Spectral reproduction from scene to hardcopy

Part I – Multi-spectral acquisition and spectral estimation using a Trichromatic Digital Camera System associated with absorption filters – New results

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Abstract

This report summarizes an experiment performed to evaluate the accuracy of the new multi-spectral acquisition system based on *a priori* spectral analysis followed by wide-band capture combining trichromatic camera and absorption filters. This report will be focused on the multi-spectral capture and spectral estimation based on a new set of complex image representing a painting and a series of printed color patches with a better distribution in color space.

Introduction

Technical background about the wide-band multi-spectral acquisition, spectral analysis and spectral estimation based on eigenvector analysis can be found in the previous report: "Spectral reproduction from scene to hardcopy. Part I – Multi-spectral acquisition and spectral estimation using a Trichromatic Digital Camera System associated with absorption filters". This research is also coupled to the spectral-based color separation processing for complex images. In the previous experiments it was possible to notice that a factor that can influence in the color accuracy of the reproduced image is the limited gamut of the printer. In order to overcome this problem, new targets should be chosen making two new improvements. The first improvement is considering as originals a set of printed complex image and uniform color patches. The patches are used to estimate quantitatively the color difference between the original and the reproductions. The complex image is used in the visual assessment of the reproduced image. Since the original and the reproductions are hardcopies generated using the same printer the reproductions will have a color gamut inside the printer's gamut. The second improvement consists of providing a better distribution of the patch samples in color space.

Experimental

I) **Measurement of samples**

Two targets were used in the experimental part. A smaller version of the GretagMacbeth ColorChecker rendition chart, 192 colored patches and a complex image representing a Matisse painting. The patches and the paint were printed using Epson Styles Photo 1200 CMYK printer. The targets are shown in Figure 1.

The spectral reflectances of the painted patches were measured using the Gretag Spectrolino. The a* x b* and a* x L* distributions for D50 illuminant and 2° observer is shown in Figure 2a and 2b, respectively.

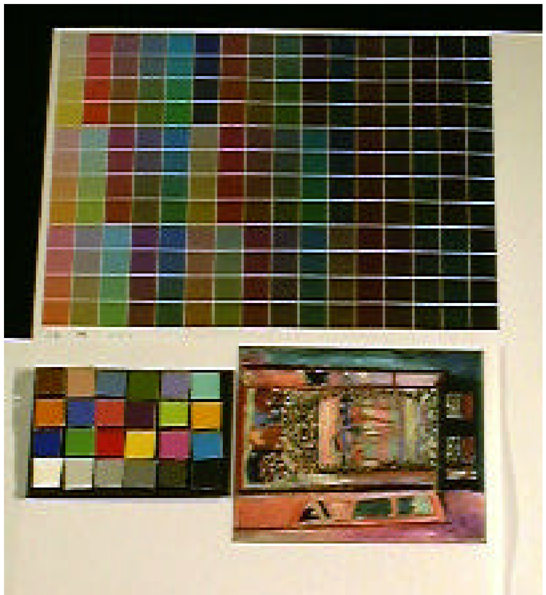
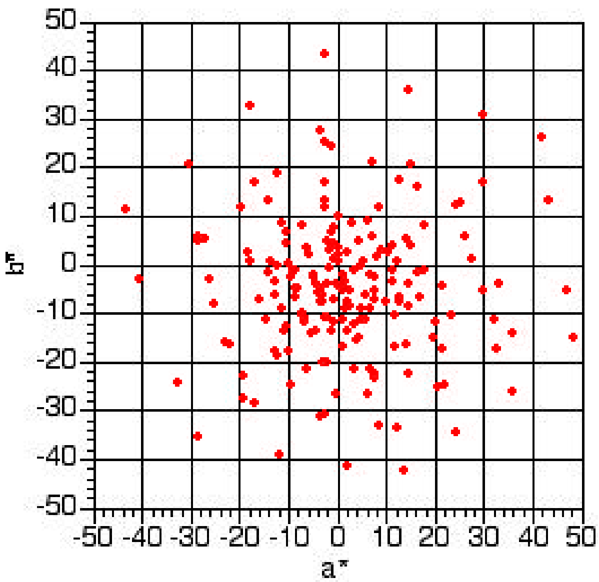
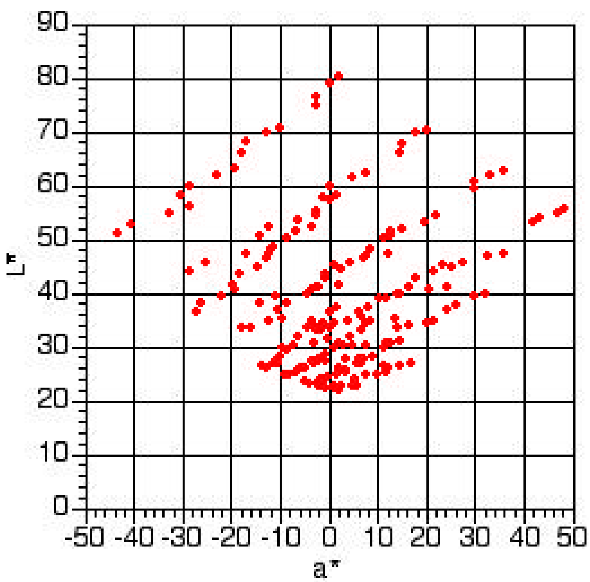


