce the amount of white colorant by considering the amount of other primary colorant laydown composition, similar to traditional black component replacement strategies, (i.e. UCR/GCR) which provides a controlling mechanism to optimize the performance of a printing system in terms of stable neutrality, color saturation and image artifact reduction [1, 3, 4, 5, 6]. Furthermore, if the intended substrate has a metallic appearance, complete coverage of the targeted imaging area with opaque white colorant will also eliminate the metallic effect provided by this special substrate, which is usually undesirable. Finally, it would be much simpler for print service providers (PSP) to switch between the normal paper substrate and the substrate with special effects without the need to create two different print files containing different white color image layers. This will greatly encourage quick adoption of the white Dry Ink into their existing workflow.

We will first describe the technical challenges and constraints to be imposed in the imaging process incorporating white colorant. An optimized color control algorithm is proposed to demonstrate that it is possible to achieve these objects by creating a devicelink ICC profile connecting between the normal **CMYK** device color space to the **CMYK+White** device color space [7, 8, 9]. By implementing this methodology, high-quality images can be printed on colored, transparent and metallic substrates while optimizing the amount of white toner necessary for such applications.

Rendition Constraints

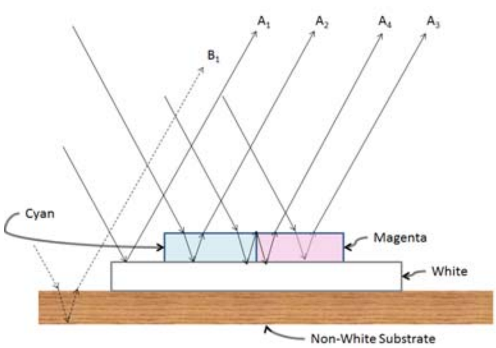

Figure 1. *Configuration I: Nonwhite Substrate with White Colorant at the bottom*

Figures 1 and 2 provide simple illustrations of how light interacts between substrate and colorants with the white colorant being both at the bottom and on the top of the primary colors, respectively. Figure 1 represents a standard practice of first laying down a uniform layer of white colorant in the image area.

The substrate influence on perceived color, B_1, is largely blocked by the white colorant layer, while $\{A_1, A_2, A_3, A_4\}$ depict individual contributions of the subtractive color mixing model from the white substrate, cyan, magenta and blue bichrome respectively and closely mimics that on a standard white substrate [10]. However, when the white colorant resides above the non-white substrate and other primary colorants, the color mixing model becomes much more complicated as shown in Figure 2. Besides B_1, the non-white substrate exerts its impact on the perceived color through multiple light penetration and scattering demonstrated by B_2 and B_3. Nonetheless, the traditional definition of *Media White Point* is provided by A_1 as opposed to B_1 on white substrate.

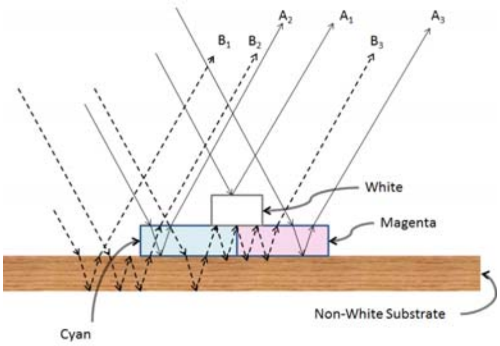

Figure 2. *Configuration II: Nonwhite Substrate with White Colorant on top*

Although it is straightforward to simply implement the first configuration when printing with white colorant and adopt the standard color management workflow with very little modification, a color rendition algorithm adjusting the light contribution from $\{B_1, B_2, B_3\}$ relative to $\{A_1, A_2, A_3\}$, which is the focus of this paper, will simplify the printing workflow, reduce the total cost of consumption, and enhance the intended visual effect with speciality substrates. For example, it is a common practice to impose a maximal Total Area Coverage (TAC) limitation to improve the reliability of the printing process and minimize the potential image artifacts such as mottle, ink bleed and hot/cold offset. Any attempt to reduce the coverage of the white colorant will result in the scenario similar to that in Figure 2. Furthermore, $\{B_1, B_2, B_3\}$ contain the intended visual effect beyond the diffused color perception when using speciality substrate and should be maximized while reproducing the target color.

