Spectral estimation of artist oil paints using multi-filter trichromatic imaging

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ABSTRACT

A practical and easy way to capture images of oil paintings and estimate their spectral reflectance as a function of position was tested. For the image acquisition, a trichromatic digital camera was used in conjunction with an absorption filter producing six channels. From an *a priori* statistical analysis of common artist oil paints, spectral reflectance was estimated. These experiments showed that it is possible to estimate the spectral reflectance with an accuracy of average ΔE^*_{94} of 1.7 and spectral reflectance rms error of 2.2%. Of particular interest is guidance towards the design of a universal calibration target for imaging paintings.

Keywords: Multi-channel visible spectrum imaging (MVSI), image input, digital image capture, artwork reproduction, multi-spectral acquisition, spectral estimation.

1. INTRODUCTION

In many museums, once an image is captured, deficiencies in the imaging capture system are usually handled through visual adjustments of tone and color balance using tools such as Adobe Photoshop™. Although these adjustments can produce pleasant results, they are not acceptable in terms of color accuracy for applications such as digitally archiving artwork.

Multi-channel visible spectrum imaging (MVSI), also known as multi-spectral imaging, can give a more accurate representation of the image.[1] In order to improve color accuracy, the National Gallery in London, UK has pioneered the development of a multi-spectral imaging system resulting in a colorimetric image archive for their collection.[2] However, colorimetric matching decisions are prone to problems associated with metamerism: intransigence to change in illumination, lack of forgiveness for differences between individuals and the standard observer, and high sensitivity to printer noise and calibration errors. Spectral-based reproduction is far more robust with respect to these limitations. Many researchers have been experimenting with MVSI techniques to capture art paintings.[3,4] These techniques are based on the spectral analysis of the paints. Although spectral information has large dimensionality because the sampling typically from 400 nm to 700 nm in intervals of 10 nm, eigenvector analysis of spectra[5,6] shows that it is possible to reduce the dimension of the spectral information without considerable loss of information due to the smoothness of natural object spectral reflectance curves.

At the Munsell Color Science Laboratory, we have been drawing upon this body of successful work and extending it to produce an end-to-end scene to hardcopy spectral reproduction system. The spectral information provides printed color reproductions that are close spectral matches to the original objects producing high-quality color matching under different illuminations and observers.[7,8] In this paper we are going to concentrate in the input part of system. The first and most direct method to capture spectral data is to increase the sampling increment above the traditional three channels using highly selective, spectrally narrow filtering. The acquisition system becomes a spatial spectrophotometer with appropriate calibration providing a method that is robust for any arbitrary spectral shape. However, we also need to consider other multi-spectral acquisition approaches that would be sufficiently easy, fast, simple to be implemented in museum archival departments, and that provide reasonably accurate spectral reflectance estimation. Considering the smoothness of the spectral curves of the most commonly used pigments, it is possible to reduce the number of channels by means of eigenvector analysis.[9]

Based on these facts we proposed a wide-band image acquisition combined with either a number of colored filters[10] or a number of differently colored light sources. The captured images are converted to a spectral reflectance image

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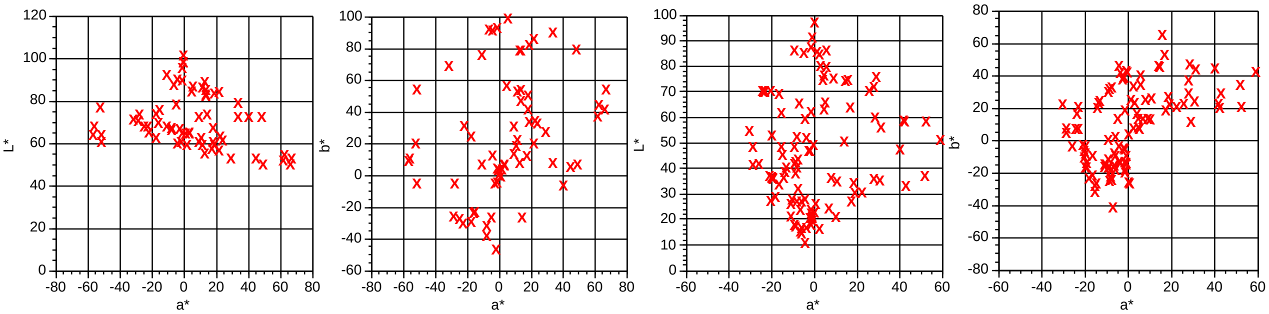
using colorant information known *a priori*. In this case, if the colorants for a particular painting are available it is possible to make targets with the colorants to perform *a priori* spectral analysis. However, generally such information is not readily available without performing either historical or chemical analyses of the paintings. It is necessary to consider the possibility of designing a "universal" oil painting target that can be used when the colorant information is not available.