Figure 1. Targets used in the experiment.



a) a* x b*

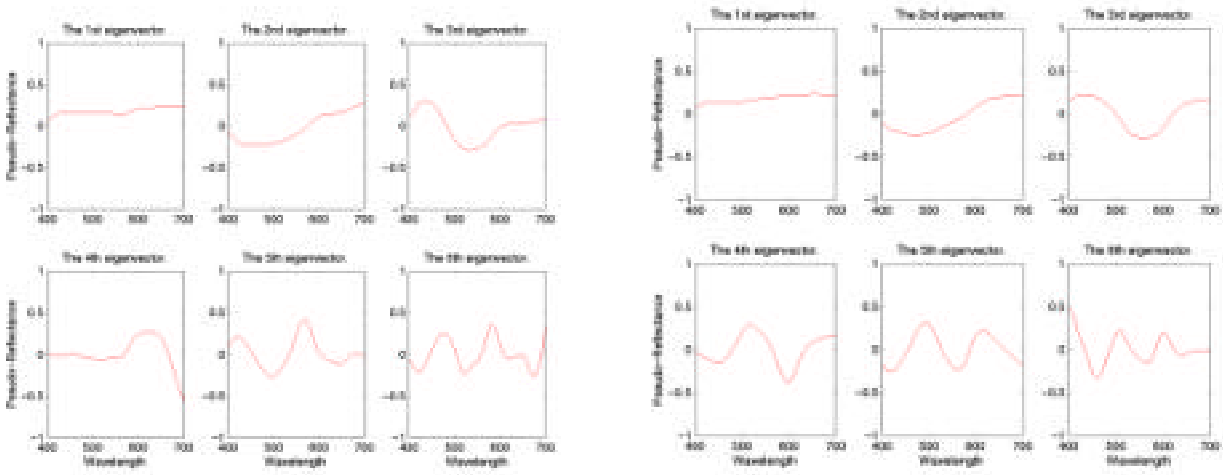


b) a* x L*

Figure 2. Colorimetric plots for patches (D50 illuminant, 2° observer).

II) **Spectral Analysis**

Principal component analysis was performed using the spectral reflectance of the painted patches. Figure 3a shows the plot of the 1st to 6th eigenvectors . Figure 3b shows the plots of the 1st to 6th eigenvectors for the GretagMacbeth ColorChecker rendition chart. It is possible to notice that the 1st, 2nd and 3rd eigenvectors are quite similar presenting major differences for the higher order eigenvectors. Let us assume that the printed patches have a color distribution sufficiently representative for a universal target that allows us to use the eigenvector derived for the printed patches to reconstruct any other target such as the GretagMacbeth ColorChecker.



a) Printed patches b) GretagMacbeth ColorChecker

Figure 3. Plot of the first to sixth eigenvectors from the reflectances of the printed patches.

Assuming the 6 eigenvectors is a good compromise between cost (number of channels) and accuracy based on results of past experiments shown in the previous report, 6 eigenvectors will be used for the spectral estimation. Table I shows the colorimetric and spectral accuracy of the spectral reconstruction for the printed patches and the GretagMacbeth ColorChecker rendition chart when 6 eigenvectors from the printed patches are used. The colorimetric accuracy is calculated using CIE94 under D50 and 2° observer. The metameric index was calculated using Fairman metameric black method, between standard -illuminant D50 and reference-illuminant A using ΔE^*_{94} in the calculations.

