Spectral Estimation Using Trichromatic Digital Cameras

Francisco H. Imai and Roy S. Berns

Munsell Color Science Laboratory
Rochester Institute of Technology

Abstract

In this paper we present an alternative way to capture multi-spectral images using a conventional trichromatic digital camera combined with either absorption filters or multi-illumination. The goal in this research has focused on reducing the cost and complexity of the image acquisition system while preserving its colorimetric and spectral accuracy. This paper describes this new paradigm and summarizes recent research results.

Keywords: colorimetry, multi-spectral image capture, metamerism, principal component analysis.

1. LIMITATIONS OF CONVENTIONAL IMAGE CAPTURE

Conventional graphic image capture involves the concatenation of two reproduction processes, photography and scanning. The photographic process, as an input device, is inherently noncolorimetric. It is impractical to achieve spectral sensitivities with the required large spectral overlap because photographic products consist of a "tripak" where the three layers are stacked one on top of another.[1] Furthermore, the photometric responses of film are nonlinear.[2] As a consequence, large color distortions can result during the image recording process. Furthermore, the variance in match equality due to metamerism can be large, resulting in a dramatic reduction in color quality.

The second stage in conventional graphic image capture is scanning and image editing. The editing can correct the inherent limitations in color photography to some extent. Although scanning often results in additional color distortions, many methods[3,4] have been published to produce highly accurate scanning of photographic media. It is possible to use a conventional scanner as a colorimetric device. Thus, the colorimetric coordinates of the photographic material can be determined accurately. Color editing has also been used to minimize the color distortions resulting from the photographic process.

In summary, it is impossible to accurately capture original objects using the conventional techniques of photography and scanning and this problem is critical in processes such as the imaging of artwork for archiving and reproduction purposes.

2. MULTI-SPECTRAL IMAGE CAPTURE

It is well known that the only way to assure a color match for all observers across changes in illumination is to achieve a spectral match. Developing a spectral-based color reproduction system requires a spectral analysis in which the spectral properties of each image element must be known. Two approaches can be taken to estimate the spectral properties of scene elements.

The first, and most direct, method is to increase the sampling increment above the traditional three channels. Conceptually, this is equivalent to using a spectrophotometer sampling the visible spectrum at constant bandpass and wavelength interval rather than a colorimeter or densitometer. Although spectrophotometer accuracy requirements have not been defined by the CIE,[5] tristimulus errors are assumed to be negligible using 5 nm wavelength increment and bandpass. Ideally, one would want to sample every 5 nm with a 5 nm triangular bandpass throughout the visible spectrum. This corresponds to 61 channels. Obviously, it is necessary to reduce the number of channels. One should be able to decrease the sampling increment without a significant loss of spectral information because of the absorption characteristics of both man-made and natural colorants. Spectral analyses of colored stimuli using linear modeling techniques typically result in less than ten eigenvectors.[6-8] Five to eight basis vectors seem to be sufficient for an accurate spectral reconstruction of artwork. Thus one should be able to greatly reduce the number of channels from 61.

The second method is to perform an *a priori* spectral analysis enabling either the optimal filter design[9-12] or a more accurate spectral reconstruction of the subsampled stimulus. This method is used routinely in photography in the conversion between integral and analytical density. Because a given photographic material uses a single set of cyan, magenta, and yellow dyes, three eigenvectors based on the absorption spectra will define the entire spectral gamut. Thus, a three channel measurement with a logarithmic response (necessary due the linear nature of the absorption spectra, not the reflectance or transmittance spectra) can be used to estimate the spectral properties of photographic images. This technique has been used to build high-accuracy device profiles for graphic arts scanners.[4] Considerable research has been performed in determining the minimum number of channels,[8,10,12-26] their spectral response, and how the multichannel information is used for spectral estimation. Issues include colorimetric accuracy, spectral accuracy, and noise propagation. For example, research at the Munsell Color Science Laboratory[13-16] has focused on using a typical monochrome digital camera (Kodak Professional DCS 200m) in conjunction with a set of seven readily available filters from Melles Griot.

The method of spectral estimation was based on an eigenvector analysis of a subset of the Munsell Book of Color sampling this system's color gamut. The first five eigenvectors were used. At first, a least-square (5 x 7) matrix, to transform the 7 camera signals into 5 estimates of the scalar coefficients corresponding to eigenvectors, is computed using the sample spectral reflectances. This calculated matrix is used for subsequent spectral reconstruction from the camera signals. In this experiment[13] using a monochrome camera and a set of 7 interference filters, the colorimetric performance for the spectral reconstruction had an average ΔE^*_{ab} of 5.1 using principal component analysis. After optimizing the spectral estimation for the camera signals an average ΔE^*_{ab} of 4.0 was obtained.

