Multi-spectral Image Acquisition and Spectral Reconstruction using a Trichromatic Digital Camera System associated with absorption filters
PART VIII General Discussion

Francisco H. Imai
Munsell Color Science Laboratory, Rochester Institute of Technology

Abstract

This part describes the results obtained in the simulations and experiments reported in the previous sessions of this report.

A) Statistical comparison of the principal component analysis in various spaces

The cumulative contributions of the eigenvectors in each space are summarized for multiple-of-three numbers of eigenvectors in Tables I to III.

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

Number of eigenvectors	Cumulative Contribution (%) for Macbeth Color Checker	Cumulative Contribution (%) for 147 painted patches	Cumulative Contribution (%) for 105 painted patches
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. Cumulative contribution of the eigenvectors in K/S space.

Number of eigenvectors	Cumulative Contribution (%) for Macbeth Color Checker	Cumulative Contribution (%) for 147 painted patches	Cumulative Contribution (%) for 105 painted patches
3	**98.86**	**99.18**	**98.42**
6	**99.92**	**99.92**	**99.98**
9	**99.99**	**99.99**	**100.00**
12	**100.00**	**100.00**	**100.00**

Table III. Cumulative contribution of the eigenvectors in the new empirical space.

Number of	Cumulative Contribution	Cumulative Contribution	Cumulative Contribution

eigenvectors	(%) for Macbeth Color Checker	(%) for 147 painted patches	(%) for 105 painted patches
3	98.49	98.57	97.48
6	99.84	99.85	99.70
9	99.97	99.98	99.98
12	100.00	100.00	100.00

From Table I to III we can observe that by statistical point of view, the eigenvectors in reflectance, K/S and new empirical spaces presented very similar performances. But, for the purpose of this study, spectral and colorimetric accuracy is required. Table IV to VI show the influence of the number of eigenvectors on the colorimetric and spectral accuracy of the spectral reconstruction of each patch, respectively, for reflectance, K/S and new empirical spaces. The colorimetric accuracy is calculated using CIE94 under D50 and 2° observer.

Table IV. Influence of the number of eigenvectors in reflectance space used in the spectral reconstruction on the colorimetric and spectral error.

Number of eigenvectors	Macbeth ColorChecker		147 painted patches		105 painted patches	
	Mean ΔE^*_{94}	reflectance factor rms error	Mean ΔE^*_{94}	reflectance factor rms error	Mean ΔE^*_{94}	reflectance factor 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

Table V. Influence of the number of eigenvectors in K/S space used in the spectral reconstruction on the colorimetric and spectral error.

Number of eigenvectors	Macbeth ColorChecker		147 painted patches		105 painted patches	
	Mean ΔE^*_{94}	reflectance factor rms error	Mean ΔE^*_{94}	reflectance factor rms error	Mean ΔE^*_{94}	reflectance factor rms error
3	4.1	0.010	1.9	0.050	2.8	0.011
6	1.4	0.039	0.9	0.022	0.5	0.012
9	0.3	0.027	0.2	0.016	0.1	0.008
12	0.2	0.017	0.2	0.014	0.02	0.001

Table VI. Influence of the number of eigenvectors in the new empirical space used in the spectral reconstruction on the colorimetric and spectral error.

Number of eigenvectors	Macbeth ColorChecker		147 painted patches		105 painted patches	
	Mean ΔE^*_{94}	**reflectance factor rms error**	**Mean ΔE^*_{94}**	**reflectance factor rms error**	**Mean ΔE^*_{94}**	**reflectance factor rms error**
3	**2.5**	**0.025**	**3.3**	**0.025**	**1.8**	**0.022**
6	**0.2**	**0.009**	**0.3**	**0.007**	**0.5**	**0.007**
9	**0.1**	**0.004**	**0.03**	**0.003**	**0.05**	**0.002**
12	**0.01**	**0.001**	**0.00**	**0.001**	**0.01**	**0.000**

Comparing Tables IV to VI, it is possible to see that the best overall result was produced in the new empirical space, followed by reflectance and K/S spaces. Particularly, the results in K/S space were not satisfactory because the influence of errors caused by low dimensionality on the inherent problems of K/S equations, for low reflectance factors.