Figures 4a and 4b show respectively the histogram of ΔE^*_{94} between the measured spectral reflectance and the spectral reflectance predicted using 6 eigenvectors of the printed patches, for the printed patches and the GretagMacbeth ColorChecker.

Table I. Spectral and colorimetric accuracy for the spectral estimation using 6 eigenvectors derived using spectral reflectances of the printed patches.

Statistical measure	Printed patches			GretagMacbeth ColorChecker		
	ΔE^*_{94}	rms reflectance factor	metameric index	ΔE^*_{94}	rms reflectance factor	metameric index
Mean	**0.8**	**0.008**	**0.2**	**0.9**	**0.026**	**0.2**
Standard Deviation	0.4	0.002	0.1	0.7	0.016	0.1
Maximum	1.7	0.014	0.3	3.8	0.077	0.5
Minimum	0.0	0.004	0.0	0.3	0.004	0.0

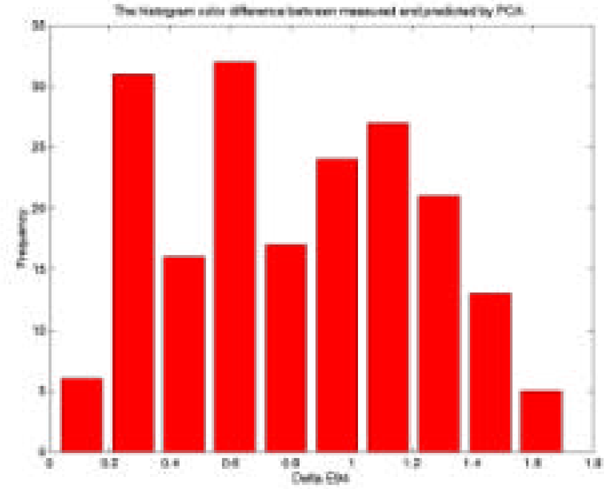


Figure 4a. ΔE^*_{94} histogram for reconstructed of the printed patches using 6 eigenvectors from the printed patches.

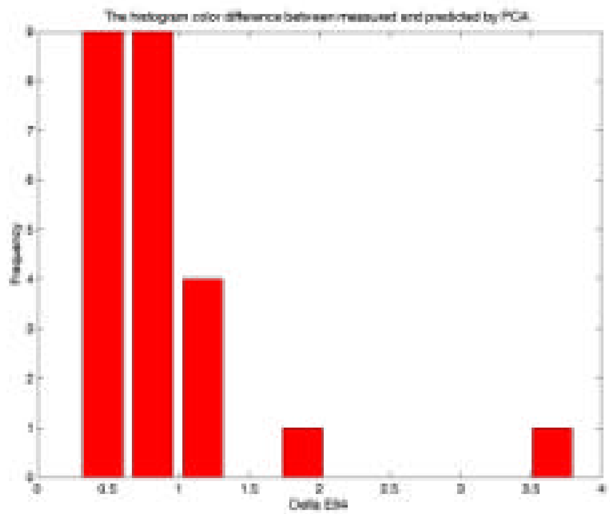
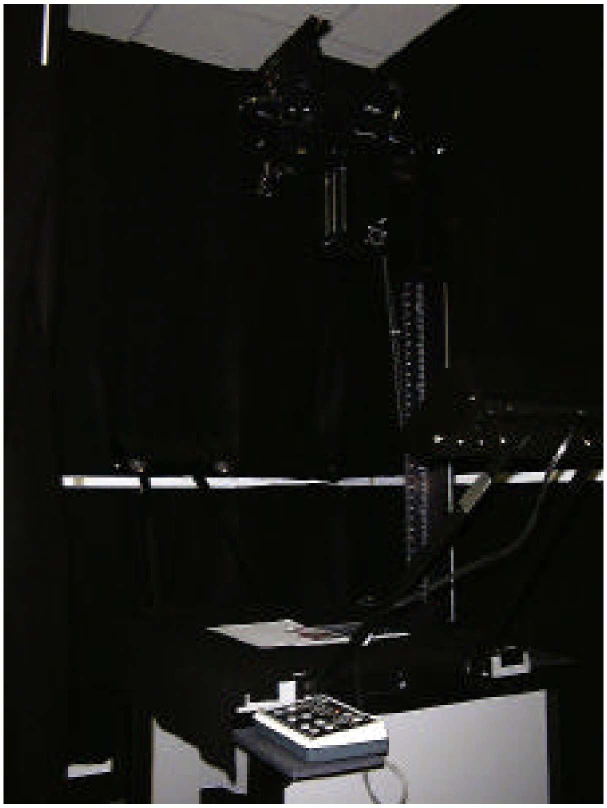


