Spectral characterization of a hyperspectral system for imaging of large art paintings

F.M.P.B. Ferreira; Universidade da Beira Interior, Unidade de Detecção Remota/Centro de Óptica, Departamento de Física; Covilhã, Portugal

P.T. Fiadeiro; Universidade da Beira Interior, Unidade de Detecção Remota/Centro de Óptica, Departamento de Física; Covilhã, Portugal

S.M.C. Nascimento; Universidade do Minho, Departamento de Física; Braga, Portugal

V.M.N. de Almeida; Universidade da Beira Interior, Unidade de Detecção Remota/Centro de Óptica, Departamento de Física; Covilhã, Portugal

M.J.T. Pereira; Universidade da Beira Interior, Unidade de Detecção Remota/Centro de Óptica, Departamento de Física; Covilhã, Portugal

J.M.D.P. Bernardo; Universidade da Beira Interior, Departamento de Física; Covilhã, Portugal

Abstract

Spectral imaging of art paintings has been carried out using multi and hyperspectral systems with spectral filters mounted in front of the imaging device. This type of configuration exposes the painting to light not used by the imaging device and it is not suitable for large paintings when high resolution is required. The purpose of this work was the development and the spectral characterization of a hyperspectral system provided with an electronically fast-tunable liquid-crystal filter, mounted in front of the light source, and with an automatic XY motorized table for accurate spatial scanning of large paintings. A GretagMacbeth ColorChecker® and 2 oil paintings were imaged by the proposed hyerspectral system and the spectral reflectance of each pixel was estimated. The quality of the spectral recovery was quantified by comparing the spectral reflectance estimated with the hyperspectral system with that measured with a telespectroradiometer. The comparisons produced average root mean square errors less than 1.3%, and average colorimetric differences less than 1.7 ΔE^*_{ab} *units and less than 1.0* ΔE_{00} *units. These data suggest that the described hyperspectral system can record spectral and colorimetric information from artistic oil paintings with high accuracy.*

Introduction

The growing interest on spectral and colorimetric characterization and reproduction of original art paintings has stimulated the development of advanced techniques to create spectral archives of art paintings [1, 2]. Spectral imaging of paintings has been carried out using multi [3-6] and hyperspectral systems [7, 8] with the spectral filters mounted in front of the imaging device. This type of configuration have problems and limitations as it exposes unnecessarily the painting to light not used by the imaging device, and is limited in the size of the paintings that can be imaged with acceptable resolution.

The purpose of this work was the development and the spectral characterization of a hyperspectral system provided with an electronically fast-tunable liquid-crystal filter, mounted in front of the light source, and with an automatic XY motorized table to allow spatial scanning of large paintings. With this configuration, the painting is less exposed to light and high spatial resolution can be achieved with a macro lens and an adequate spatial scanning procedure. Image synthesis is accomplished by combining the different scanned areas, which were accurately positioned during acquisition.

To assess the quality of spectral recovery by the system, the GretagMacbeth ColorChecker® color rendition chart with 24 colors and 2 oil paintings were imaged and the spectral reflectance of each pixel was estimated. The quality of spectral recovery was quantified by comparing the average of the estimated spectral reflectance over small areas with that measured with a telespectroradiometer. For the Macbeth ColorChecker chart, an average root mean square error less than 1%, and an average colorimetric difference of approximately 1.2 ΔE^*_{ab} units and less than 0.8 ΔE_{00} units were obtained. For the 2 oil paintings, the values for the average root mean square error and colorimetric differences in ΔE^*_{ab} and ΔE_{00} units were 1.27%, 1.65 and 0.98, respectively.