Since each of the optical filter spectral transmittance curves has a similar shape, one can think of the image collection, prior to detection, as a spectral filtering followed by a sampling operation. This view of image acquisition lends itself to spectral reconstruction via interpolation schemes such as cubic-spline[10] and modified-discrete-sine-transformation (MDST) interpolation.[22] The spectral reconstruction by principal component analysis presented better performance than these interpolation techniques and this result was expected given the spectral width of the seven channels limiting the high spectral-frequency components in the detected signal. However, König and Praefcke[27] found that certain interpolation techniques such as the smooth inverse may produce acceptable results.

The number of available bits also has a large effect on accuracy. Dynamic range, sampling rate, and spatial resolution should also be analyzed for artwork imaging. Artwork viewers are sensitive to changes in bit-depth for color images[28] and a 10 bit quantization has been found to yield acceptable results.

Multi-spectral image capture has been used by England's National Gallery to accurately record the colorimetric values (CIELAB) of paintings for archival and conservation purposes.[31] The MARC camera in the VASARI project produced results of ΔE^*_{ab} 2 to 3 for the GretagMacbeth ColorChecker depending on the lighting used. However, this system was optimized for colorimetric performance and does not estimate spectral data.

3. PROBLEMS IN TRADITIONAL MULTI-SPECTRAL IMAGE CAPTURE USING INTERFERENCE FILTERS

König and Praefcke[29] analyzed practical problems of designing and operating a multi-spectral scanner using a set of narrow-band interference filters and a monochrome CCD camera, the most common configuration for multi-spectral image capture. When using interference filters for image acquisition, a major problem is caused by the transmittance characteristic of the filters that depends on the angle of incidence. For example, in order to image a painting with horizontal dimensions of 1 meter with a distance of 2 meters between the painting and the filter, there is angle of incidence ~14° for points in the extremities. Simulations[29] have shown that this causes color differences of 2 ΔE^*_{ab} units in relation to the image obtained at 0° angle of incidence. Another problem is that the surfaces of the interference filters are not exactly coplanar resulting in spatial shift and distortion of the captured image. We also need to consider that there are inter-reflections caused by reflections between the spectral filters and the original image, and between the interference filters and the camera lens. These technical problems make it unrealistic and impractical for image acquisition using interference filters, for example in museums, without a considerable degree of expertise in multi-spectral imaging.

4. SPECTRAL ESTIMATION USING MULTI-ILLUMINANT OR MULTI-FILTER TRICHROMATIC IMAGE CAPTURE

Conventional image capture, both chemical and digital, is largely trichromatic. Three channels are used to record color information. The trichromatic systems should have spectral responsivities that are linearly transformable from color matching functions (sometimes called the Luther condition). Essentially, these trichromatic-based systems are a subset of multi-channel-based systems.

We believe that a conventional trichromatic digital camera combined with either absorption filters or different light sources can provide an alternative way to capture multi-spectral images for artwork paintings. The pigments used in paintings have smooth spectral curves that do not require many channels to perform a spectral reconstruction. A multiple-of-three channels through either multi-filter or multi-illuminant approach can make the image acquisition easier than the traditional monochrome camera and interference-filter-based multi-spectral acquisition because it can provide three channels per imaging shot. The multi-illuminant/filter trichromatic image capture also avoids the inherent problems related to imaging using interference filters. This trichromatic camera approach also has relatively low cost since the cost-performance relation of commercial trichromatic digital cameras has decreased rapidly. Having the conventional trichromatic signal recorded in the trichromatic-based multimedia imaging devices also makes it easier to display the image on a CRT through appropriate color management. Although it was more difficult for wide-band systems to address metamerism due to spectral mismatches, the residual spectral and colorimetric errors can be minimized using iterative methods or non-linear methods.

As in the traditional multi-spectral image capture, the spectral reflectance of each pixel of a painting can be estimated using *a priori* spectral analysis with direct measurement and imaging of color patches to establish a relationship between the digital counts and spectral reflectance.