Figure 4b. ΔE^*_{94} histogram for the GretagMacbeth ColorChecker reconstructed using 6 eigenvectors from the printed patches.

From Table I and Figures 4a and 4b we can conclude that the eigenvectors of the printed patches can be used to reconstruct the spectral reflectances of the GretagMacbeth ColorChecker with good accuracy.

III) **Imaging and spectral estimation**

Based on previous experiments, Kodak Wratten filters number 38 (light-blue filter), 66 (very-light-green) were used in conjunction with an IBM Pro/3000 digital camera system to generate 9 signals: the RGB signals without Wratten filtering, and the signals generated using the filters number 38 and 66. The imaging system is shown in Figure 5a. A white spatial correction was performed in a pixel basis using a white card board to correct non-uniformity of the illumination as shown in Figure 5b. Six eigenvectors from the printed patches and 9 digital signals were used to generate a 9 by 6 transformation matrix by regression. This transformation seems to be preferable than the 9 by 9 transformation matrix (using 9 eigenvectors) in order to have a more stable transformation. Matrix generated by regression using high order components works wonderfully for the training set but as soon as the test set differs from the training set, unpredictable results might occur. The results for the spectral estimation for both printed patches and the GretagMacbeth ColorChecker are shown in Table II.



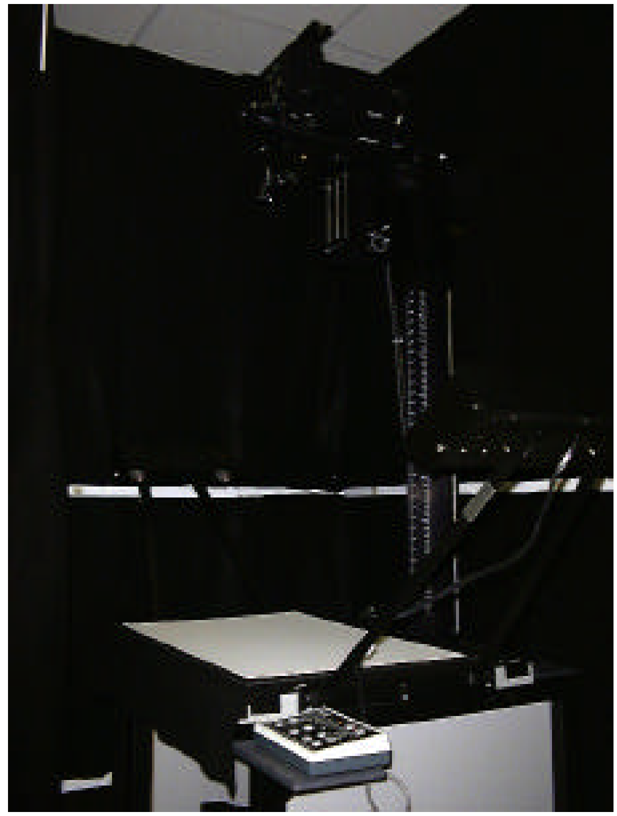


Figure 5a. IBM PRO/3000 and imaged targets. **Figure 5b.** White spatial correction using a white card board.

Table II. Spectral and colorimetric accuracy for the spectral estimation derived using a transformation derived from 9 digital counts to the weight of 6 eigenvectors of the printed patches.

Statistical measure	Printed patches			GretagMacbeth ColorChecker		
	ΔE^*_{94}	rms reflectance factor	metameric index	ΔE^*_{94}	rms reflectance factor	metameric index
Mean	**1.0**	**0.013**	**0.2**	**1.2**	**0.029**	**0.2**
Standard Deviation	0.5	0.005	0.1	0.7	0.015	0.1
Maximum	2.6	0.042	0.6	3.3	0.077	0.5
Minimum	0.1	0.007	0.0	0.4	0.007	0.1

Figures 6a and 6b show the histogram of ΔE^*_{94} between the measured spectral reflectance and the spectral reflectance predicted using a transformation matrix from 9 digital counts to the weights of 6 eigenvectors of the printed patches, for the printed patches and the GretagMacbeth ColorChecker, respectively.