Methods

Apparatus

The imaging system used a Peltier-cooled digital camera with spatial resolution of 1344 × 1024 pixels and 12-bit precision (Hamamatsu, model C4742-80-12AG) and a fast-tunable liquid-crystal filter (VariSpec, model VIS-10, Cambridge Research & Instrumentation, Inc., MA) mounted in front of a stabilized Xenon light source with an infrared blocking filter. The camera had an electronic shutter allowing the control of the exposure time between 10 μs and 4200 s. The peak-transmission wavelength of the liquid-crystal filter could be selected in the range 400–720 nm and the bandwidth (FWHM) was 10 nm at 550 nm, decreasing to 7 nm at 400 nm and increasing to 16 nm at 720 nm. The filter had a 35 mm aperture and a field of view of ±7 deg. An infrared blocking filter was also attached to the liquid-crystal filter to avoid some infrared contamination during the image acquisition. The lens attached to the camera was 12.5–75.0 mm focal length (Schneider, model 1533), with a variable numerical aperture set to *f*/11, and typically operating in macro mode. The system provides an image size of 7.3 × 5.7 cm^2, corresponding to a resolution of 18 pixels/mm. To perform the image data acquisition of paintings, the system was mounted on a XY motorized table (Newport, model ESP300 + 2 × ILS250), with a resolution of 1.5 μm . The complete painting can be analyzed by acquiring and imaging individually adjacent areas.

The settings of the camera, of the tunable filter, and of the XY motorized table were controlled and synchronized by a routine running on the host computer and developed in-house in MatLab.

As shown in Figure 1, the geometry of the illumination was 45º/0º, where LS represents the light source, LCF the fast-tunable liquid-crystal filter, DC the digital camera, MO the macro objective lens, PH the painting holder, and MT the XY motorized table.

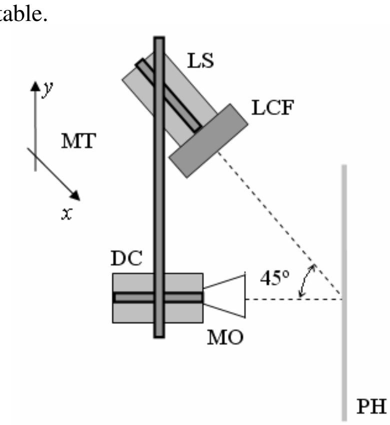

Figure 1. *Schematic diagram of the hyperspectral apparatus.*

Acquisition and Processing

The 2 objects, the Macbeth ColorChart and the paintings, under study were sequentially illuminated with monochromatic light in the spectral range of the filter in 10 nm increments, from 400–720 nm, and for each wavelength an image was acquired. A uniform white reference surface (Labsphere, model SRT-99-050, Spectralon diffuse reflectance target), with 99% reflectance, was used to determine the exposure time for each of the 33 wavelengths, and the corresponding hyperspectral images of the white reference were acquired. The exposure time for each wavelength was variable and was computed before acquisition such that, the maximum signal in the image was 96% of the maximum allowed by the digital camera. The hyperspectral images of the objects under study can be acquired with the same exposure times of the white reference. Both, objects and white reference were placed in the same plan on the painting holder. To correct for dark current noise effect, noise images were acquired using the same exposure time, but with the camera lens covered [3], and each noise image was subtracted from the object and white reference images for each wavelength. To correct for the effects of camera sensitivity, optical path transmittance through the lens and tunable filter, as well as for the spatial distribution of the illuminant, the quotient between the corrected hyperspectral image data from the object and from the white reference was calculated. The spectral reflectance of each pixel was then estimated by multiplying the result of such quotient by the known spectral reflectance of the white reference.

Accuracy and Precision

The performance of the system in recovering spectral reflectance was tested using small colored areas selected from the Macbeth ColorChart and from 2 oil paintings. The spectral reflectances estimated by the hyperspectral system were then compared with the corresponding spectra measured with a telespectroradiometer (SpectraColorimeter, PR-650, Photo Research Inc., Chatsworth, CA).

To quantify the performance of the hyperspectral system in recovering the spectral reflectance, hyperspectral images of the 24 patches of the Macbeth ColorChart were acquired and processed. Each color patch was divided into nine small areas, as exemplified for the first patch in figure 2 that is three areas on top, three in the middle and three on bottom.

