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Using the Matrix R Method for Spectral Image Archives

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ABSTRACT

Conventional color digital cameras can only produce three-channel images so they are limited when high-quality color reproduction is required. Alternatively, spectral imaging increases the number of channels and can retrieve spectral reflectance for each scene pixel. The major goal of spectral imaging is high spectral accuracy, while it may also be beneficial to achieve high colorimetric accuracy for a specific viewing condition. A new spectral reconstruction method, called the matrix R method, was developed to achieve both goals simultaneously. An experiment was performed to test this method. The experimental results have been very promising; average color difference for all targets evaluated was about 1.3 CIEDE2000 and 2.0% RMS. These results suggest that this new method is a promising method for building digital image databases for museums, archives and libraries.

1. INTRODUCTION

There is an urgent need to build digital image databases with adequate colorimetric accuracy for museums, achieves and libraries. Conventional color acquisition devices capture spectral signals by acquiring only three samples, critically under-sampling spectral information and suffering from metamerism. Alternatively, spectral devices increase the number of samples and can reconstruct spectral information for each scene pixel. Retrieving spectral reflectance of each pixel is highly desirable, since spectral information can be used to render images under any illuminant and for any observer. The advantages of spectral imaging have been summarized by Berns.[1] Spectral imaging has been widely developed over the last ten years for archiving cultural heritage at a number of institutions worldwide. In our laboratory, three spectral acquisition systems have been developed and tested for archiving digital images.[2]

The major goal of spectral imaging is high spectral accuracy, though it would be beneficial to also achieve high colorimetric accuracy for a specific illuminating and viewing condition. A new spectral reconstruction method, called the matrix R method, was developed to achieve both goals simultaneously. This method is a learning-based reconstruction, that is to say, a calibration target is required to build the camera model. Spectral reflectances of the target are estimated from camera signals using the linear least squares method (LLS) to minimize the root-mean-square (RMS) error. Concomitantly, tristimulus values of the target are predicted from the same camera signals using nonlinear optimization to minimize color differences for a defined illuminant and observer. Because the colorimetric optimization is nonlinear, the estimated spectra have dissimilar tristimulus values.

In 1953, Wyszecki hypothesized that a spectrum can be decomposed into a fundamental stimulus and a metameric black.[3] A method for performing the decomposition was developed by Cohen[4] and used by Fairman[5] for correcting parameric pairs. This principle of decomposition can be used to combine the advantages of the two optimizations described above, the topic of this publication, or as a method of combining images captured at multiple resolutions.[6]

2. THEORY

The matrix R method combines the benefits of spectral and colorimetric transformations. These two transformations will be introduced first, followed by a discussion of the matrix R method.

A spectral transformation can be derived to convert multi-channel camera signals, $\mathbf{D}$, to estimated spectral reflectance factor, $\hat{\mathbf{R}}$, shown in Eq. (1). The transformation matrix, $\mathbf{T}$, is derived using the linear least squares method to minimize the RMS error between measured and predicated spectral reflectance of a calibration target, shown in Eq. (2):

$$\hat{\mathbf{R}} = \mathbf{TD} \tag{1}$$

$$\mathbf{T} = \mathbf{R} \times PINV(\mathbf{D}) \tag{2}$$

where $PINV(\mathbf{D})$ means pseudoinverse of matrix $\mathbf{D}$. For example, for a six-channel camera and the use of a GretagMacbeth ColorChecker DC as the calibration target, the measured spectral reflectances, $\mathbf{R}$, is a (n×240) matrix (n is the number of wavelengths) and the corresponding camera signals, $\mathbf{D}$, is a (6×240) matrix, so the resulting transform matrix, $\mathbf{T}$, is a (n×6) matrix. This simple spectral reconstruction method will be referred as the pseudoinverse method.

A second transformation can be derived to convert camera signals to tristimulus values. Similar to commercial profiling software, a camera profile was generated by first linearizing the camera signals to photometric data, followed by a matrix multiplication. The camera signals for each channel were corrected using the gain-offset-gamma (GOG) model, commonly used to characterize CRT displays,[7] and then converted to tristimulus values:

$$\mathbf{D}_{\mathbf{L,i}} = (\alpha_i \mathbf{D}_\mathbf{i} + \beta_i)^{\gamma_i} \tag{3}$$

$$\mathbf{N}_\mathbf{c} = \mathbf{M}\mathbf{D}_\mathbf{L} \tag{4}$$

where $\mathbf{D}_{\mathbf{L,i}}$ is the linearized camera signals for the ith channel, α_i, β_i and γ_i are the gain, offset and gamma values for each ith channel, and $\mathbf{N}_\mathbf{c}$ is a tristimulus vector. The parameters of the GOG model and transformation matrix, $\mathbf{M}$, are optimized to minimize the weighted sum of mean and maximum CIEDE2000 color difference between measured and predicted tristimulus values of the calibration target for a defined illuminant and observer. For a three-channel camera, $\mathbf{M}$ is a (3 × 3) matrix, while for an m-channel camera, $\mathbf{M}$ is a (3 × m) matrix. Finally, the matrix R method is used to combine both the spectral and colorimetric transformations.