A set of spectral reflectances, **r**, is measured and then the corresponding set of eigenvectors, **e**, is calculated by principal component analysis. Then, the set of eigenvalues, α, corresponding to the eigenvectors, **e**, is calculated using the spectral reflectances, **r**. A relationship between eigenvalues and digital counts, **C** obtained using trichromatic camera and absorption filters can be established by the equation

$$\mathbf{A} = \alpha \mathbf{C}^{\mathbf{T}}[\mathbf{C}\mathbf{C}^{\mathbf{T}}]^{-1} \qquad (1)$$

where $\mathbf{T}$ denotes transpose matrix.

The matrix **A** can be used to calculate the eigenvalues, α, from digital counts to reconstruct the spectral reflectance.

5. EXPERIMENTS

In our experiments, we considered two different imaging systems and three targets. For imaging systems, we used a high-resolution trichromatic IBM PRO\3000 digital camera system (3,072 x 4,096 pixels, R, G, B filter wheel, 12 bits per channel that has a 45°/0° imaging configuration using tungsten illumination) and a Kodak DCS560 digital camera (3,040 x 2,008 pixels, built-in R, G, B array sensors, 12 bits per channel). Both IBM PRO\3000 and Kodak DCS560 digital camera systems provide linear TIFF data files. The spectral sensitivities of the IBM PRO\3000 digital camera system were measured, as well as the spectral radiant power of the illuminant used in this imaging system. A GretagMacbeth ColorChecker and two paintings as well as their corresponding painted patches were imaged. One of the paintings and its corresponding painting patches were generated using a mixture of GALERIA acrylic paints produced by Winsor & Newton (Cadmium Red Hue, Permanent Green Deep, Ultramarine, Cerulean Blue Hue, Permanent Magenta, Cadmium Yellow Medium Hue). The acrylic painted patches were made with mixtures of two and three colorants generating 218 patches. The other paint and the corresponding painted patches were generated using post-color paints (Cerulean Blue and Rose Violet made by Sakura, Ultramarine, Permanent Yellow, Sap Green and Black made by Pentel). The post-color painted patches were made with mixtures of two colorants generating 105 patches. The paint produced using post-color paints, as well as its corresponding patches were coated with Krylon Kamar Varnish that is a non-yellowing protection.

Different combinations of trichromatic signals were obtained from either multi-illuminant or multi-filter approaches. In the multi-filter approach we combined, for both imaging systems, trichromatic signals without filtering, the trichromatic signals with a light-blue filter (Kodak Wratten filter number 38), and with very-light-green filter (Kodak Wratten filter number 66) positioned in front of the camera lens. For the multi-illuminant approach, we took advantage of the portability of Kodak DCS560 digital camera, combining different trichromatic signals obtained from targets imaged in the GretagMacbeth SpectraLight II Booth under Illuminants A and filtered tungsten D65.

Performance of principal component analysis in reflectance space.

At first, a statistical analysis was performed so as not to introduce noise into the digitizing system. The spectral reflectances of the GretagMacbeth ColorChecker and the two sets of painted patches were measured and principal component analysis was performed. Table I shows the cumulative contribution for each multiple-of-three first principal components. Table II shows the influence of the number of eigenvectors on the colorimetric accuracy and spectral accuracy of the spectral reconstruction. The colorimetric accuracy is calculated using CIE94 under D50 and the 2° observer.

It is possible to notice from Tables I and II that the performance of principal component analysis depends on the samples. We believe that the use of six eigenvectors to reconstruct spectra is a compromise between accuracy and our aim of reducing the number of channels. Theoretically, using six eigenvectors to reconstruct spectra gives colorimetric error less than a ΔE^*_{94} unit and spectral reflectance rms error less than 1.5% for the samples considered.

Table I. Cumulative contribution of the eigenvectors in reflectance space.

Number of eigenvectors	Cumulative Contribution (%)		
	GretagMacbeth ColorChecker	Painted patches set 1	Painted patches set 2
3	**98.34**	**98.50**	**96.69**
6	**99.80**	**99.83**	**99.60**
9	**99.97**	**99.98**	**99.97**
12	**100.00**	**100.00**	**100.00**

Table II. Influence of the number of eigenvectors in reflectance space used in the spectral reconstruction on the colorimetric and spectral error. ΔE^*_{94} calculated for D50 and the 2° observer.

Number of eigen vectors	GretagMacbeth ColorChecker		Acrylic painted patches		Post-color painted patches	
	Mean ΔE^*_{94}	rms error	Mean ΔE^*_{94}	rms error	Mean ΔE^*_{94}	rms error
3	**3.1**	**0.032**	**4.1**	**0.027**	**3.1**	**0.036**
6	**0.3**	**0.013**	**0.4**	**0.009**	**1.0**	**0.012**
9	**0.2**	**0.007**	**0.1**	**0.004**	**0.08**	**0.003**
12	**0.002**	**0.002**	**0.01**	**0.001**	**0.06**	**0.002**

Estimation of spectral reflectance using simulated digital counts.