Comparing Table I and II, Figure 4a, 4b and 6a, 6b it is possible to notice that the accuracy of the estimation using real digital counts was slightly worse than the theoretical simulation as expected but an average ΔE^*_{94} of 1.0 and 1.2 are excellent results for the spectral estimation considering the noise introduced by the digital imaging. Figures 7a and 7b show two examples of a spectral match for the printed patches. Figures 7c and 7d show two examples of a spectral match for the GretagMacbeth ColorChecker.

The generated transformation matrix was used to generate a spectral image of all the targets for spectral printing. A trichromatic rendering is shown in Figure 8. The spectral image was converted to a XYZ image (D50 and 2 degree observer) and then converted to a D65 white point using Bradford transformation and finally displayed using sRGB and 1.8 gamma factor.

A visual inspection comparing the original printing and the rendered image show very high color accuracy. Some artifacts, probably due to some aliasing between the printing patterns and the CCD were observed, that was particularly noticeable in the printed patches. Such artifacts can lead to lower accuracy in the average match for the patches after the spectral printer processing.

Figures 9a to 9l show spectral plots of arbitrary pixels of various color regions of the printed painting spectral image. The coordinates of the entire image is also indicated for each plot.

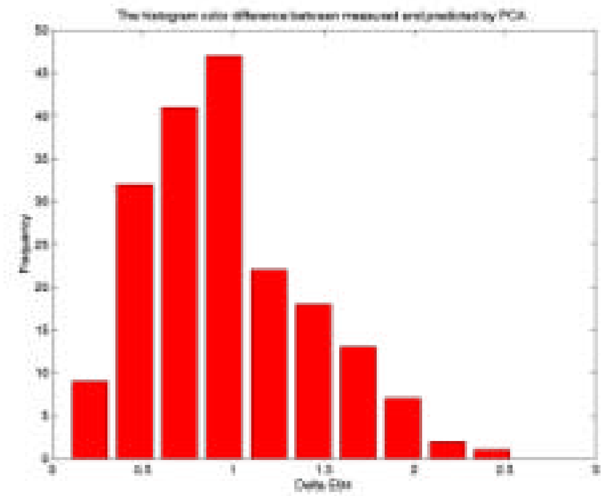


Figure 6a. ΔE^*_{94} histogram for reconstructed of the printed patches using 6 eigenvectors from the printed patches.

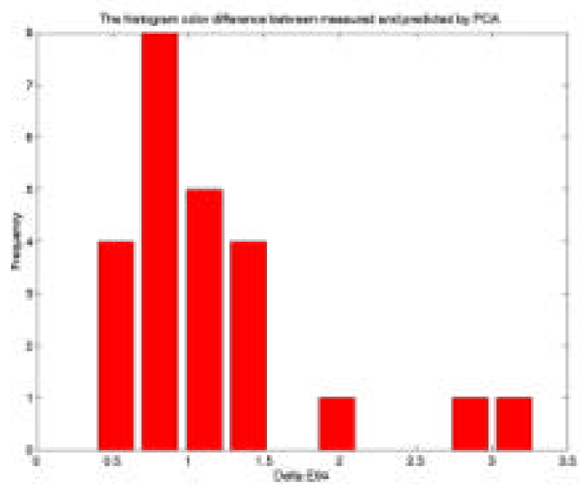
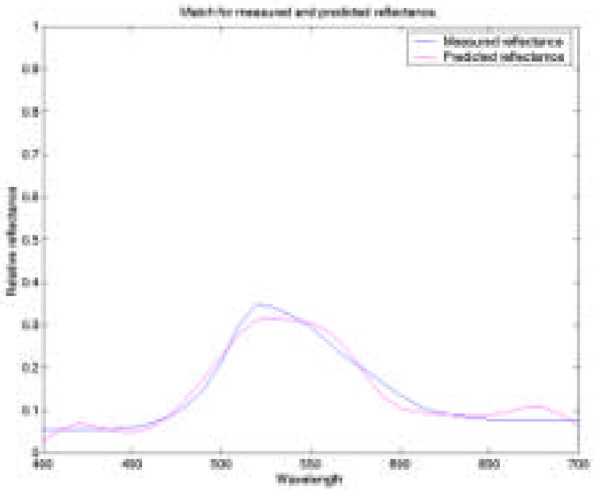
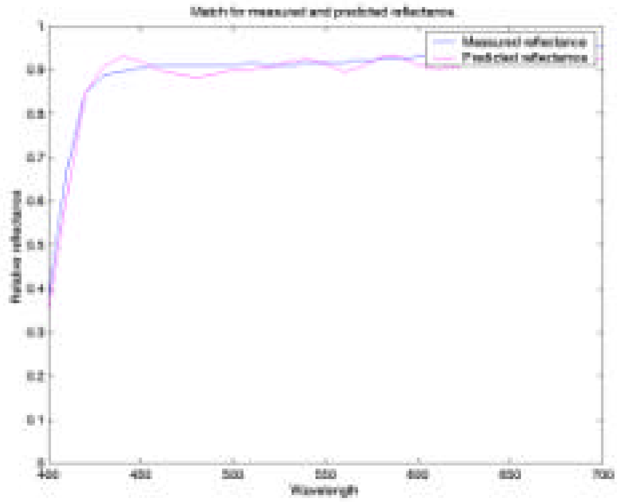