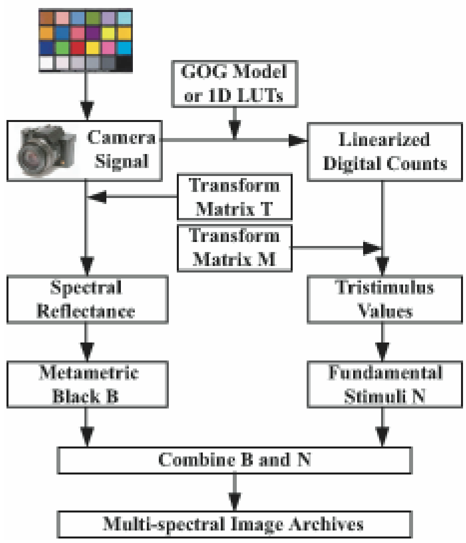

Figure 1: Flowchart of Matrix R

As illustrated in the left branch of the flowchart, the multi-channel camera signals are converted to spectral reflectance, which in turn are used to calculate metameric blacks. On the right branch of the flowchart, the multi-channel camera signals are linearized and transformed to tristimulus values, from which the fundamental stimuli are calculated. The hybrid spectral reflectance factors, $\hat{\mathbf{R}}_\mathbf{c}$, are calculated combining the metameric black and fundamental stimulus:

$$\hat{\mathbf{R}}_\mathbf{c} = \mathbf{A}(\mathbf{A}'\mathbf{A})^{-1}\mathbf{N}_\mathbf{c} + \left(\mathbf{I} - \mathbf{A}(\mathbf{A}'\mathbf{A})^{-1}\mathbf{A}'\right)\hat{\mathbf{R}} \tag{5}$$

where $\mathbf{A}$ is a (n × 3) matrix of ASTM weights applicable to the defined illuminant and observer pair and $\mathbf{I}$ is an (n × n) identity matrix (n counts wavelength). The matrix R method combines the benefits of both spectral and colorimetric transformations, so the method can provide high accuracy both spectrally and colorimetrically.

3. EXPERIMENTAL

The matrix R method was tested using a Sinarback 54H color-filter-array (CFA) digital camera. The camera has a Kodak KAF-22000CE CCD with a resolution of 5440 × 4880 pixels. The camera was modified in two ways. The built-in infrared (IR) cut-off filter in the camera was removed and replaced with a Unaxis visible bandpass filter. Second, a filter slider was used to collect two sequential sets of RGB images, producing six-channel camera images. In each position, there was an optimized[2] glass absorption filter. Coincidentally, the combination of the Unaxis and one of two glass filters had almost the same spectral transmittance as the Sinarback built-in IR cut-off filter, so one of the RGB images simulated a production camera.

The camera was set up perpendicular to the target. The lighting system included two Broncolor HMI F1200 sources, placed 45° on either side of the sample plane. A GretagMacbeth ColorChecker DC was used as the calibration target, and the other targets listed in Table 1 were used as verification targets. The spectral reflectances of these targets were measured using a GretagMacbeth SpectroEye bidirectional spectrophotometer. Following flat fielding and image registration, transformations were derived as described in Eqs. (1) – (5).

Table 1: Lists of the name, abbreviation and number of patches for each target

No.	Name	Abbreviation	Number of Patches
1	GretagMacbeth ColorChecker DC	CCDC	240
2	GretagMacbeth ColorChecker	CC	24
3	ESSER TE221 scanner target	ESSER	264
4	A custom target of Gamblin conservation color	Gamblin	60
5	An acrylic-medium blue target	Blue	56
6	Two small oil paintings	Fish & Flower	22
7	All the targets	All targets	666

4. RESULTS

Figure 2 illustrates the colorimetric performance for both the production and modified cameras for illuminant D65 and the 1931 standard observer. For the production camera, Eqs. (3) and (4) were used. For the modified camera, two methods were evaluated, the pseudoinverse [Eqs. (1) and (2)] and the matrix R [Eqs. (1) – (5)] methods. As expected, the modified camera demonstrates better colorimetric accuracy than the production camera for both the calibration and verification targets since it uses more channels. Moreover, the matrix R method achieved even higher colorimetric accuracy than the pseudoinverse method. It means that the nonlinear optimization is an effective technique to improve colorimetric performance, and the matrix R method takes advantage of this technique efficiently.