One can simulate the digital counts using a camera model given by $\mathbf{C}=(\mathbf{DF})^T\mathbf{Sr}$, where **D** is the camera spectral sensitivities, **F** is the spectral transmittance of the filters, **S** is the illumination spectral power distribution, **r** is the object spectral reflectance, and **C** is the simulated digital counts. The estimation of the spectral reflectance using simulated digital counts gives a performance of the spectral estimation for each target, for each trichromatic signal combination, without introducing noise from the measured digital counts.

The measured spectral sensitivities of IBM PRO\3000 were used to simulate the digital counts. The performance under various trichromatic signal combinations using 6 signals are summarized in the Tables III, IV, V, respectively for GretagMacbeth ColorChecker, acrylic painted patches, and post-color painted patches. ΔE^*_{94} calculation was performed for illuminant D50 and 2° observer. The metameric index was calculated using the Fairman metameric black method, between standard illuminants D50 and A using ΔE^*_{94} in the calculations.[30]

Table III. Spectral reconstruction of GretagMacbeth ColorChecker using 6 eigenvectors and 6 simulated digital counts from IBM PRO\3000 digital camera system.

Results	ΔE^*_{94} (D50, 2°)	reflectance factor rms error	Metameric Index (ΔE^*_{94}) (D50, A)
6 eigenvectors and 6 signals: R,G,B without filter and with light-blue absorption filter			
Average	**0.4**	**0.021**	**0.3**
Std Dev	0.3	0.010	0.4
Max	1.1	0.053	1.8
Min	0.04	0.002	0.04
6 eigenvectors and 6 signals: R,G,B without filter and with very-light-green absorption filter			
Average	**0.2**	**0.018**	**0.2**
Std Dev	0.2	0.007	0.2
Max	0.8	0.038	0.9
Min	0.03	0.002	0.01
6 eigenvectors and 6 signals: R,G,B with light-blue and with very-light-green filters			
Average	**0.4**	**0.022**	**0.2**
Std Dev	0.5	0.009	0.2
Max	1.8	0.038	0.8
Min	0.06	0.002	0.02

Table IV. Spectral reconstruction of the acrylic painted patches using 6 eigenvectors and 6 simulated digital counts from IBM PRO\3000 digital camera system.

Results	ΔE^*_{94} (D50, 2°)	reflectance factor rms error	Metameric Index (ΔE^*_{94}) (D50, A)
6 eigenvectors and 6 signals: R,G,B without filter and with light-blue absorption filter			
Average	**0.3**	**0.014**	**0.3**
Std Dev	0.3	0.007	0.3
Max	1.3	0.031	1.4
Min	0.02	0.002	0.0
6 eigenvectors and 6 signals: R,G,B without filter and with very-light-green absorption filter			
Average	**0.2**	**0.012**	**0.2**
Std Dev	0.2	0.006	0.2
Max	0.7	0.030	1.0
Min	0.01	0.002	0.01
6 eigenvectors and 6 signals: R,G,B with light-blue and with very-light-green filters			
Average	**0.3**	**0.017**	**0.3**
Std Dev	0.2	0.011	0.2
Max	1.1	0.063	0.9
Min	0.04	0.003	0.01

Table V. Spectral reconstruction of the post-color painted patches using 6 eigenvectors and 6 simulated digital counts from IBM PRO\3000.

Results	ΔE*$_{94}$ (D50, 2°)	reflectance factor rms error	Metameric Index (ΔE*$_{94}$) (D50, A)
6 eigenvectors and 6 signals: R,G,B without filter and with light-blue absorption filter			
Average	**0.8**	**0.019**	**0.4**
Std Dev	0.5	0.006	0.3
Max	1.9	0.034	1.0
Min	0.09	0.006	0.01
6 eigenvectors and 6 signals: R,G,B without filter and with very-light-green absorption filter			
Average	**0.9**	**0.017**	**0.4**
Std Dev	0.5	0.006	0.2
Max	2.4	0.030	1.4
Min	0.07	0.005	0.02
6 eigenvectors and 6 signals: R,G,B with light-blue and with very-light-green filters			
Average	**0.8**	**0.016**	**0.3**
Std Dev	0.4	0.005	0.2
Max	2.0	0.029	0.8
Min	0.3	0.004	0.05

It is possible to see from Tables III, IV and V that although the combination of R, G, B signals without filter and with very-light-green filter (Kodak Wratten Filter 66) presented best colorimetric and spectral performance for GretagMacbeth ColorChecker and the painted patches set 1, the spectral and colorimetric performances were not significantly different for various combinations of trichromatic signals.