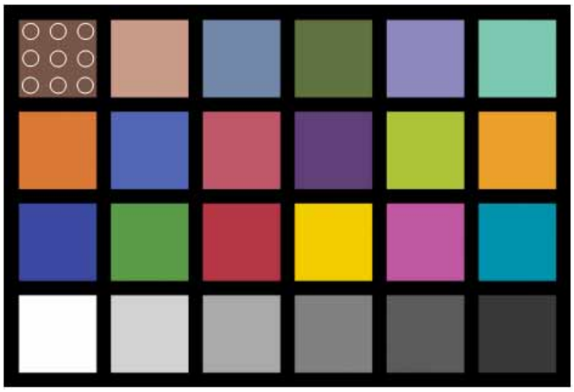

Figure 2. *Picture of GretagMacbeth ColorChart® with the identification of the relative position for the selected areas.*

These selected areas had the same shape and size as those measured by the telespectroradiometer, which correspond to 1º field of measuring.

Two artistic oil paintings, kindly granted by a local painter, Mr. Alves de Sousa, were also used to recover their spectral reflectances. The dimensions of these two paintings are 24 × 18 cm^2. The paints surface are smooth, however some brush marks are visible. Due to the size of the acquired images, a total of 20 images were necessary to completely scan the oil paintings. Each painting, was divided into 155 small areas, with the same shape and size as those measured by the telespectroradiometer for later comparison.

Results

The quality of the colorimetric recovery was assessed using the CIELAB color differences between the estimated color and corresponding measurement obtained with the telespectroradiometer expressed in ΔE^*_{ab} and ΔE_{00} units [9-11], using the standard illuminant D65 and 2º standard observer.

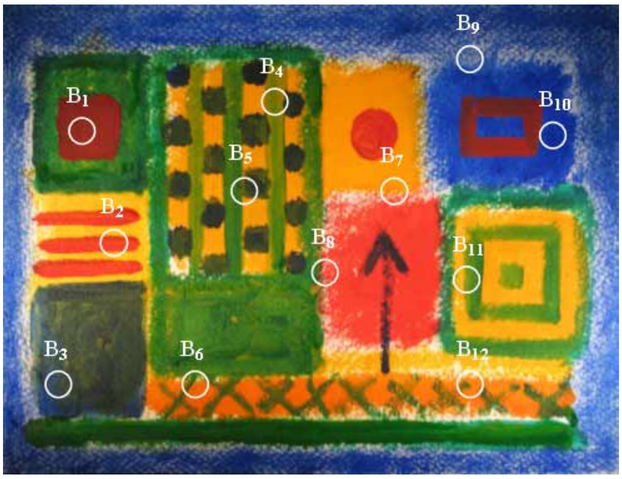

Figure 3. *Pictures of the 2 oil paintings analyzed in this study.* (A) (B)

Table 1. Quality of the spectral recovery for the Macbeth ColorChart.

Color Name	Parameters			
	ΔE^*_{ab}	ΔE_{00}	*RMSE* (%)	*GFC* (%)
Dark Skin	1.36	1.03	0.40	99.96
Light Skin	0.33	0.22	0.60	99.99
Blue Sky	0.44	0.36	0.40	99.99
Foliage	1.02	0.85	0.50	99.97
Blue Flower	0.49	0.39	0.60	99.99
Bluish Green	1.08	0.75	0.80	99.99
Orange	2.45	1.38	1.00	99.97
Purplish Blue	0.57	0.26	0.60	99.97
Moderate Red	1.02	0.55	0.70	99.99
Purple	0.66	0.39	0.90	99.91
Yellow Green	2.22	0.88	1.10	99.98
Orange Yellow	2.44	0.85	1.30	99.99
Blue	1.30	0.80	3.10	97.62
Green	2.06	0.95	0.60	99.97
Red	1.95	1.13	1.00	99.98
Yellow	2.29	0.66	1.40	99.99
Magenta	1.20	0.58	0.90	99.99
Cyan	1.36	0.90	0.70	99.99
White	0.61	0.52	1.10	100
Neutral 8	0.64	0.64	1.00	99.99
Neutral 6.5	0.78	0.77	0.90	99.99
Neutral 5	0.69	0.79	0.40	99.99
Neutral 3.5	1.00	0.97	0.50	99.98
Black	1.31	0.93	0.30	99.88
Average	1.22	0.73	0.90	99.88
Standard Deviation	0.67	0.29	0.60	0.48

