Optimization of Constrained Color Correction Matrix to Balance Color and Noise Performance

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ABSTRACT

In digital color imaging, unless a preferred color reproduction is desired, the color of scenes should be reproduced as accurate as possible, on the other side, the intrinsic imaging noise will propagate from the captured image and deteriorate final image quality. Studies have seldom shown how the color accuracy or noise reduction should be emphasized, except [7], but noise is not well described. The noise and color performance should be balanced to get better perceived image quality. In a previous paper, [9] a new comprehensive error metric as a flexible trade-off between color accuracy and noise is proposed. The color correction matrix that converts the device signals to device-independent color signals is analytically optimized by minimizing this comprehensive error metric. By changing the weights for the color and noise components, one can expect a reproduced image that achieves better color accuracy yet more noise, or an image that has worse color accuracy but also less noise, depending on applications and capture conditions. Since no constraints were applied to the color correction matrix, the white-balanced signals may not hold after correction. In this paper, practical linear constraints are exerted onto the matrix and a closed form of the constrained color correction matrix is derived analytically. This approach is much faster with almost the same accuracy as iterative method.

1. INTRODUCTION

The digital color imaging technology has been widely used in everyday life and scientific applications in these days. Usually, these color imaging devices are designed to mimic human visual system in order to obtain trichromatic reproduction of scenes in the visible range [11, 13]. There are two types of trichromatic reproductions, the exact colorimetric color reproduction and the preferred color reproduction. The former tries to exactly reproduce the tristimulus values, i.e. in terms of CIE XYZ or CIELAB values, of objects that represent the human visual response. The latter does not strive for the exact tristimulus values but give an "eye-catching" replication of scenes; however, it is not substantially different from the former and may be achieved with additional transformation reflecting observers' visual preference on natural scene upon the exact colorimetric reproduction. In this paper, for convenience, only the exact colorimetric reproduction will be discussed. The criteria to the evaluation and optimal design of digital imaging pipelines have been usually proposed to minimize the errors caused by transfer device raw signals into the representations of human visual perceptions by CIE. Vora and Trussell's ν-factor [10] characterizes this error with the fundamental subspace difference between the color matching functions of human visual system and the spectral sensitivity functions of digital imaging devices. It has been proven that even the ν-factor is perfect (when it achieves one), the imaging noise which is intrinsic in capture process will deteriorate the reproduction performance drastically, and due to physical limitation of color filter fabrication, this perfect condition cannot be obtained really. To consider noise effect, Sharma and Trussell's *Figure of Merit* (FOM) [2] combines the signal-independent Gaussian noise and color performance together, and the *Unified Measure of Goodness* (UMG) [5] incorporates the signal-dependent Poisson-distributed photon-noise into the formulation. These efforts have been very successful in the design of colorimetric cameras for artworks archiving and provide tools for the design of next-generation consumer digital cameras [10, 11]. However it is still unknown how the color accuracy and propagated noise reduction can be balanced under different illumination conditions.

In previous papers, [9] a new index, the *comprehensive error metric* (CEM), which is essentially a flexible combination of color performance and noise performance is proposed. Weight coefficients are assigned to both components and different weight combinations can be used to emphasize either color reproduction accuracy or granulation noise reduction. The color correction matrix that converts the device signals into device-independent color representations is obtained through the minimization of CEM. In this paper, the optimal color correction matrix with constraints is devised analytical. The paper is organized as follows: first the signal pipeline used in the study is described, and the metrics to color and noise performance are proposed, followed by the introduction of comprehensive error metric. The second section describes the minimization of CEM and devises the constrained optimal color correction matrix analytically. Finally the simulated experiment is designed and discussed, and the color and noise performance variation is observed when different weights are chosen.

2. METHOD

Digital cameras reproduce colors of objects to match the human visual perception. Figure 1 illustrates a simplified signal processing pipeline for typical color imaging cameras. The surface reflectance of imaging target (**R**, represented with discrete samplings in visible range) is captured by camera with spectral sensitivity SS under a scene illuminant (e.g. D65), the noise described by a typical noise model [4] is applied to the signal of each channel for each sample. The raw signal is white-balanced and is converted to standard RGB (ITU-R BT. 709) space by a 3-by-3 matrix with 9 variables to be optimally determined. Then the ITU-R BT. 709 RGB values are converted to CIE XYZ under D65 through a defined constant matrix. Finally the CIE XYZ values are transformed to CIELAB under D65.