If we establish that a reproduction is acceptable if ΔE^*_{94} is less than a unity and spectral reflectance rms error less than 1%, while 6 eigenvectors are enough to reconstruct spectra in the new empirical space, 9 eigenvectors are required in reflectance space and more than 12 necessary in K/S space. It is also possible to notice that the performance depends on the samples used to perform principal component analysis.

B) Spectral reconstruction using simulated camera digital counts in various spaces, targets and trichromatic signal combinations

Influence of combination of trichromatic signals in reflectance space

Target I: GretagMacbeth ColorChecker

Table VII summarizes the result obtained for various combinations of signals.

Table VII. Spectral reconstruction using 6 eigenvectors and 6 signals

Patch	**ΔE^*_{94}**	**reflectance factor rms error**	**Metameric Index**
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 without filter and with didymium filter			
Average	**0.5**	**0.021**	**0.8**

Std Dev	0.4	0.009	0.9
Max	1.4	0.044	3.3
Min	0.05	0.002	0.02
6 eigenvectors and 6 signals: R,G,B with light-blue and with didymium filters			
Average	**0.5**	**0.021**	**0.5**
Std Dev	0.4	0.010	0.5
Max	1.8	0.051	1.8
Min	0.08	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
6 eigenvectors and 6 signals: R,G,B with very-light-green and didymium filters			
Average	**0.4**	**0.019**	**0.3**
Std Dev	0.3	0.008	0.4
Max	1.1	0.037	1.9
Min	0.06	0.002	0.05

Effect of changing the number of eigenvectors to 9 channels and 9 eigenvectors

Table VIII shows comparison of spectral reflectance performance in reflectance space for GretagMacbeth ColorChecker using various combination of 3 set of trichromatic signals.

Table VIII. Spectral reconstruction using 9 eigenvectors; 9 signals.

Patch	**ΔE^*_{94}**	**reflectance factor rms error**	**Metameric Index**
9 eigenvectors and 9 signals: R,G,B without filter and with very-light-green and 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
9 eigenvectors and 9 signals: R,G,B with didymium, very-light-green and light-blue absorption filters			
Average	**0.3**	**0.009**	**0.08**
Std Dev	0.2	0.003	0.04
Max	1.1	0.012	0.17
Min	0.06	0.002	0.01
9 eigenvectors and 9 signals: R,G,B without filter, with didymium and light-blue absorption filters			

Average	**0.2**	**0.012**	**0.07**
Std Dev	0.1	0.005	0.04
Max	0.5	0.027	0.2
Min	0.04	0.002	0.02
9 eigenvectors and 9 signals: R,G,B without filter, with didymium and very-light-green absorption filters			
Average	**0.2**	**0.011**	**0.1**
Std Dev	0.1	0.005	0.1
Max	0.5	0.022	0.6
Min	0.01	0.002	0.01

Looking the Table VII it is possible to see that the combination of R, G, B without filter and using very-light-green filter produced the best overall results. It is possible that these signal combinations give the best signal-to-noise ratio improving the performance.

When 9 signals is used instead of 6 signals we can see improvement in reflectance factor rms error comparing Tables VII and VIII. However, the color difference did not improve dramatically. Moreover the various possible combinations of three signals did not affect the spectral reconstruction performance at all.

Target II: Set of 147 painted patches

Table IX summarizes the result of spectral reconstruction performance in reflectance space obtained for 147 painted patches using various combinations of signals.