The light mixing model detailed previously leads to the following constraints in color rendition:

- The media white point in the printer device color space should correspond to 0% coverage of all primary colors and 100% coverage of white colorant.

  Configuration I The coverage of white colorant at the D_{max} point of each primary color should be 100%.

  Configuration II The coverage of white colorant at the D_{max} point of each primary color should be 0%.

- If minimal light contribution from the nonwhite substrate is required, maximizing the black component replacement is the optimal solution.
- If the light contribution from the nonwhite substrate is preferred, a black component replacement strategy is chosen to balance the need between image quality and printing process stability.

Proposed Algorithm

While researchers have proposed various color rendition algorithms to incorporate white colorant into the standard four-color printing process [11], the rendition constraints described in the previous section can be imposed directly into the printer device color space as alternative to the *Profile Connection Space* (PCS) inside an ICC profile [1]. For instance, the standard definition of the *Media White Point* of a printer output ICC profile is the **CIEXYZ** measurement on the associated substrate areas with no colorant coverage and complete von Kries chromatic adaptation is assumed when converting from *Relative Colorimetry* to *Absolute Colorimetry* [12]. While this color appearance model usually works well on white, off-white and light gray substrates, the discrepancy between the visual assessment and relative colorimetric measurement begins to grow on color substrates. As a result, a devicelink ICC profile approach is proposed to directly connect from a device **CMYK** source color space to the device **CMYK+White** destination color space.

We will first decompose the problem into two independent components relating to a nonwhite/speciality substrate: material property and embedded color/special effect. The material property, $\vec{f}_m$, influences the image formation with primary colorants, **CMYK**, where the reflectance spectrum of the basic substrate is flat:

$$\vec{f}_m(c,m,y,k) = \psi_c(\lambda | c,m,y,k), \tag{1}$$

where $\psi(\cdot)$ is the relative reflectance spectrum in the logarithmic transformed space, Ψ, and λ is the wavelength of the reflected light. The embedded color/special effect, $\psi_s(\lambda)$, produces a global bias component in Ψ. According to the *Kubelka-Munk* theory, the linearity of the color mixing behavior in Ψ is largely satisfied [13]. As a result, the measured relative reflectance spectrum from the nonwhite/speciality substrate, ψ_a, can be expressed as follows:

$$\psi_a(\lambda) = \psi_c(\lambda | c,m,y,k) + \psi_s(\lambda). \tag{2}$$

Since the white colorant is on the top in *Configuration II*, $\psi_a(\lambda)$ is modified by the layer of white colorant as follows

$$\hat{\psi}_a(\lambda) = g(\psi_a(\lambda)) = g(\psi_c(\lambda) + \psi_s(\lambda)) \tag{3}$$

Where $g(\psi_c(\lambda)) = \psi_c(\lambda)$. The objective is to minimize the perceived color difference between $\psi_c(\lambda)$ and $\hat{\psi}_a(\lambda)$ at each pixel location (u,v):

$$\min_g \ \|\psi_c(\lambda) - \hat{\psi}_a(\lambda)\| \tag{4}$$

Based on the Neugebauer equations and color dot-overlap analysis, we can dichotomize the colorant coverage at each pixel location (u,v) via a probabilistic model [10]:

$$P_c^{uv} = \bigcup_{i=1}^{4} p_i + \bigcup_{i,j=1,i>j}^{4} p_{ij} + \bigcup_{i,j,k=1,i>j>k}^{4} p_{ijk} + p_{4c} \tag{5}$$

$$P_s^{uv} = 1 - P_c^{uv} \tag{6}$$

where P_c is the probability that at least one primary colorant and substrate occur and P_s is the probability with only the presence of substrate. Therefore, Equations 2 and 3 can be rewritten as follows:

$$\psi_a^{uv}(\lambda) = P_s^{uv}\psi_s(\lambda) + P_c^{uv}(\bar{\psi}_c(\lambda) + \psi_s(\lambda)). \tag{7}$$