$$\mathbf{R} \xrightarrow[\substack{D65\text{: Scene}\\ \text{Illuminant}}]{\text{SS}} \begin{bmatrix} R_{raw} \\ G_{raw} \\ B_{raw} \end{bmatrix} \xrightarrow{\textbf{WB}} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \xrightarrow{\textbf{CC}} \begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} \xrightarrow[\substack{\text{sRGB}\rightarrow\\ \text{CIE XYZ}}]{\mathbf{M}_{709}} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \xrightarrow{\textbf{CIE}} \begin{bmatrix} L^* \\ a^* \\ b^* \end{bmatrix}_{D65}$$

Figure 1: Signal processing pipeline in a digital camera, where **R** denotes the reflectance spectra of the imaging objects.

The color reproduction accuracy is defined as the difference between the reproduced CIELAB coordinates and the reference coordinates, which can be described by the following color difference equation:

$$\Delta E = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}} \tag{1}$$

where $\Delta L^* = L^* - L^*_{\text{ref}},\ \Delta a^* = a^* - a^*_{\text{ref}},\ \Delta b^* = b^* - b^*_{\text{ref}}$, and ΔE is the CIE 1976 color difference.

According to the noise propagation rules [1, 6, 9], the final variance-covariance matrix for each imaging sample in CIELAB color space is obtained through the cascade of each individual transformation,

$$\Sigma_{L^*a^*b^*} = [J_F] \cdot [M_{709}] \cdot [M'_{3\times 3}] \cdot [\Sigma_{RGB}] \cdot [M'^T_{3\times 3}] \cdot [M^T_{709}] \cdot [J^T_F] \tag{2}$$

where J_F is the Jacobian matrix [2] from CIE XYZ tristimulus values to CIELAB coordinates, and the device noise is represented with a diagonal symmetric matrix Σ_{RGB} and the final noise in CIELAB is as follows:

$$\Sigma_{RGB} = \begin{bmatrix} \sigma_r^2 & & \\ & \sigma_g^2 & \\ & & \sigma_b^2 \end{bmatrix};\ \Sigma_{L^*a^*b^*} = \begin{bmatrix} \sigma^2_{L^*} & \sigma_{L^*a^*} & \sigma_{L^*b^*} \\ \sigma_{L^*a^*} & \sigma^2_{a^*} & \sigma_{a^*b^*} \\ \sigma_{L^*b^*} & \sigma_{a^*b^*} & \sigma^2_{b^*} \end{bmatrix} \tag{3}$$

In this paper, to consider the different perceived noise levels in lightness and chrominance directions, a noise metric as a weighted average of the RMS noise components is proposed:

$$NM = (\sigma^2_{L^*}/w_L^2 + \sigma^2_{a^*}/w_a^2 + \sigma^2_{b^*}/w_b^2)^{1/2} \tag{4}$$

where w_L, w_a and w_b are weights for luminance L^* and chrominance a^* and b^*.

An objective cost function, or the comprehensive error metric (CEM) is the weighted average of both color metric and noise metric and is generally defined as:

$$\text{CEM}_0 = \sqrt{E\left[(w'_c \cdot \Delta E)^2\right] + E\left[(w'_n \cdot NM)^2\right]} = \sqrt{w_c \cdot E\left[\Delta E^2\right] + w_n \cdot E\left[NM^2\right]} \tag{5}$$

where $w'_c + w'_n = 1,\ w_c = w'^2_c$ and $w_n = w'^2_n$, and $E[\cdot]$ is the expectation operation.

The constraints such as the sum of each row is constant are applied to the color correction matrix to keep the white balanced signal still white balanced after color correction process:

$$\sum_{j=1}^{3} k_{ij} = 1, \text{ for } i\text{=1,2,3} \tag{6}$$

The constrained color correction matrix is then analytically optimized with *Lagrange multipliers*. In general, to find values that minimize

$$z = F(x_1, x_2, \cdots, x_n) \tag{7}$$

subject to the following *k* restrictions,

$$G_i(x_1, x_2, \cdots, x_n) = 0, \quad i = 1, \cdots, k \tag{8}$$

In this case the unrestricted minimum of the function

$$Z = F(x_1, x_2, \cdots, x_n) - \sum_{i=1}^{k} \pi_i G_i(x_1, x_2, \cdots, x_n) \tag{9}$$

is found, where the π_i, *Lagrange multipliers*, are unspecified constants to be determined later. It is assumed that values of π_i can be found so that the unrestricted minimum solution satisfies the restrictions. The *n* equations resulting from the vanishing of the *n* partial derivatives of this expression at a minimum are solved for $\{x_i\}_{i=1}^{n}$ in terms of $\{\pi_i\}_{i=1}^{k}$. These values are substituted into the *k* expressions $G_i(x_1, x_2, \cdots, x_n) = 0$, and the resulting *k* equations in $\{\pi_i\}_{i=1}^{k}$ are solved for $\{\pi_i\}_{i=1}^{k}$. Reference [9] already described unconstrained optimization of color correction matrix, and then Equations (6)-(9) are implemented analytically.