Table IX. Spectral reconstruction using 6 eigenvectors and 6 signals

Patch	ΔE^*_{94}	**reflectance factor rms error**	**Metameric Index**
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 without filter and with didymium filter			
Average	**0.6**	**0.015**	**0.9**
Std Dev	0.5	0.009	0.8
Max	2.2	0.041	4.0
Min	0.04	0.002	0.01
6 eigenvectors and 6 signals: R,G,B with light-blue and with didymium filters			
Average	**0.5**	**0.015**	**0.5**
Std Dev	0.4	0.009	0.5
Max	1.6	0.046	2.2
Min	0.03	0.002	0.03
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
6 eigenvectors and 6 signals: R,G,B with very-light-green and didymium filters			
Average	**0.4**	**0.014**	**0.4**
Std Dev	0.3	0.008	0.3
Max	1.4	0.047	1.3
Min	0.1	0.002	0.01

As in the spectral reconstruction of GretagMacbeth ColorChecker, the spectral reconstruction of 147 painted patches presented best performance for the combination of R, G, B signals without filter and using very-light-green filter. It is also possible to see that the spectral and colorimetric performances were not significantly different for various combinations of trichromatic signals.

Target III: Set of 105 painted patches

Table X summarizes the result of spectral reconstruction performance in reflectance space obtained for 105 painted patches using various combinations of signals.

Table X. Spectral reconstruction using 6 eigenvectors and 6 signals

Patch	**ΔE^*_{94}**	**reflectance factor rms error**	**Metameric Index**
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 without filter and with didymium filter			
Average	**1.1**	**0.017**	**0.7**
Std Dev	0.6	0.006	0.6
Max	2.6	0.031	2.7
Min	0.1	0.005	0.03
6 eigenvectors and 6 signals: R,G,B with light-blue and with didymium filters			
Average	**1.0**	**0.018**	**0.6**
Std Dev	0.7	0.006	0.4
Max	2.7	0.031	1.8
Min	0.1	0.005	0.03
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
6 eigenvectors and 6 signals: R,G,B with very-light-green and didymium filters			
Average	**0.9**	**0.016**	**0.4**
Std Dev	0.5	0.006	0.3
Max	2.1	0.029	1.5
Min	0.09	0.004	0.04

In the case of this set of 105 painted patches the 6 possible combinations of trichromatic signals produced similar spectral and colorimetric performances. It shows that although the spectral reconstruction performance in reflectance space depends on the sample data, the results for different combinations of trichromatic signals were not significantly different.

Influence of combination of trichromatic signals in Kubelka-Munk space

Target I: GretagMacbeth ColorChecker

Table XI summarizes the result of spectral reconstruction performance in K/S space obtained for GretagMacbeth ColorChecker using various combinations of signals.

Table XI. Spectral reconstruction using 6 eigenvectors and 6 signals

Patch	ΔE^*_{94}	**reflectance factor rms error**	**Metameric Index**
6 eigenvectors and 6 signals: R,G,B without filter and with light-blue absorption filter			
Average	**4.2**	**0.123**	**2.4**
Std Dev	4.8	0.030	2.3
Max	18.4	0.154	8.5
Min	0.2	0.024	0.03
6 eigenvectors and 6 signals: R,G,B without filter and with very-light-green absorption filter			
Average	**5.2**	**0.089**	**1.8**
Std Dev	4.6	0.084	2.1
Max	17.1	0.268	8.1
Min	0.4	0.000	0.03

Target II: Set of 147 painted patches

Table XII summarizes the result of spectral reconstruction performance in K/S space obtained for 147 painted patches.

Table XII. Spectral reconstruction using 6 eigenvectors and 6 signals

Patch	ΔE^*_{94}	**reflectance factor rms error**	**Metameric Index**
6 eigenvectors and 6 signals: R,G,B without filter and with light-blue absorption filter			
Average	**14.9**	**0.351**	**5.5**
Std Dev	26.7	1.032	15.1
Max	135.1	5.696	95.4
Min	0.2	0.002	0.08

Target II: Set of 105 painted patches

Table XIII summarizes the result of spectral reconstruction performance in K/S space obtained for 105 painted patches.