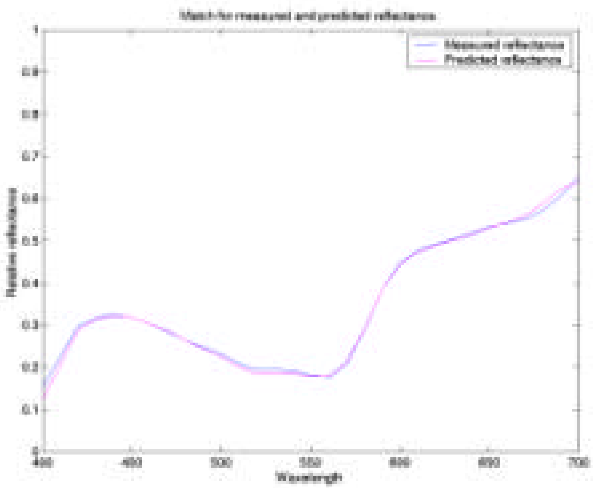
Figure 6b. ΔE^*_{94} histogram for the GretagMacbeth ColorChecker reconstructed using 6 eigenvectors from the printed patches.



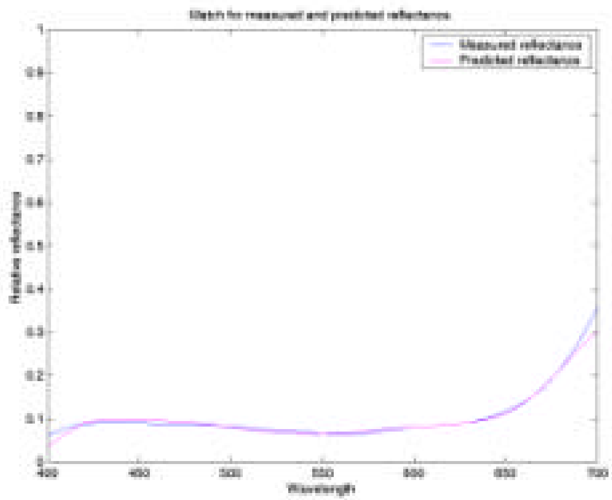
a GretagMacbeth ColorChecker green Patch



b GretagMacbeth ColorChecker white Patch



c Printed patch 10 (magenta – first column from left to right and 10th row from top to bottom)



d Printed patch 132 (dark brown – 12th column from left to right and 1st row from top to bottom).

Figure 7. Comparison between measured spectral reflectance (blue curve) and estimated spectral reflectance (magenta curve).