Table VI summarizes the performance of the spectral reconstruction of GretagMacbeth ColorChecker from 9 simulated digital counts from IBM PRO\3000 digital camera system.

Table VI. Spectral reconstruction of GretagMacbeth ColorChecker using 9 eigenvectors and 9 simulated digital counts from IBM PRO\3000 digital camera system.

Results	ΔE*$_{94}$ (D50, 2°)	reflectance factor rms error	Metameric Index (ΔE*$_{94}$) (D50, A)
9 eigenvectors and 9 signals: R,G,B without filter, with very-light-green and with light-blue absorption filters			
Average	**0.2**	**0.009**	**0.07**
Std Dev	0.1	0.003	0.05
Max	0.4	0.019	0.2
Min	0.04	0.020	0.02

From Tables III and VI it is possible to get much better accuracy increasing the dimensionality, in the simulations.

The results of the simulations show the robustness of this method giving good colorimetric and spectral performance under various trichromatic combinations.

Estimation of the spectral reflectance using measured digital counts

This estimation applies basically the same idea of the linear method using simulated digital counts, but instead of simulated digital counts using a camera model, spectral reflectance is estimated from measured digital counts averaged over each imaged patch.

Table VII summarizes the colorimetric and spectral performances of the spectral reconstruction for three targets (GretagMacbeth ColorChecker and 2 sets of painted patches) using measured digital counts from 2 sets of trichromatic signals (R, G, B without filter and R, G, B with very-light-green Wratten absorption filter number 66), from IBM PRO\3000 digital camera system.

Table VII. Spectral reconstruction using 6 eigenvectors and 6 digital counts (R, G, B without filter and R, G, B with very-light-green Wratten absorption filter number 66) from IBM PRO\3000 digital camera system.

Results	ΔE*$_{94}$ (D50, 2°)	reflectance factor rms error	Metameric Index (ΔE*$_{94}$) (D50, A)
GretagMacbeth ColorChecker			
Average	**2.1**	**0.031**	**0.8**
Std Dev	1.6	0.014	0.5
Max	6.2	0.074	1.5
Min	0.5	0.009	0.03
Acrylic painted patches			
Average	**5.9**	**0.046**	**2.6**
Std Dev	4.5	0.019	1.8
Max	29.7	0.120	9.1
Min	0.5	0.009	0.2
Post-color painted patches			
Average	**1.6**	**0.030**	**2.0**
Std Dev	1.4	0.010	1.2
Max	12.2	0.054	5.7
Min	0.2	0.010	0.2

Comparing the results of the spectral reconstruction summarized in Tables III, IV, V and VII, it is possible to see that the performance was worse in the reconstruction using measured digital counts than the reconstruction using simulated digital counts. This result was expected because of the introduction of noise and typical experimental error.

Table VIII summarizes the comparison of colorimetric and spectral performances of the spectral reconstruction for the acrylic painted patches using measured digital counts from 9 digital counts (R, G, B without filter, R, G, B with very-light-green, and R, G, B with light-blue filter) from IBM PRO\3000 digital camera system.

Table VIII. Spectral reconstruction of GretagMacbeth ColorChecker using 9 eigenvectors and 9 digital counts from IBM PRO\3000 digital camera system.

Results	**ΔE^*_{94} (D50, 2°)**	**reflectance factor rms error**	**Metameric Index (ΔE^*_{94}) (D50, A)**
9 eigenvectors and 9 signals: R,G,B without filter, with very-light-green and with light-blue absorption filters			
Average	**4.6**	**0.034**	**1.4**
Std Dev	3.2	0.014	1.0
Max	14.7	0.088	7.0
Min	0.4	0.008	0.1

Comparing Tables VII and VIII it is possible to notice that increasing the dimensionality from 6 to 9 eigenvectors increased the spectral and colorimetric accuracy of the estimation, but not dramatically.

Table IX summarizes the colorimetric and spectral performances of the spectral reconstruction for three targets (GretagMacbeth ColorChecker and 2 sets of painted patches) using measured digital counts from 6 digital counts (R, G, B without filter and R, G, B with very-light-green Kodak Wratten absorption filter number 66), from Kodak DCS560 camera.