In this paper we present a method of spectral reflectance estimation for paintings using a transformation from digital signals to reflectance based on *a priori* analysis of a general oil painting target.

2. EXPERIMENTAL

In our experiments we used two oil paint targets. One of the oil painting targets, that we call *Ross target* (painted by Ross Merrill, Head of Conservation at the National Gallery of Art, Washington, DC), was created using 68 pigments dispersed in linseed oil representing blues, greens, yellows, reds, earth colors, browns and radiant colors commonly used by artists. Another oil painting target, called *van Gogh target*,[8] was created by Roy Berns, consisting of 106 patches made from cobalt blue, prussian blue, naples yellow, yellow ochre, cadmium red medium, ivory black, and titanium white, representative of the colors present in one van Gogh self-portrait painted in 1889, part of the Whitney collection at the National Gallery of Art, Washington. The paints chosen for the *van Gogh target* were based on spectral measurements performed on the self-portrait painting. All the spectral measurements were performed using the GretagMacbeth SpectroEye 45/0 spectrophotometer. The color distributions of *Ross* and *van Gogh targets* are shown in Figure 1.



a*) Ross target* a* x L* b*) Ross target* a* x b* *a) van Gogh target* a* x L* *b) van Gogh target* a* x b*

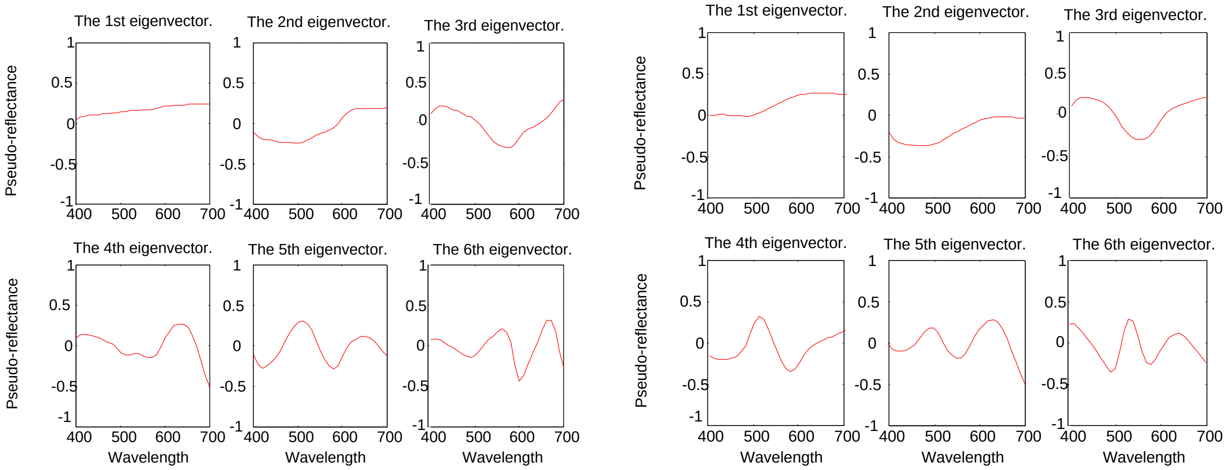
Figure 1. Colorimetric plots for the *Ross* and *van Gogh target* (under D50 illuminant, 2° observer).

Both *Ross* and *van Gogh targets* were imaged using the same illuminants, set of absorption filters, camera system and imaging geometry. For the imaging system we used a medium-spatial resolution trichromatic IBM Pro 3000 digital camera system[8] that consists of a monochrome scanning back and a filter wheel (3,072 x 4,096 pixels, R, G, B filter wheel, dark current corrected 12 bits per channel that has a 45°/0° imaging configuration using tungsten-halogen illumination). Multi-channel images were obtained combining the IBM trichromatic images without external filtering and with a Kodak Wratten filter number 38 (light blue filter). White spatial correction was performed to the captured image to account for spatial non-uniformity of the illumination. The *Ross target* was used as a calibration target. The eigenvectors of the *Ross target* were computed from its measured spectral reflectances. A transformation was derived to convert digital signals to spectral reflectances using the computed eigenvectors. The transformation derived for the *Ross target* was used to estimate the spectral reflectances of the *van Gogh target* from the digital counts of the *van Gogh target.*

The evaluation of the spectral reflectance of the MVSI acquisition system is then subdivided in two parts. At first, eigenvector analysis is evaluated theoretically reconstructing the spectral reflectances from the derived eigenvectors and eigenvalues and comparing the estimated reflectances with the measured spectral reflectances. In the following stage the spectral reflectance is estimated from the eigenvectors and actual digital counts. The estimated spectral reflectances are then compared to the original spectral reflectances.

3. RESULTS

Figure 2 show the first six eigenvectors for the spectral reflectances of both *van Gogh* and *Ross targets*.



a) *van Gogh target* b*) Ross target*

Figure 2. First to sixth eigenvectors of the spectral reflectances for the *van Gogh* and *Ross targets*.