$$\begin{aligned}\hat{\psi}_a^{uv}(\lambda) &= g(\psi_a^{uv}(\lambda)) \\ &= P_s^{uv} g(\psi_s(\lambda)) + P_c^{uv} g(\bar{\psi}_c(\lambda) + \psi_s(\lambda))\end{aligned} \tag{8}$$

where $\bar{\psi}_c(\lambda)$ is the logarithmic relative reflectance spectrum of the mixed colorants with 100% area coverage. As a result, the original minimization problem in Equation 4 can be expressed as following:

$$\min_{g} \; P_s^{uv}\|g(\psi_s(\lambda))\| + P_c^{uv}\|\bar{\psi}_c(\lambda) - g(\bar{\psi}_c(\lambda) + \psi_s(\lambda))\| \quad (9)$$

where each term can be minimized independently. The first term is minimized if $g(\cdot)$ reaches its minimum, which means that the coverage of white colorant is 100%. As described in the first constraint, the second term is minimized if the white coverage is 100% in *Configuration I* and 0% in *Configuration II*. Thus, the optimal solution of white colorant coverage based on the theoretical analysis is 1 at every pixel location in *Configuration I* and P_s^{uv} at the pixel location (u,v) in *Configuration II*. However, the white colorant is imaged through the digital halftone formation process in practice instead of a uniform layer of white colorant assumed in the *Kubelka-Munk* theory, which results in lower efficiency in blocking $\psi_s(\lambda)$. Hence, the actual white colorant coverage, $w(u,v)$, is

$$w(u,v) = P_s^{uv} + \xi(P_s^{uv}). \quad (10)$$

$\xi(\cdot)$ is experimentally determined with three constraints: $\xi(\cdot) \geq 0$, $\xi(0) = 0$, and $\xi(1) = 0$.

The main source of cost associated while solving the minimization problem (9) in *Configuration II* comes from the second term, $\|\bar{\psi}_c(\lambda) - g(\bar{\psi}_c(\lambda) + \psi_s(\lambda))\|$, and it is controlled by the ratio $\frac{\psi_s(\lambda))}{\bar{\psi}_c(\lambda)}$. As explained in the color rendition constraints, $\psi_c(\lambda)$ can be modified by different strategies in black component replacement. However, since it is impossible to physically separate the colorant and/or special effect from the substrate, the proposed approach is to identify a generic ICC output profile of a substrate with white background and construct a devicelink profile connecting two printer **CMYK** color spaces to enforce different black replacement strategies [14].

Experimental Results

Table 1: Media White Point in CIELAB without white Dry Ink

Paper Index	CIELAB L*	CIELAB a*	CIELAB b*
Paper 1	90.7	-3.5	41.8
Paper 2	73.5	38	27.7
Paper 3	79.7	27.1	-0.1
Paper 4	81.8	-19.3	10.7
Paper 5	76.4	-11.1	-8.9
Paper 6	57.1	10.9	22.9

Six color substrates are tested in the experiment and their *Media White Point* in **CIELAB** color space are listed in Table 1 with hue angles evenly distributed. After depositing 100% coverage of white Dry Ink in one pass, the fabricated *Media White Point* is summarized in Table 2. It clearly demonstrates that the variations in L^* and chroma are significantly reduced. In comparison, while the *Media White Point* of the standard *Grade 1* paper is $(95, 0, -2)$ in the **CIELAB** color space, the b^* value of uncoated smooth paper with optical brightener agent (OBA) could reach beyond -9. Therefore, it can be argued that the fabricated *Media White Points* are largely acceptable except for *Paper 2* with high chroma. *Paper 6* is the darkest paper with brownish tint, of which color is close to a brown package substrate. The fabricated *Media White Point* is nearly neutral with relatively high L^*.