3. RESULTS

In this section, a camera with the spectral sensitivity functions as shown in Figure 2 is used to capture the Macbeth ColorChecker under CIE illuminant D65. Figure 3 shows how the average color difference and noise metric changes when the noise weight changes from 0 to 1. When the weight for noise component grows, the average color difference becomes larger, while the average noise metric reduces gradually. They are in a obvious tradeoff. For two specific weight combinations, the captured images are shown in Figures 4 and 5. Much granulation noise can be observed on the reproduced image shown in Figure 4, since no weight has been assigned to noise component. However noise appears much less in Figure 5, since noise component is weighted much more than that in Figure 4. It may be carefully observed that the color in Figure 5 shifts from the color in Figure 4, which is observed to be closer to the original Macbeth ColorChecker.

4. CONCLUSIONS

In this paper, a comprehensive error metric which is a combination of color difference and noise metric is proposed. An analytical approach is adopted to obtain a close-form of the optimal color conversion matrix with constraints, and the color and noise values for each patch and for all patches can be calculated. Depending on the weights chosen for color and noise components, either better color reproduction accuracy yet more noise, or washed-out color reproduction but less noise can be achieved under varieties of illumination conditions. The compromise between color and noise components is verified with a simulated experiment. In reality, the human visual system may not interpret the color and noise separately as shown in this paper, however, the methodology may be used to derive similar results when a metric more appropriate than the current CEM is proposed.

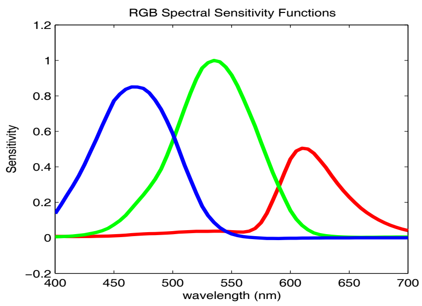

Figure 2: The camera spectral sensitivity functions used in the simulated experiment.

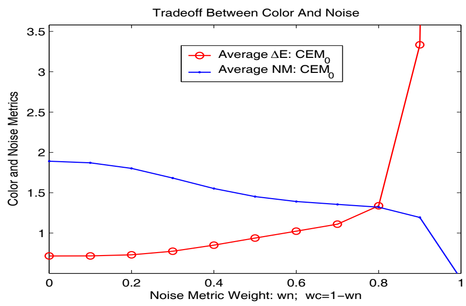

Figure 3: Average color difference and noise metric vary according to the selection of color and noise weights.

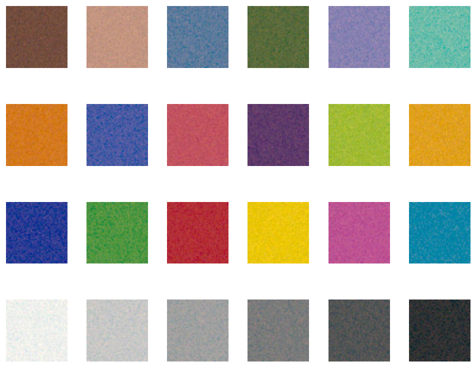

Figure 4: Reproduced Macbeth ColorChecker when w_c=1.0 and w_n=0.0.

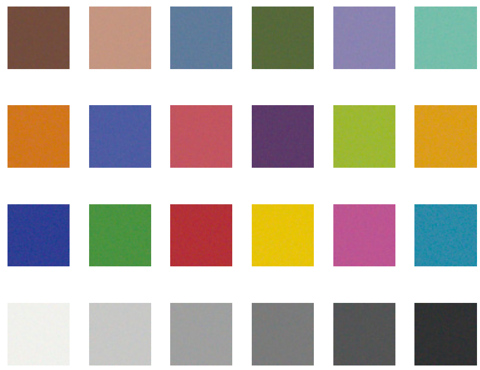

Figure 5: Reproduced Macbeth ColorChecker when w_c=0.2 and w_n=0.8.

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