From Figure 2 it is possible to see that the eigenvectors for the *van Gogh target* is very similar to those of the *Ross target*. This indicates that the transformation from digital counts to spectral reflectance derived for our calibration target (in this case *Ross target*) possibly can be used for the pigments of a particular painting (in this case the *van Gogh target*). Therefore we estimated the spectral reflectance of the *van Gogh target* using the eigenvectors and the transformation derived from the *Ross target*; table I shows the colorimetric and spectral performance.

Table I. Cumulative variance contribution and influence of the number of eigenvectors used in the spectral reconstruction of the *Ross target* and *van Gogh target* on the colorimetric and spectral error. ΔE$^*_{94}$ calculated for D50 and the 2° observer of the eigenvectors in reflectance space. (The eigenvectors were derived from the *Ross target* in both cases.)

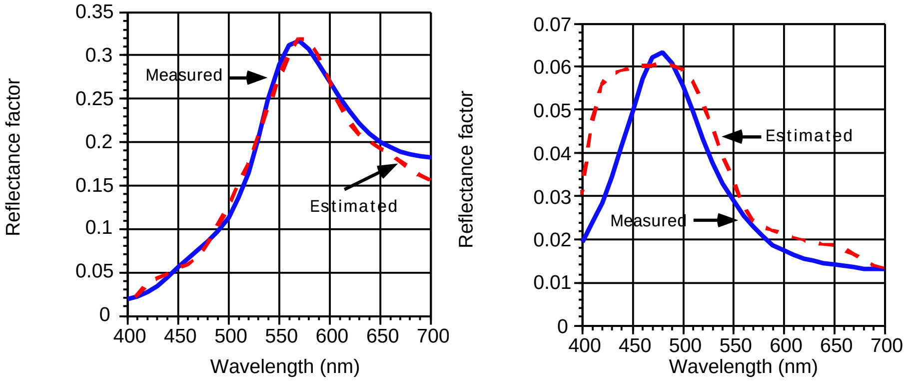
Number of eigenvectors	Cumulative variance contribution (%)	Ross Target		Van Gogh Target	
		Mean ΔE$^*_{94}$ (D50, 2°)	Spectral reflectance rms error factor	Mean ΔE$^*_{94}$ (D50, 2°)	Spectral reflectance rms error factor
3	97.28	2.6	0.022	4.2	0.029
6	**99.61**	**0.7**	**0.011**	**0.6**	**0.010**
9	99.93	0.1	0.003	0.3	0.005
12	99.99	0.03	0.002	0.05	0.002

From Table I it is possible to notice that six eigenvectors can reconstruct the original spectrum with 99.6% accuracy. From the colorimetric and spectral evaluations, we can conclude that the use of six eigenvectors to reconstruct spectra is a good compromise between accuracy and our aim of reducing the number of channels. Theoretically, using six eigenvectors to reconstruct spectra gives colorimetric error less than one ΔE$^*_{94}$ unit and spectral reflectance rms error of approximately 1%. The spectral reflectance of the *van Gogh target* was estimated from its digital counts using the transformation derived for the *Ross target*. The results are summarized in Table II. The metameric index was calculated using the Fairman metameric black method, between standard illuminants D50 and A using ΔE$^*_{94}$ in the calculations.[11]

Table II. Colorimetric and spectral accuracy of van Gogh oil painting target spectral estimation using six signals (R,G,B without filter and with light-blue absorption filter) using transformation derived from the Ross target.

Measure	ΔE$^*_{94}$(D50, 1931)	reflectance factor rms error	Metameric Index (ΔE$^*_{94}$,D50, 1931)
Average	**1.7**	**0.022**	**0.3**
Std Dev	1.0	0.016	0.2
Max	4.5	0.091	1.1
Min	0.3	0.004	0.03

From Table II, it is seen that the *van Gogh target* spectral reflectances are reasonably well estimated using the *Ross target* as the calibration target. Figure 3 shows the best and worst spectral matches between the measured and estimated reflectances. The best spectral match was found for a mixture of yellow ochre, naples yellow and prussian blue and the worst match was a very dark mixture of cobalt blue, prussian blue and ivory black. Generally these dark colors are very difficult to match.



a) Best spectral match

b)Worst spectral match

Figure 2. Comparison of the spectral reflectances between measured and estimation. (Note scale differences in reflectance factor.)

4. CONCLUSIONS

Our experiments showed that it is possible to estimate spectral reflectance with an average accuracy of 1.7 ΔE^*_{94} and a 2.2% spectral reflectance rms error using a target of commonly used oil paints. These results are encouraging regarding the design a universal target to derive the eigenvectors that are necessary for the spectral estimation. The use of a universal target will be fundamental for the cases in which we do not know the spectral characteristics of the pigments of a particular painting.

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