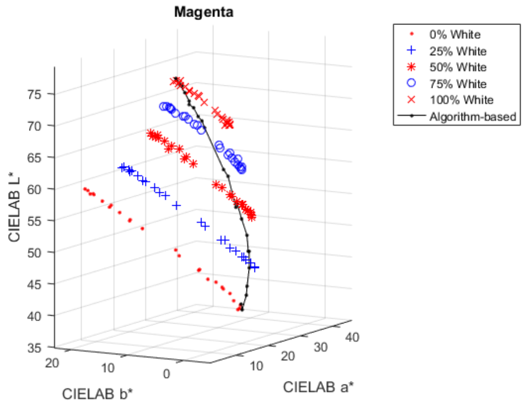

Figure 3. Magenta ramp based on proposed rendition algorithm

Table 2: Media White Point in CIELAB with white Dry Ink

Paper Index	CIELAB L*	CIELAB a*	CIELAB b*
Paper 1	90.6	-0.5	13.1
Paper 2	85.1	14.7	6.4
Paper 3	86.3	12.8	-0.1
Paper 4	87.2	-8.6	3.1
Paper 5	84.8	-5.9	-4.3
Paper 6	79.5	1.3	1.4

Besides the fabricated *Media White Point*, the tone scale smoothness and color gamut are essential to demonstrate the validity of the proposed image rendition algorithm with white Dry Ink under *Configuration II*. Figure 3 shows the magenta ramp with 0%, 25%, 50%, 75%, 100% white Dry Ink coverage and the final magenta ramp when applying the proposed rendition algorithm and Figure 4 illustrates all four primary color ramps on Paper 6 and those on the *Grade 1* standard paper in absolute colorimetry. Figure 5 shows that the resulting primary color ramps printed on silver substrate follow the same trajectories in the a^*-b^* color plane as those on the *Grade 1* standard paper, which indicates that the perceived color rendition between the standard white substrate and silver substrate using the proposed algorithm are very similar. Figures 6 to 9 compare the effectiveness of the proposed image rendition algorithm with white colorant under *Configuration II*. Even in the case of *Paper 2* with the least neutral fabricated *Media White Point*, Figure 8 still shows significant improvement in terms of perceptually acceptable color rendition.

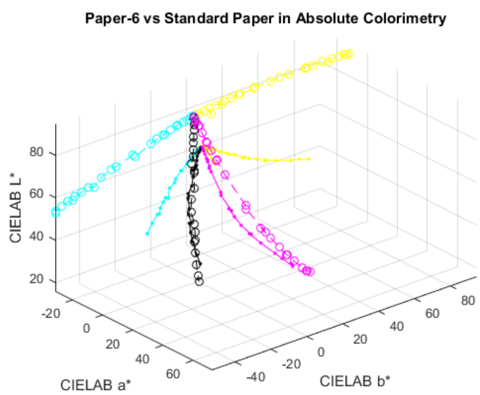

Figure 4. Fabricated primary ramp comparison between paper 6 and standard white substrate in absolute colorimetry

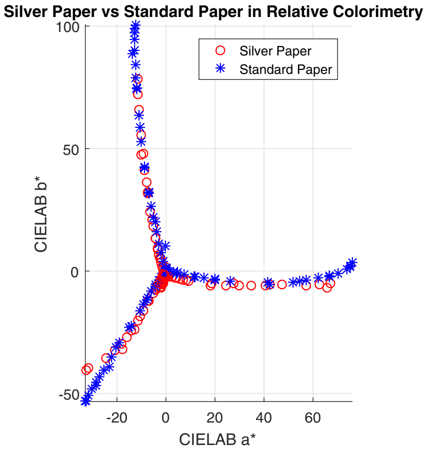

Figure 5. *Fabricated primary ramp comparison between silver paper and standard white substrate in relative colorimetry*

Figure 6. *Digital packaging application comparison on Paper 6 with white colorant in Configuration II*

Figure 7. *Digital packaging application comparison on Paper 6 with white colorant in Configuration II*

Conclusion

An optimized image rendition algorithm with white colorant is devised to reproduce perceptually pleasing color rendition on nonwhite and speciality substrates. A set of substrate with diverse hue and chroma selection is tested to demonstrate the effectiveness of the proposed algorithm. This automatic **CMYK+White** workflow for different white configurations significantly reduces the burden of graphic designers and press operators. Consequently, it will empower digital printing technologies to fulfill new applications such as digital packaging and short-run marketing by incorporating wider selections of nonwhite and speciality substrates.

Figure 8. *Short-run marketing application comparison on Paper 2 with white colorant in Configuration II*

Figure 9. *Short-run marketing application comparison on Paper 4 with white colorant in Configuration II*

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Author Biography

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