Table XIII. Spectral reconstruction using 6 eigenvectors and 6 signals

Patch	ΔE^*_{94}	**reflectance factor rms error**	**Metameric Index**
6 eigenvectors and 6 signals: R,G,B without filter and with light-blue absorption filter			
Average	**1.6**	**0.028**	**0.6**

Std Dev	1.1	0.032	0.6
Max	7.2	0.129	2.8
Min	0.2	0.004	0.02
Same combination above but without digital counts normalization			
Average	14.5	0.167	3.9
Std Dev	17.7	0.270	7.1
Max	92.5	1.414	51.3
Min	1.2	0.011	0.02

Comparing Tables XI to XIII with the respective spectral reflectance reconstruction in reflectance space it is possible to observe that the reconstruction in Kubelka-Munk space presented much worse performance than in reflectance space.

Table XI shows that the choice of different set of trichromatic signals does not affect the spectral reconstruction performance.

From Table XIII, we can see that the use of a normalized transformation given by equation (1) can improve the spectral reconstruction but it still presented worse performance than the corresponding reconstruction in reflectance space.

$$\mathbf{D}'_\mathbf{c} = \frac{1}{2\mathbf{Dc}} + \frac{\mathbf{D_c}}{2} - 1, \qquad (1)$$

where $\mathbf{D}'_\mathbf{c}$ is the transformed digital count, $\mathbf{D_c}$ is the normalized digital count.

Although the reconstruction in Kubelka-Munk space presented better results than the reconstruction in reflectance space in some patches with low spectral reflectances, for example, purple patch of the GretagMacbeth ColorChecker, the reconstruction in Kubelka-Munk space presents an inherent problem when applied to patches with high spectral reflectance factor generating huge errors. Therefore, Kubelka-Munk seems not to be a suitable space for spectral reconstruction.

<u>Influence of combination of trichromatic signals in New empirical space</u>

A normalization was also derived for the new empirical space given by equation (2).

$$\mathbf{D}'_\mathbf{c} = 1 - \sqrt{\mathbf{D_c}} \qquad (2)$$

where $\mathbf{D}'_\mathbf{c}$ is the transformed digital count, $\mathbf{D_c}$ is the normalized digital count.

Target I: GretagMacbeth ColorChecker

Table XIV summarizes the result of spectral reconstruction performance in new empirical space obtained for GretagMacbeth ColorChecker using various combinations of signals.

Table XIV. Spectral reconstruction using 6 eigenvectors and 6 signals

Patch	ΔE^*_{94}	**reflectance factor rms error**	**Metameric Index**
6 eigenvectors and 6 signals: R,G,B without filter and with light-blue absorption filter			
Average	**0.9**	**0.020**	**0.4**
Std Dev	0.4	0.009	0.3
Max	2.4	0.043	1.0
Min	0.5	0.006	0.05
6 eigenvectors and 6 signals: R,G,B without filter and with very-light-green absorption filter			
Average	**1.8**	**0.028**	**0.6**
Std Dev	0.7	0.014	0.3
Max	3.2	0.066	1.4
Min	0.6	0.004	0.08
6 eigenvectors and 6 signals: R,G,B without filter and with didymium filter			
Average	**0.9**	**0.022**	**0.6**
Std Dev	0.4	0.011	0.4
Max	1.8	0.055	1.9
Min	0.3	0.003	0.08
6 eigenvectors and 6 signals: R,G,B with light-blue and with didymium filters			
Average	**0.8**	**0.022**	**0.5**
Std Dev	0.4	0.011	0.4
Max	1.9	0.051	1.9
Min	0.2	0.004	0.04
6 eigenvectors and 6 signals: R,G,B with light-blue and with very-light-green filters			
Average	**1.9**	**0.029**	**0.8**
Std Dev	0.9	0.013	0.5
Max	3.5	0.066	2.0
Min	0.6	0.005	0.1
6 eigenvectors and 6 signals: R,G,B with very-light-green and didymium filters			
Average	**1.3**	**0.019**	**0.4**
Std Dev	0.7	0.007	0.2
Max	3.2	0.033	0.9
Min	0.5	0.004	0.03

Looking the Table XIV it is possible to see that the combination of R, G, B without filter and using very-light-green filter produced the worse results.