Table IX. Spectral reconstruction using 6 eigenvectors; 6 digital counts (R, G, B without filter and R, G, B with very-light-green Wratten absorption filter number 66) from Kodak DCS560 camera captured under illuminant D65.

Results	**ΔE^*_{94} (D50, 2°)**	**reflectance factor rms error**	**Metameric Index (ΔE^*_{94}) (D50, A)**
GretagMacbeth ColorChecker			
Average	**1.0**	**0.021**	**0.5**
Std Dev	0.8	0.008	0.6
Max	3.0	0.044	3.1
Min	0.2	0.007	0.1
Acrylic painted patches			
Average	**3.5**	**0.047**	**1.3**
Std Dev	4.4	0.035	1.3
Max	36.2	0.082	10.4
Min	0.2	0.005	0
Post-color painted patches			
Average	**2.8**	**0.022**	**1.8**
Std Dev	1.3	0.007	1.2
Max	6.2	0.041	5.1
Min	0.4	0.007	0.1

The spectral reconstruction using signals from the Kodak DCS560 was better than the results obtained from the IBM digital camera system. We believe that the Kodak DCS560 digital camera, being more sensitive to light relative to the IBM PRO\3000 digital camera system, has a wider dynamic range that could increase the signal/noise ratio, giving us better spectral reconstruction. However, it is possible to see that the spectral reproduction worked well for both imaging systems. It shows that this technique of spectral reconstruction can be used either for a camera with R, G, B filter (IBM DCS) or a camera with built-in R, G, B array (Kodak DCS560).

In order to test the performance of the multi-illuminant approach, the signals of the pictures taken using the Kodak DCS560 under illuminant A and D65 are used to reconstruct the spectra of the three targets considered in this research. Table X summarizes the results.

Table X. Spectral reconstruction using 6 eigenvectors; and 6 digital counts (R, G, B under illuminant A and R, G, B under illuminant D65) from Kodak DCS560 camera.

Results	**ΔE^*_{94} (D50, 2°)**	**reflectance factor rms error**	**Metameric Index (ΔE^*_{94}) (D50, A)**
GretagMacbeth ColorChecker			
Average	**1.6**	**0.030**	**1.2**
Std Dev	1.1	0.014	0.9
Max	4.9	0.075	4.1
Min	0.5	0.010	0.2
Acrylic painted patches			
Average	**3.9**	**0.053**	**2.0**
Std Dev	4.5	0.04	2.0
Max	34.5	0.285	12.5
Min	0.6	0.004	0.1
Post-color painted patches			
Average	**2.2**	**0.018**	**0.7**
Std Dev	1.3	0.006	0.6
Max	8.1	0.033	3.0
Min	0.1	0.007	0.04

Tables IX and X show that the performance of the multi-illuminant approach was very similar to the multi-filter approach using the same imaging system and both methods presented reasonable colorimetric and spectral accuracy except for the painted patches set 1 and it also happened with the IBM PRO\3000 digital camera system using multi-filter approach as shown in Table VII. It is possible that the acrylic painted patches, having less smoother spectral curves compared to the spectra of the post-color painted patches, are much more sensitive to noise in the spectral reconstruction using reduced dimensionality. Therefore, there is a strong dependence of the spectral reconstruction performance on the database used for principal component analysis.

6. CONCLUSIONS

An alternative way to capture multi-spectral images using a conventional trichromatic digital camera combined with either absorption filters or multi-illumination was presented. To verify the performance of this system, two different trichromatic camera systems, one with R, G, B filter wheel and the other with built-in R, G, B array, were used to image three different targets constituted by the GretagMacbeth ColorChecker and two sets of painted patches (one made using acrylic paints and the other made using post-color paints). The multi-illuminant and multi-filter approaches were also compared for one of the camera systems. The performance for each approach, target and camera system was evaluated in terms of colorimetric accuracy (mean ΔE^*_{94}), spectral reflectance factor rms error and metameric index.

The experiments were performed in three steps: spectral analysis, spectral reconstruction using simulated camera signals and spectral reconstruction using measured digital counts. The spectral analysis shows the theoretical feasibility of using eigenvector analysis to reconstruct reflectance spectra. The spectral reconstruction using simulated camera signals allows the analyses of the results without signal noise introduced by camera during imaging. The spectral reconstruction using measured digital counts was performed to check the performance of the system in a real condition.