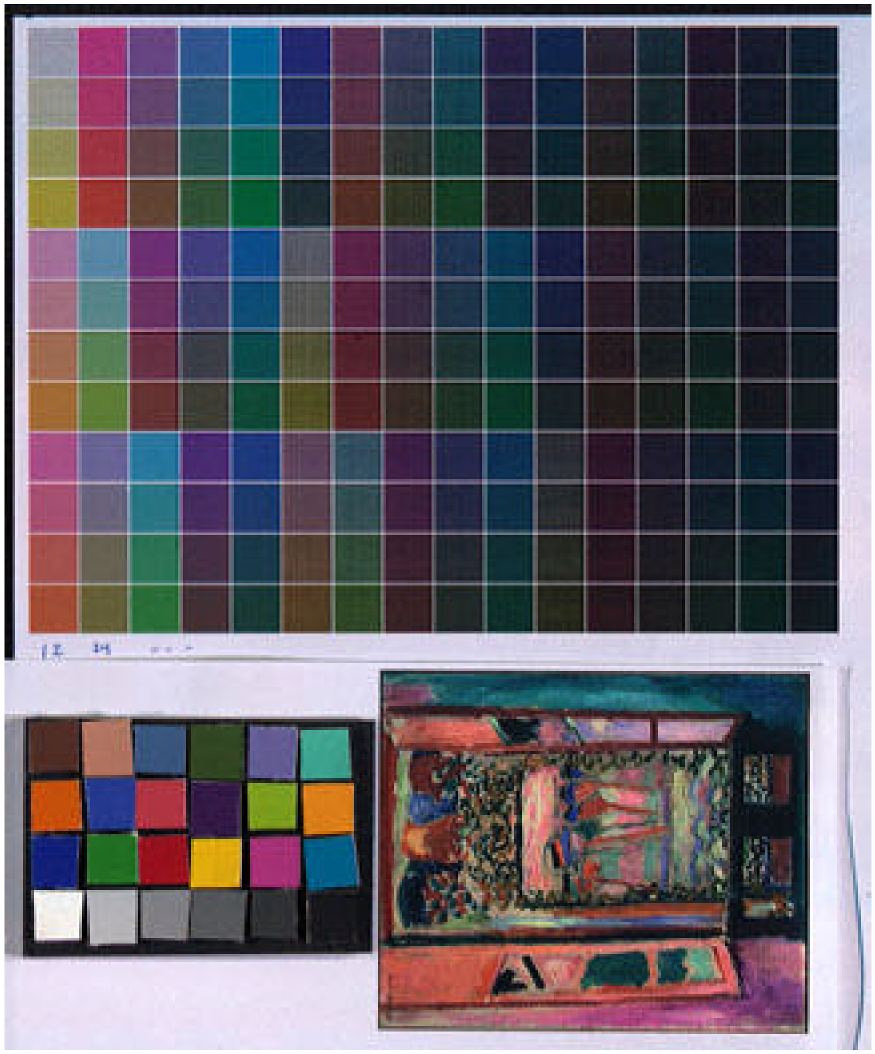
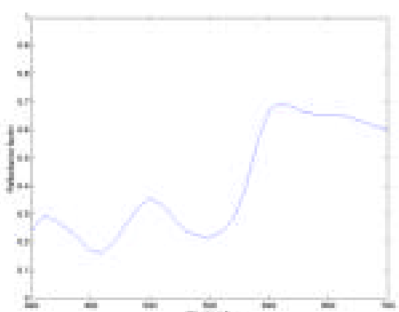
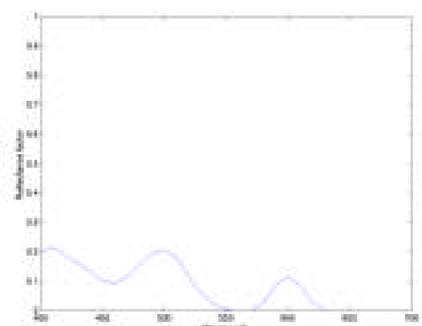


Figure 8. Rendering of the generated spectral image.

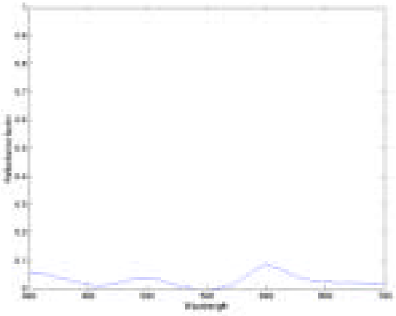


a) Beige
(coordinates x=640, y=1050)