Target II: Set of 147 painted patches

Table XV summarizes the result of spectral reconstruction performance in new empirical space obtained for 147 painted patches using various combinations of signals.

Table XV. Spectral reconstruction using 6 eigenvectors and 6 signals

Patch	ΔE^*_{94}	**reflectance factor rms error**	**Metameric Index**
6 eigenvectors and 6 signals: R,G,B without filter and with light-blue absorption filter			
Average	**0.8**	**0.014**	**0.4**

Std Dev	0.4	0.008	0.3
Max	2.6	0.040	1.7
Min	0.1	0.001	0.01
6 eigenvectors and 6 signals: R,G,B without filter and with very-light-green absorption filter			
Average	**0.9**	**0.016**	**0.3**
Std Dev	0.5	0.011	0.2
Max	3.1	0.054	1.0
Min	0.1	0.001	0.02
6 eigenvectors and 6 signals: R,G,B without filter and with didymium filter			
Average	**0.7**	**0.015**	**0.6**
Std Dev	0.5	0.009	0.6
Max	2.6	0.043	3.0
Min	0.08	0.001	0.02
6 eigenvectors and 6 signals: R,G,B with light-blue and with didymium filters			
Average	**0.7**	**0.014**	**0.4**
Std Dev	0.4	0.008	0.4
Max	2.0	0.038	2.1
Min	0.09	0.001	0.03
6 eigenvectors and 6 signals: R,G,B with light-blue and with very-light-green filters			
Average	**0.9**	**0.016**	**0.3**
Std Dev	0.5	0.011	0.2
Max	3.1	0.054	1.0
Min	0.1	0.001	0.02
6 eigenvectors and 6 signals: R,G,B with very-light-green and didymium filters			
Average	**1.0**	**0.013**	**0.3**
Std Dev	0.7	0.008	0.2
Max	3.3	0.039	1.2
Min	0.1	0.001	0.03

From Table XV, it is possible to observe that the spectral reconstruction using R, G, B signals without filter and with didymium filter produced the best results. However the spectral and colorimetric performances were not significantly different for different set of trichromatic signals.

Target III: Set of 105 painted patches

Table XVI summarizes the result of spectral reconstruction performance in new empirical space obtained for 105 painted patches using various combinations of signals.

Table XVI. Spectral reconstruction using 6 eigenvectors and 6 signals

Patch	**ΔE^*_{94}**	**reflectance factor rms error**	**Metameric Index**
6 eigenvectors and 6 signals: R,G,B without filter and with light-blue absorption filter			
Average	**0.6**	**0.017**	**0.6**
Std Dev	0.4	0.008	0.3
Max	1.8	0.040	1.7
Min	0.1	0.005	0.03
6 eigenvectors and 6 signals: R,G,B without filter and with very-light-green absorption filter			
Average	**0.6**	**0.013**	**0.2**
Std Dev	0.4	0.005	0.1
Max	2.6	0.038	0.8
Min	0.06	0.005	0.00
6 eigenvectors and 6 signals: R,G,B without filter and with didymium filter			
Average	**0.7**	**0.021**	**1.0**
Std Dev	0.5	0.010	0.5
Max	2.1	0.046	2.3
Min	0.08	0.006	0.06
6 eigenvectors and 6 signals: R,G,B with light-blue and with didymium filters			
Average	**0.7**	**0.020**	**0.7**
Std Dev	0.3	0.010	0.4
Max	1.5	0.046	1.8
Min	0.1	0.006	0.04
6 eigenvectors and 6 signals: R,G,B with light-blue and with very-light-green filters			
Average	**0.5**	**0.013**	**0.4**
Std Dev	0.4	0.005	0.3
Max	2.1	0.027	1.7
Min	0.09	0.003	0.01
6 eigenvectors and 6 signals: R,G,B with very-light-green and didymium filters			
Average	**0.8**	**0.014**	**0.2**
Std Dev	0.6	0.006	0.2
Max	3.2	0.029	0.8
Min	0.1	0.004	0.03

In the case of this set of 105 painted patches the 6 possible combinations of trichromatic signals produced similar spectral and colorimetric performances.