From the results of these experiments we can conclude that:

1. The performance of principal component analysis depends on the particular samples and that the use of six eigenvectors to reconstruct spectra is a compromise between accuracy and cost.
2. Different combinations of various absorption filters do not affect the performance of the spectral reconstruction according to the spectral estimation using simulated digital counts from the IBM PRO\3000 digital camera system.
3. The spectral reconstruction using a trichromatic camera with multi-filter approach from measured digital counts produced similar results in two different digital camera systems, although the Kodak DCS560 digital camera presented better results because of its wider dynamic range increasing signal-to-noise ratio.
4. The spectral estimation using trichromatic signals with multi-filter and multi-illuminant approaches presented similar performance.
5. The performance of spectral estimation depends highly on the samples used for principal component analysis, especially when using measured digital counts which are affected by noise in the imaging system combined with low dimensionality of the estimation. Iterative methods[3,4] can be used to improved the performance. Non-linear methods and alternative spaces other than reflectance space also can be used to improve the spectral estimation using principal component analysis. [32]
6. The estimation of spectral reflectance using trichromatic digital camera and either multi-filtering or multi-illumination presented colorimetric accuracy similar to the traditional approaches using monochrome camera and interference narrow-band filters (e.g. the experiments performed with a Kodak DCS200 camera and seven interference filters,[13] and the MARC camera[31] in the VASARI project).

This method can overcome some inherent problems of imaging using a traditional monochrome camera combined with interference filters, reducing the cost and complexity of the image acquisition system while preserving its colorimetric and spectral accuracy.

The spectral reflectance of each pixel of an image of the GretagMacbeth ColorChecker as well as the images of two paintings were reconstructed using the eigenvectors and 6 by 6 transformation matrix, derived for the patches, that converts digital counts to eigenvalues. The images were displayed on a CRT monitor after appropriate color management and the result was satisfactory.

For a spectral-based color system, besides the multi-spectral acquisition system we need the ability to print using multiple inks. If the printer has a large set of inks from which to choose from, it should be possible to select a subset of inks that achieve a spectral match between original objects and their printed reproductions by multispectral image estimation, ink selection minimizing metamerism, and spectral-based printing models including separation algorithms.[33] The implementation of a proofing system to produce multi-ink prints is in progress.[34] This proofing will allow us to judge the quality of the reproductions using this new method with the quality of traditional graphic reproduction using RGB to CMYK look-up-table and the quality of images generated using conventional narrow-band filtering multi-spectral capture.

Another issue that should be addressed is the inherent low resolution of digital cameras contrasting with the large size of many paintings. One possible solution for this lack of spatial resolution is the creation of a hybrid system that combines a high resolution trichromatic image via scanning of a large-format photograph with a low-resolution multispectral image.[35-36]

The research presented in this paper is part of our effort to integrate multi-spectral imaging capture with multi-ink printing, and also addressing the problems of spatial resolution.