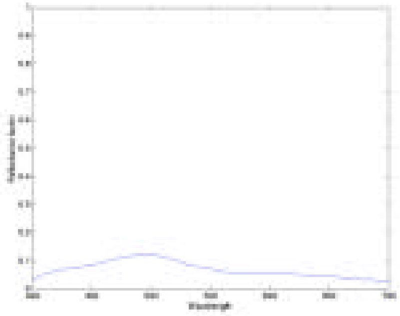
b) Black
(coordinates x=740, y=1050)



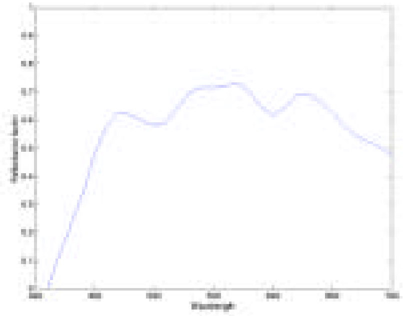
c) Dark Blue
(coordinates x=1080, y=1000)



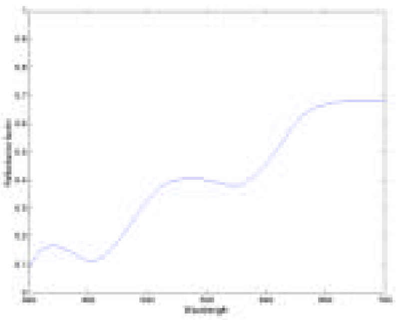
d) Dark brown
(coordinates x=665, y=1025)



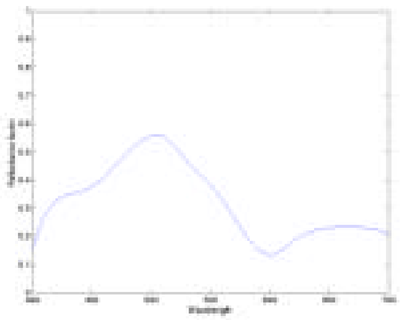
e) Dark green
(coordinates x=900, y=1400)



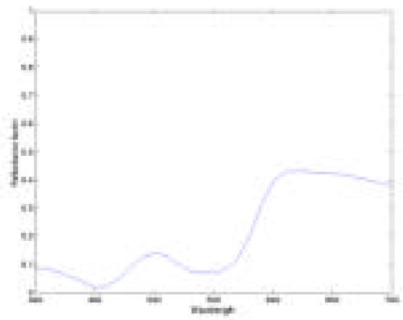
f) Emerald Green
(coordinates x=580, y=1140)



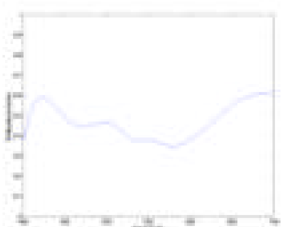
g) Light beige
(coordinates x=600, y=1215)



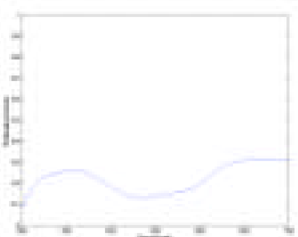
h) Light blue
(coordinates x=880, y=1000)



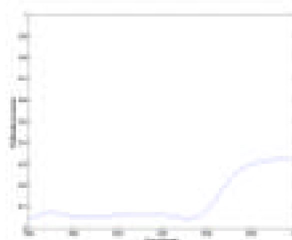
i) Light brown
(coordinates x=580, y=1225)



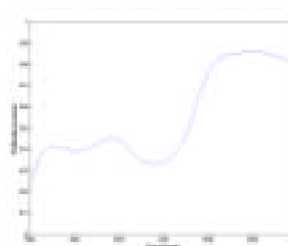
j) Light purple
(coordinates x=850, y=1050)



k) Magenta
(coordinates x=600, y=1005)



l) Median brown
(coordinates x=600, y=1120)



m) Pink
(coordinates x=910, y=1150)

Figure 9. Spectral plots of various regions of the printing.

Discussions

The experiment showed that spectral reconstruction using eigenvectors generated from a printed target with patches with better distribution in the color space produced very good results in terms of spectral, colorimetric accuracy as well as visual match. This approach worked well even for a different target, such as the GretagMacbeth ColorChecker. One big issue that should be examined more carefully will be directed to find ways to minimize the artifacts generated by the interaction of the camera imaging system and the printing patterns.