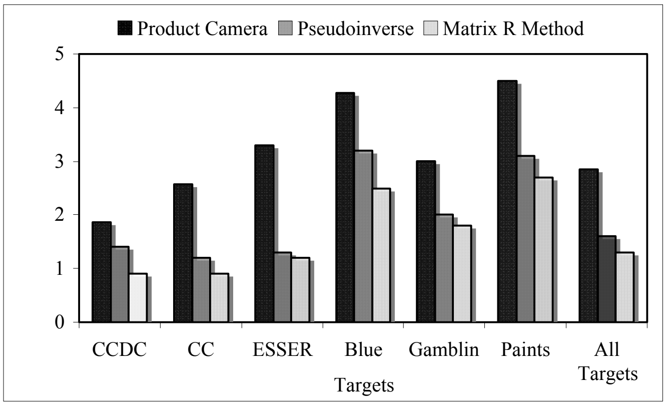

Figure 2: Comparison of average color difference

Table 2: Performance matrices comparing a conventional small aperture in-situ spectrophotometer with the modified Sinarback 54H spectral image using the matrix R method

Target	CIEDE2000 (D65, 2°)			RMS (%)			Metameric Index (D65 – Horizon, CIEDE2000)		
	Mean	Max.	Std. Dev.	Mean	Max.	Std. Dev.	Mean	Max.	Std. Dev.
CCDC	0.9	3.2	0.7	1.5	3.9	0.6	0.7	7.6	1.0
CC	0.9	2.3	0.6	1.6	2.6	0.6	0.4	2.0	0.5
ESSER	1.2	4.1	0.8	1.9	6.8	1.0	0.5	5.1	0.6
Blue	2.5	7.8	1.5	3.5	10.0	2.1	1.4	7.3	1.6
Gamblin	1.8	4.0	0.9	2.8	8.5	1.5	0.6	2.4	0.6
Fish & Flower	2.7	6.8	1.8	2.9	8.7	1.7	1.1	8.9	1.9
All Targets	1.3	7.8	1.0	2.0	10.0	1.2	0.7	8.9	1.0

Table 2 summarizes the performance matrices of the matrix R method, including color difference, % RMS error and a metameric index that consists of a parameric correction[5] for illuminant D65 and color difference under Horizon illuminant. (Horizon is a popular light source in museums.) For the calibration target, the CCDC, the average performance was about 0.9 ΔE_{00} and 1.5% RMS. Because of the similarity of spectral properties of ColorChecker and ESSER to those of the calibration target, their spectral and colorimetric performances are comparable. However, due to broad spectral variability of the paint targets, their average performances were slightly poorer than those of the three previous targets. Figure 3 shows the average spectral differences and one minus the correlation coefficient for the CCDC and the blue targets. Both targets show poor correlation between measured and predicated reflectances at short wavelengths because of low spectral sensitivity of the camera and low spectral power of the taking illuminant. The average spectral difference curve for the blue target varied across wavelength: this target is quite different spectrally from the calibration target. For example, the long wavelength reflectance "tail" of cobalt blue is difficult to match unless the calibration data includes a colorant with similar spectral properties.

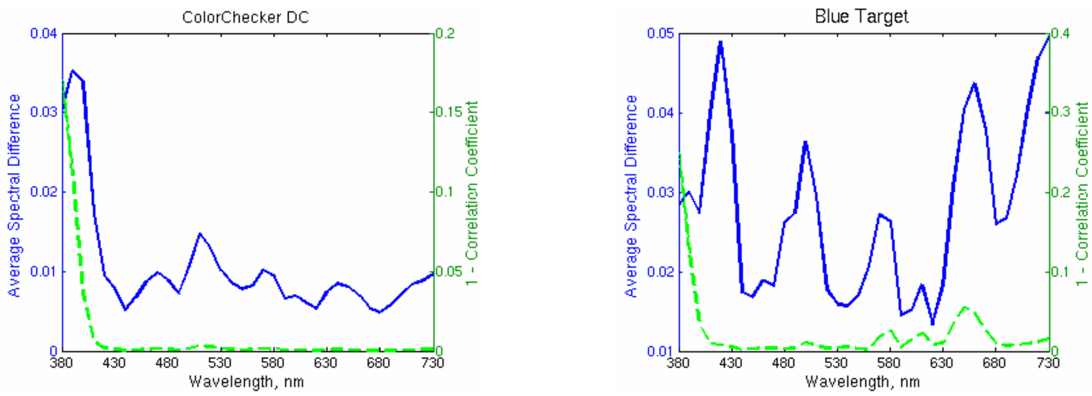

Figure 3: Average spectral difference (left axes, solid lines) and one minus correlation coefficient (right axes, dashed lines) for GretagMacbeth ColorChecker DC and the blue target.

5. CONCLUSIONS

The image acquisition system, a modified Sinarback 54H digital camera coupled with two absorption filters, is a practical spectral system that can achieve both high spectral and colorimetric accuracy when images are processed using the method described in this paper. The matrix R method combines the benefits of both spectral imaging and colorimetric imaging, and is a very promising method for building image databases for museums, archives and libraries.

ACKNOWLEDGMENTS

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