References

1. N. Ohta, "Colorimetric analysis in the design of color films: a perspective", *J. Imaging Sci. Tech*. **36**, 63, (1992).
2. R. W. G. Hunt, *The Reproduction of Colour in Photography, Printing & Television, 5th Ed.* Fountain Press, England, 1995.
2. M. A. Rodriguez and T. G. Stockham, "Producing colorimetric data from densitometric scans", *Proc. SPIE* **1913**, 413, (1993).
4. R. S. Berns and M. J. Shyu, "Colorimetric characterization of a desktop drum scanner using a spectral model", *J. Electronic Imaging* **4**, 360, (1995).
5.Commission Internationale de l'E´clairage (CIE), Colorimetry, 2nd ed., Publ. CIE No. 15-2, Bureau Central de la CIE, Austria, 1986.
6. T. Jaaskelainen, J. Parkkinen and S. Toyooka, "Vector-subspace model for color representation", *J. Opt. Soc. A*, **7**, 725, (1990).
7. L. T. Maloney, "Evaluation of linear models of surface spectral reflectance with small numbers of parameters", *J. Opt. Soc. Am. A*, **10**, 1673, (1986).
8. M. J. Vrhel, R. Gershon and L. S. Iwan, "Measurement and analysis of object reflectance spectra", *Color Res. and Appl.*, **19**, 4, (1994).
9. K. Engelhardt and P. Seitz, "Optimum color filters for CCD digital cameras", *Appl. Opt.*, **32**, 3015, (1993).
10. D. S. Vent, *Multichannel Analysis Of Object-Color Spectra*, M. S. Thesis, Rochester Institute of Technology, 1994.
11. M. J. Vrhel and H. J. Trussel, "Color correction using principal components", *Color Res. and Appl.*, **17**, 328, (1992).
12. H. Haneishi, T. Hasegawa, N. Tsumura and Y. Miyake, "Design of color filters for recording artworks," *Proc. IS&T's 50th Annual Conference,* 369, (1997).
13. P. D. Burns, *Analysis of image noise in multispectral color acquisition*, Ph.D. Dissertation, Rochester Institute of Technology, 1997.
14. P. D. Burns and R. S. Berns, "Error propagation in color signal transformations", *Color Res. Appl.* **22**, 280, (1997).
15. P. D. Burns and R. S. Berns, Modeling colorimetric error in electronic image acquisition, *Proc. of Optics and Imaging in the Information Age, IS&T*, 147, (1997).
16. P. D. Burns and R. S. Berns, "Analysis of multispectral image capture", *Proc. 4th IS&T/SID Color Imaging Conference*, 19, (1996).
17. M. L. Simpson and J. F. Jansen, "Imaging colorimetry: a new approach", *Appl. Opt.*, **30**, 4666, 1991.
18. K. Martinez, J. Cupitt and D. Saunders, "High resolution colorimetric imaging of paintings", *Proc. SPIE* **1901**, 25, (1993).
19. L. T. Maloney, "Evaluation of linear models of surface spectral reflectance with small numbers of parameters", *J. Opt. Soc. Am. A* **10**, 1673, (1986).
20. H. J. Trussell, "A review of sampling effects in the processing of color signals", *Proc. 2nd IS&T/SID Color Imaging Conf.*, 26, (1994).
21. T. Keusen, *Optimierta Auswertung Multispektraler Abtastsignale*, DfwG-Tagung, Illmenau, 1994.
22. T. Keusen and W. Praefcke, "Multispectral color system with an encoding format compatible to conventional tristimulus model", *Proc. IS&T/SID 3rd Color Imaging Conf.*, 114, (1995).
23. H. Maitre, F. Schmitt, J Crettez, Y. Wu and J. Y. Hardeberg, "Spectrophotometric image analysis of fine art paintings", *Proc. 4th IS&T/SID Color Imaging Conf.*, 50, (1996).
24. A. Abrardo, V. Cappelline, M. Cappelline and A. Mecocci, "Art-works colour calibratrion using the VASARI scanner", *Proc. 4th IS&T/SID Color Imaging Conf.*, 94, (1996).
25. H. J. Trussell, "A review of sampling effects in the processing of color signals", *Proc. 2nd IS&T/SID Color Imaging Conf.*, 26, (1994).
26. J. Cuppit, D. Saunders and K. Martinez, "Digital imaging in European museums", *Proc. SPIE* **3025**, 144, (1997).
27.König, F. and Præfke, W., A multispectral scanner, *Proc. CIM'98 Colour Imaging in Multimedia*, University of Derby, 63 (1998).
28. M. Ester, Image quality and viewer perception, Leonardo Digital Image – Digital Cinema, Supplemental Issue, 51, (1990).
29. König, F. and Præfke, W., The practice of multispectral image acquisition, in *International symposium on electronic capture and publishing, Proc. SPIE* **3409**, 34, (1998).
30. H. S. Fairman, Metameric correction using parametric decomposition, *Color Res. Appl.*, **12**, 261, (1997)
31 Saunders, D., Cupitt, J., *Image processing at the National Gallery: The VASARI Project*, National Gallery technical bulletin, **14**, 72 (1993).
32 F. H. Imai and R. S. Berns, A comparative analysis of spectral reflectance reconstruction in various spaces using a trichromatic camera system, *Proc. of The Seventh Color Imaging Conference: Color Science, Systems, and Applications: Putting it all together*, in press, (1998).
33 D.-Y. Tzeng and R. S. Berns, "Spectral-Based Ink Selection for Multiple-Ink. Printing I. Colorant Estimation of Original Object", *Proc. 6th IS&T/SID Color Imaging Conf.*, 106, (1988).
34 M. Rosen, Lippmann2000: A spectral image database under construction, Proc. of the International Symposium on Multispectral Imaging and Color Reproduction for Digital Archives, in press, (1999).
35 R. S. Berns, F. H. Imai, P. D. Burns and Di-Y. Tzeng, Multi-spectral-based color reproduction research at the Munsell Color Science Laboratory, *Proc. of SPIE Europto Series*, Vol. **3409**, pg. 14, (1998).
36 F. H. Imai and R. S. Berns, High-resolution Multi-Spectral Image Archives: A Hybrid Approach, *Proc. of The Sixth Color Imaging Conference: Color Science, Systems, and Applications*, 224, (1998).