Table 2. Quality of the spectral recovery for the 2 oil paintings.

Oil painting selected areas	Parameters			
	ΔE^*_{ab}	ΔE_{00}	*RMSE* (%)	*GFC* (%)
A_1	1.22	1.00	0.90	99.99
A_2	1.56	1.69	0.50	99.88
A_3	1.37	1.11	1.00	99.99
A_4	2.05	1.50	3.20	99.99
A_5	1.04	0.68	0.17	100
A_6	0.75	0.42	0.90	100
A_7	0.85	0.66	1.30	99.72
A_8	0.90	0.85	0.80	99.99
A_9	2.21	1.67	1.00	99.91
A_{10}	0.46	0.40	2.10	99.72
A_{11}	2.21	1.35	0.90	99.98
A_{12}	1.14	0.63	1.60	99.99
B_1	0.58	0.43	0.70	99.96
B_2	3.06	1.57	1.10	99.98
B_3	1.41	1.13	0.80	99.91
B_4	3.90	1.58	0.80	99.95
B_5	2.03	1.14	0.70	99.95
B_6	2.49	1.05	0.70	99.99
B_7	1.07	0.79	1.50	99.98
B_8	2.27	0.77	1.70	99.98
B_9	1.09	0.37	4.00	99.54
B_{10}	2.14	0.62	1.70	99.63
B_{11}	1.70	0.77	1.00	99.96
B_{12}	2.07	1.23	1.40	99.97
Average	1.65	0.98	1.27	99.92
Standard Deviation	0.83	0.42	0.85	0.13

The quality of the spectral recovering was quantified using the root mean square error formulae (*RMSE*) and the goodness-of fit coefficient (*GFC*) [12], between the estimated and measured by the telespectroradiometer.

Table 1 shows the results for evaluation of the spectral recovery quality for the Macbeth ColorChart. The values for the colorimetric accuracy, as well as the root mean square error and the goodness-of fit coefficient concern the average of the nine selected areas for each color patch.

Relatively to the presented results, it is possible to verify that the average of the color differences was 1.22 ΔE^*_{ab} units, with a minimum value of 0.33 units and a maximum of 2.45 units. Concerning the ΔE_{00}, the average value was 0.73 units, with a minimum and maximum values of 0.22 and 1.38 units, respectively. For neutral colors, the color differences are approximately the same. The values for ΔE^*_{ab} are in range of those shown on previous studies, for color reproduction of the Macbeth ColorChart [1, 13].