Tables XIV to XVI show that although the spectral reconstruction performance in reflectance space depends on the sample data, the results for different combinations of trichromatic signals were not significantly different.

C) Spectral reconstruction using measured camera digital counts in various spaces, targets and trichromatic signal combinations

Influence of combination of trichromatic signals in reflectance space

Target I: GretagMacbeth ColorChecker

Table XVII summarizes the comparison of colorimetric and spectral performances of spectral reconstruction in reflectance space for two different camera systems using measured digital counts.

Table XVII. Spectral reconstruction using 6 eigenvectors; 6 signals (R, G, B without filter and R, G, B with very-light-green Wratten absorption filter number 66).

Patch	ΔE^*_{94}	**reflectance factor rms error**	**Metameric Index**
Signals from IBM DCS			
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
Signals from Sony Digital Still Camera			
Average	**3.4**	**0.035**	**1.5**
Std Dev	2.1	0.017	1.8
Max	9.3	0.076	8.0
Min	0.3	0.006	0.2

From Table XVII, it is possible to observe that when measured digital counts were used instead of simulated digital counts, for the IBM DCS it is possible to see that the colorimetric and spectral performances are worse because the introduction of additional noise. The spectral reconstruction using signals from the high-end IBM DCS was better than the results obtained for a Sony Digital Still Camera, however, the performance was not considerably different. 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 (Sony Digital Still Camera).

Target II: 147 painted patches

Table XVIII summarizes the comparison of colorimetric and spectral performances of spectral reconstruction in reflectance space for 147 painted patches using measured digital counts.

Table XVIII. Spectral reconstruction using 6 eigenvectors; 6 signals (R, G, B without filter and R, G, B with very-light-green Wratten absorption filter number 66).

Patch	**ΔE^*_{94}**	**reflectance factor rms error**	**Metameric Index**
Signals from IBM DCS			
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

Target III: 105 painted patches

Table XIX summarizes the comparison of colorimetric and spectral performances of spectral reconstruction in reflectance space for 105 painted patches using measured digital counts.

Table XIX. Spectral reconstruction using 6 eigenvectors; 6 signals (R, G, B without filter and R, G, B with very-light-green Wratten absorption filter number 66).

Patch	**ΔE^*_{94}**	**reflectance factor rms error**	**Metameric Index**
Signals from IBM DCS			
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

The comparison of Tables XVIII and XIX shows that the performance of the spectral reconstruction in reflectance space using measured digital counts depends on the sample considered.

Influence of combination of trichromatic signals in Kubelka-Munk space

Target I: GretagMacbeth ColorChecker

Table XX summarizes the comparison of colorimetric and spectral performances of spectral reconstruction in K/S space for two different camera systems using measured digital counts.

Table XX. Spectral reconstruction using 6 eigenvectors; 6 signals (R, G, B without filter and R, G, B with very-light-green Wratten absorption filter number 66).

Patch	ΔE^*_{94}	**reflectance factor rms error**	**Metameric Index**
Signals from IBM DCS			
Average	**5.7**	**0.108**	**2.4**
Std Dev	3.2	0.121	2.2
Max	11.6	0.608	9.1
Min	0.9	0.001	0.2
Signals from Sony Digital Still Camera			
Average	**3.4**	**0.035**	**1.5**
Std Dev	2.1	0.017	1.8
Max	9.3	0.076	8.0
Min	0.3	0.006	0.2

Comparing Table XX with Table XVII, it is possible to observe that the spectral reconstruction using measured digital counts for GretagMacbeth ColorChecker performed worse in K/S space than in reflectance space. In K/S space the reconstruction using Sony Digital Still Camera performed better than the reconstruction using IBM DCS.

Influence of combination of trichromatic signals in new empirical space

IBM DCS

Target I: GretagMacbeth ColorChecker

Table XXI summarizes the result of spectral reconstruction performance in new empirical space obtained for GretagMacbeth ColorChecker using various combinations of IBM DCS signals.

Table XXI. Spectral reconstruction using 6 eigenvectors and 6 signals

Patch	ΔE^*_{94}	reflectance factor rms error	Metameric Index
6 eigenvectors and 6 signals: R,G,B without filter and with light-blue absorption filter			
Average	**1.9**	**0.029**	**0.8**
Std Dev	0.9	0.013	0.5
Max	3.5	0.066	2.0
Min	0.6	0.005	0.1
6 eigenvectors and 6 signals: R,G,B without filter and with very-light-green absorption filter			
Average	**1.8**	**0.028**	**0.6**
Std Dev	0.7	0.014	0.3
Max	3.2	0.066	1.4
Min	0.6	0.004	0.08
6 eigenvectors and 6 signals: R,G,B with light-blue and with very-light-green filters			
Average	**2.1**	**0.037**	**1.0**
Std Dev	1.0	0.019	1.0
Max	4.4	0.082	4.5
Min	0.8	0.005	0.03

Target II: 147 painted patches

Table XXII summarizes the result of spectral reconstruction performance in new empirical space obtained for 147 painted patches using various combinations of IBM DCS signals.

Table XXII. Spectral reconstruction using 6 eigenvectors and 6 signals

Patch	ΔE^*_{94}	**reflectance factor rms error**	**Metameric Index**
6 eigenvectors and 6 signals: R,G,B without filter and with light-blue absorption filter			
Average	**3.1**	**0.027**	**1.3**
Std Dev	2.3	0.015	1.1
Max	17.5	0.076	6.4
Min	0.1	0.003	0.04
6 eigenvectors and 6 signals: R,G,B without filter and with very-light-green absorption filter			
Average	**5.0**	**0.046**	**1.9**
Std Dev	4.5	0.029	1.3
Max	30.5	0.124	8.1
Min	0.3	0.006	0.03
6 eigenvectors and 6 signals: R,G,B with light-blue and with very-light-green filters			
Average	**9.2**	**0.100**	**3.6**
Std Dev	4.9	0.067	3.1
Max	25.3	0.332	14.5
Min	0.5	0.004	0.05

Target III: 105 painted patches

Table XXIII summarizes the result of spectral reconstruction performance in new empirical space obtained for 105 painted patches using various combinations of IBM DCS signals.

Table XXIII. Spectral reconstruction using 6 eigenvectors and 6 signals

Patch	ΔE^*_{94}	**reflectance factor rms error**	**Metameric Index**
6 eigenvectors and 6 signals: R,G,B without filter and with light-blue absorption filter			
Average	**1.9**	**0.025**	**1.0**
Std Dev	1.5	0.010	0.7
Max	8.9	0.055	4.8
Min	0.3	0.008	0.03
6 eigenvectors and 6 signals: R,G,B without filter and with very-light-green absorption filter			
Average	**1.8**	**0.025**	**1.3**
Std Dev	1.5	0.010	0.8
Max	12.6	0.055	4.1
Min	0.3	0.009	0.06
6 eigenvectors and 6 signals: R,G,B with light-blue and with very-light-green filters			

Average	**3.6**	**0.038**	**1.8**
Std Dev	2.3	0.018	1.2
Max	11.0	0.113	6.7
Min	0.5	0.010	0.3

From Tables XXI to XXIII, it is possible to observe that the spectral reconstruction using measured digital counts in new empirical space could improve the performance if compared with spectral reconstruction using measured digital counts in reflectance and Kubelka-Munk spaces (Tables XVII to XX). Although the combination of trichromatic signals does not seem to affect the colorimetric and spectral performance for GretagMacbeth ColorChecker, it affected the performance for the set of 147 and 105 painted patches. For the painted patches the combination of R, G, B without filter and with light-blue absorption filter presented the best results.

Sony Digital Still Camera

Target: GretagMacbeth ColorChecker

Table XXIV summarizes the results of colorimetric and spectral performances of spectral reconstruction in new empirical space for GretagMacbeth ColorChecker using Sony Digital Still Camera measured digital counts.