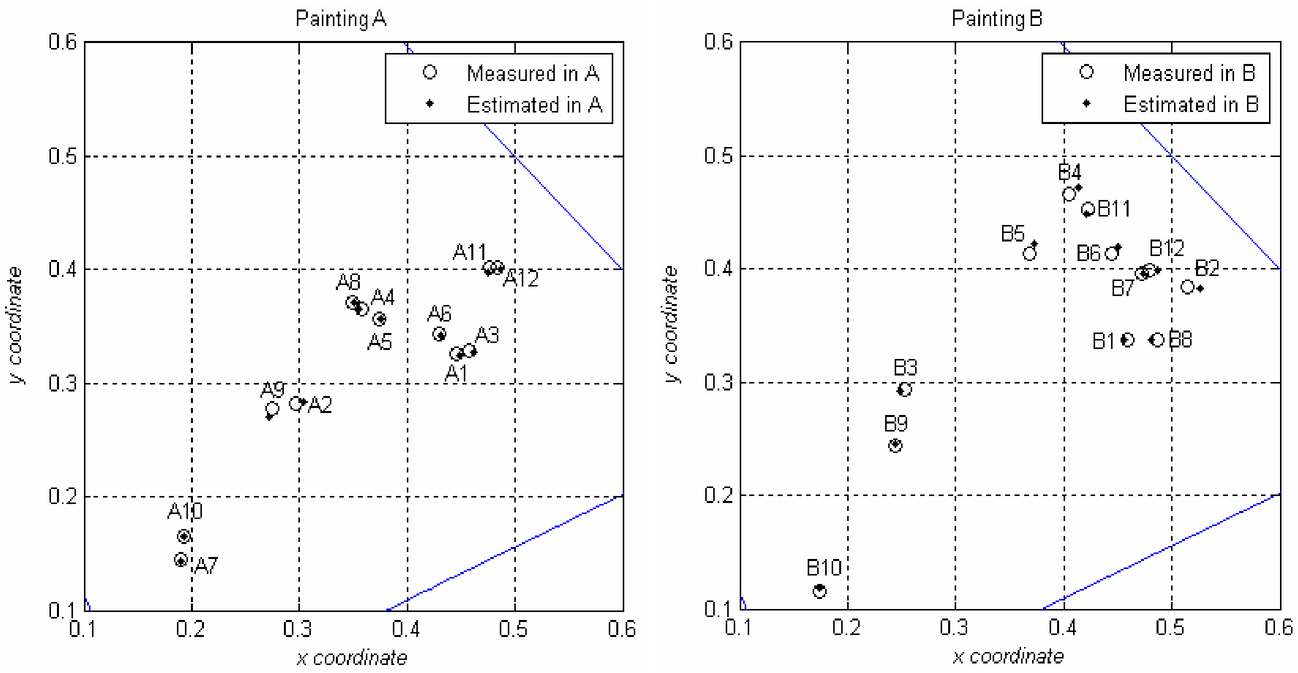

Figure 4. *Chromaticity distributions in the CIE (x,y) 1931 diagram of the 12 selected areas for the painting A and B.*

Concerning the average of the spectral root mean square error, the result was less than 1.0%, in the range of 0.3% and 3.1%. The higher value corresponds to the “Blue” patch where the pigment of this color depicts some fluorescence not taken into account by the system.

Figure 3 shows the pictures of the 2 artistic oil paintings analyzed and the corresponding 12 selected areas for comparison measurements are indicated by white circumferences.

The results for evaluation of the spectral recovery quality for the 2 oil paintings are shown in table 2. For the ΔE^{*}_{ab}, the range values was of 0.46 and 3.90 units, with a average of 1.65 units. Regarding to the ΔE_{00}, the achieved values were between 0.37 and 1.69 units, and an average of 0.98 units. Finally, for the root mean square errors, the values are in the range 0.17% to 4.00%, and an average of 1.27%. For the goodness-of fit coefficient, which has an average of 99.92%, it was found a minimum value of 99.54% and a maximum value of 100%. However, these results, in terms of colorimetric and spectral accuracy and precision, can be acceptable for a good quality of color reproduction and spectral matching [1, 12].

Some colored areas have high colorimetric errors and lower spectral differences. It was also possible to find some colored areas with low colorimetric errors and higher spectral differences. This appears to result from the fact that, for the first case, some of the selected areas have different color brush strokes, whereas for the second case, the selected areas consist in a single color brush stroke of blue ink, which contaminates the spectral reflectances as it occurred in the Macbeth ColorChart.

Figure 4 shows in the CIE *(x,y)* 1931 diagram the chromaticity distribution of the 12 selected areas for each oil painting. The values estimated by the hyperspectral system are represented by black dots, and the corresponding measurements made by the telespectroradiometer are represented by circumferences.