Table XXIV. Spectral reconstruction using 6 eigenvectors; 6 signals (R, G, B without filter and R, G, B with very-light-green Wratten absorption filter number 66).

Patch	ΔE^*_{94}	**reflectance factor rms error**	**Metameric Index**

Signals from Sony Digital Still Camera			
Average	**11.0**	**0.176**	**3.2**
Std Dev	10.7	0.137	4.0
Max	43.5	0.663	18.3
Min	0.4	0.017	0.6

Iterative method using measured digital counts (Sony Digital Still Camera)

In order to improve the performance of spectral reconstruction in new empirical space using measured digital counts from Sony Digital Still Camera, an iterative method was used to calculate the eigenvector coefficients from normalized digital counts. Simplex method was used in the simulation. Every patch converged after 7 iterations.

Table XXV summarizes the results of colorimetric and spectral performances of spectral reconstruction in new empirical space for GretagMacbeth ColorChecker using Sony Digital Still Camera measured digital counts and iterative method.

Table XXV. Spectral reconstruction using 6 eigenvectors; 6 signals (R, G, B without filter and R, G, B with very-light-green Wratten absorption filter number 66).

Patch	ΔE^*_{94}	reflectance factor rms error	Metameric Index
Signals from Sony Digital Still Camera			
Average	**2.9**	**0.024**	**1.1**
Std Dev	2.8	0.009	0.9
Max	14.6	0.038	3.4
Min	0.6	0.004	0.08

The comparison of Tables XXIV and XXV shows that iterative method was effective to improve the spectral and colorimetric performance of a spectral reconstruction using measured digital counts. However, this method is very time-consuming for high-resolution images because it needs to process the images in a pixel basis.

GENERAL CONCLUSIONS

The performance of a spectral reconstruction method using trichromatic camera and a set of absorption filters was evaluated. The variables were:

- Space in which reconstruction is made: Reflectance, K/S., new empirical space.

- Combination of trichromatic signals using different absorption filters.
- Different samples: GretagMacbeth ColorChecker, 2 set of painted patches.
- Different trichromatic camera systems: IBM DCS and Sony DCS.

The performance was evaluated in terms of colorimetric accuracy (mean ΔE^*_{94}), spectral reflectance rms error and metameric index

1. 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 analysis the results without signal 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.

2. The combination of various absorption filters (light-blue and very-light-green) does not affected much the spectral performance of the system. However, trichromatic camera without filter and with light-blue filter gives the signals with the best overall colorimetric and spectral performance.

3. The performance of the spectral reflectance depends on the sample used to calculate the eigenvectors and the transformation matrix from digital counts to eigenvalues.

4. The spectral reconstruction using trichromatic camera and a set of absorption filters presented colorimetric accuracy (in reflectance and new empirical spaces) similar to the traditional approach using monochrome camera and interference narrow-band filters (e.g. the experiments Dr. Peter Burns performed with Kodak DCS200 camera and 7 interference filters).

5. For future practical purposes, based on the experimental results, I recommend the use of the trichromatic digital camera system with 6 digital counts (from the trichromatic signals without filter and trichromatic signals with light-blue filters) to perform the imaging of an artwork painting under tungsten illuminant. Then, the eigenvalues obtained from the digital counts are used with the eigenvectors in the new empirical space to reconstruct the spectral reflectance of each pixel of the image.

6. The analysis of the performance of multi-illuminant approach using a trichromatic camera , instead of multi-filter approach, in order to produce 6 signals, is in progress.

7. The spectral reflectance of each pixel of an image of the GretagMacbeth ColorChecker as well as the images of two paintings using, respectively the same paints used to make the set of 147 and 105 patches were reconstructed using the eigenvectors and 6x6 digital counts to eigenvalues transformation matrix derived for the patches. The images were displayed on CRT monitor after appropriate color management and the result was satisfactory. However, a printer should be calibrated to produce prints that can be used in future psychophysical comparisons to judge the quality of the reproductions.