In some areas, a slight deviation between the measured and estimated values can be observed. These deviations are more perceptibly in diagram of the painting B, which has higher colorimetric errors than painting A.

Conclusions

The quality of the spectral recovery obtained by the system described in this paper is better than that reported by previous studies using configurations with the spectral filters mounted in front of the imaging device [5, 6, 8]. These data suggest that this system can record spectral and colorimetric information from artistic oil paintings with an accuracy that is adequate for most applications.

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References

[1] R. S. Berns, "The science of digitizing paintings for color-accurate image archives: A review," Journal of Imaging Science and Technology, vol. 45, pp. 305-325, (2001).

[2] K. Martinez, J. Cupitt, D. Saunders, and R. Pillay, "Ten years of art imaging research," Proceedings of the IEEE, vol. 90, pp. 28-41, (2002).

[3] H. Haneishi, T. Hasegawa, A. Hosoi, Y. Yokoyama, N. Tsumura, and Y. Miyake, "System design for accurately estimating the spectral reflectance of art paintings," Applied Optics, vol. 39, pp. 6621-6632, (2000).

[4] S. Baronti, A. Casini, F. Lotti, and S. Porcinai, "Multispectral imaging system for the mapping of pigments in works of art by use of principal-component analysis," Applied Optics, vol. 37, pp. 1299-1309, (1998).

[5] F. H. Imai, M. R. Rosen, and R. S. Berns, "Multi-spectral imaging of van Gogh's self-portrait at the National Gallery of Art, Washington, DC," in Pics 2001: Image Processing, Image Quality, Image Capture, Systems Conference, Proceedings, pp. 185-189, (2001).
[6] R. S. Berns, L. A. Taplin, F. H. Imai, E. A. Day, and D. C. Day, "Spectral Imaging of Matisse's Pot of Geraniums: A case study," in Eleventh Color Imaging Conference: Color Science and Engineering - Systems, Technologies, Applications, pp. 149-153, (2003).
[7] S. M. C. Nascimento, F. P. Ferreira, and D. H. Foster, "Statistics of spatial cone-excitation ratios in natural scenes," Journal of the Optical Society of America A - Optics Image Science and Vision, vol. 19, pp. 1484-1490, (2002).
[8] J. A. Carvalhal, J. M. M. Linhares, S. M. C. Nascimento, M. H. Regalo, and M. C. V. P. Leite, "Estimating the best illuminants for appreciation of art paintings," in AIC Colour 05 - Proceedings of the 10th Congress of the International Colour Association, vol. 1, Proceedings of the 10th Congress of the International Colour Association, pp. 383-386, (2005).
[9] K. Mclaren, "Development of CIE 1976 (LAB) Uniform Color Space and Color-Difference Formula," Journal of the Society of Dyers and Colourists, vol. 92, pp. 338-341, (1976).
[10] M. R. Luo, G. Cui, and B. Rigg, "The development of the CIE 2000 colour-difference formula: CIEDE2000," Color Research and Application, vol. 26, pp. 340-350, (2001).
[11] M. R. Luo, G. Cui, and B. Rigg, "Further comments on CIEDE2000," Color Research and Application, vol. 27, pp. 127-128, (2002).
[12] F. H. Imai, M. R. Rosen, and R. S. Berns, "Comparative study of metrics for spectral match quality," in CGIV'2002: First European Conference on Colour in Graphics, Imaging, and Vision, Conference Proceedings, pp. 492-496, (2002).
[13] P. D. Burns and R. S. Berns, "Analysis multispectral image capture," in Fourth Color Imaging Conference: Color Science, Systems and Applications - Final Program and Proceedings of IS&T/SID, pp. 19-22,(1996).

Author Biography

Francisco Ferreira graduated in 1996 in Applied Physics by University of Beira Interior . Since 1997 is assistant research in the Department of Physics at the University of Beira Interior, teaching courses in the fields of optics and vision science. Actually is a PhD student. The research interests are in colorimetry and color vision, in particular, applications on hyperspectral systems and imaging.