A New Multi-spectral Imaging System for Examining Paintings

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Abstract

A new multi-spectral system developed at the National Gallery is presented. The system is capable of measuring the spectral reflectance per pixel of a painting. These spectra are found to be almost as accurate as those recorded with a spectrophotometer; there is no need for any spectral reconstruction apart from a simple cubic spline interpolation between measured points. The procedure for recording spectra is described and the accuracy of the system is quantified. An example is presented of the use of the system to scan a painting of *St Mary Magdalene* by Crivelli. The multi-spectral data are used in an attempt to identify some of the pigments found in the painting by comparison with a library of spectra obtained from reference pigments using the same system. In addition, it is shown that the multi-spectral data can be used to render a colour image of the original under a chosen illuminant and that interband comparison can help to elucidate features of the painting, such as retouchings and underdrawing, that are not visible in trichromatic images.

Introduction

It is now over a decade since the National Gallery in London developed the first multispectral imaging system to examine paintings. This system (VASARI) was based on a monochrome digital camera and a filter system that provided seven bands across the visible range (400 to 700 nm).[1] The resulting seven-band images produced extremely accurate colourimetric images of paintings for the National Gallery's long-term programme of colour monitoring,[2,3] but the multispectral data could not be used to derive convincing reconstructions of the reflectance spectra on a per pixel basis. Since the development of the VASARI system, the National Gallery has, like other research groups,[4,5] been aiming to develop multispectral imaging systems for paintings that have a higher spectral resolution. Reconstructing the reflectance data opens new possibilities, including more accurate comparison of colour changes over time, the identification of pigments by comparison to standard libraries of reflectance spectra – such as those held at the National Gallery, or available on the Internet[6] – and the simulation of the appearance of paintings after the removal of discoloured or yellow varnishes. In addition, the recording of spectral rather than simple colourimetric data under a given illuminant will allow the colours in the painting to be rendered faithfully under any illuminant.

The EU-funded CRISATEL project, in which the National Gallery is a partner, is developing a multispectral camera with very high spatial resolution.[7,8] To model the performance of this large-format camera during its development, a lower-resolution monochrome digital camera with a cooled CCD sensor and 14 bit electronics is being used along with 13 interference filters. These filters cover the spectral range from 400 to 1000 nm, and have a bandwidth of 40nm in the visible range and 100 nm in the near-infrared region (Fig. 2). Both the camera and the lights are mounted on an X-Y scanning stage such that the illumination and viewing geometry are fixed over the entire scan. The system is capable of scanning a 1 m^2 painting at 20 pixels per millimetre resolution in 20 minutes. This paper describes the calibration of the system, results from multispectral imaging of paintings and the application of the technique to the identification of certain pigments in paintings at the National Gallery.

System Characteristics and Calibration

The camera used in the system is a black and white Zeiss AxioCam normally used in microscopy. It has a 1300×1030 cooled (30° C below ambient temperature) CCD sensor with a pixel size of $6.7 \times 6.7\mu$m; it is capable of sampling at 3900×3090 pixels in micro-scanning mode. The lighting system consists of two identical 82V, 410W tungsten lamps connected through optical fibres to six lights that are evenly placed around the optical axis, illuminating the target at roughly 45°. A filter wheel that holds the 13 interference filters is placed between the detector and the lens. The lens is a Schneider Componon-S enlarging lens with a focal length of 80 mm. The camera needs to be refocused with each change of filter because of the variation in filter thickness. This is achieved by adjusting the lens focus. The closest object distance gives a resolution of 20 pixels per millimetre on the painting. An f-number of 5.6 was chosen to give the highest efficiency without vignetting and distortion. The transmittance of the lens provided by Schneider, the measured relative spectral sensitivity of the CCD, and the relative spectral emittance of the lights are shown in Fig. 1.

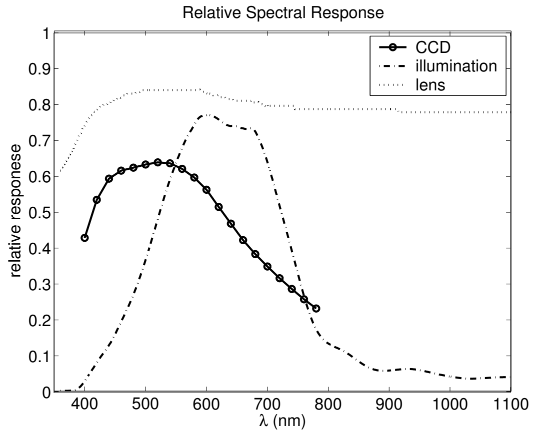

Figure 1: *Spectral emittance of the lights, transmittance of lens, and sensitivity of CCD. The scale on the vertical axis is arbitrary.*

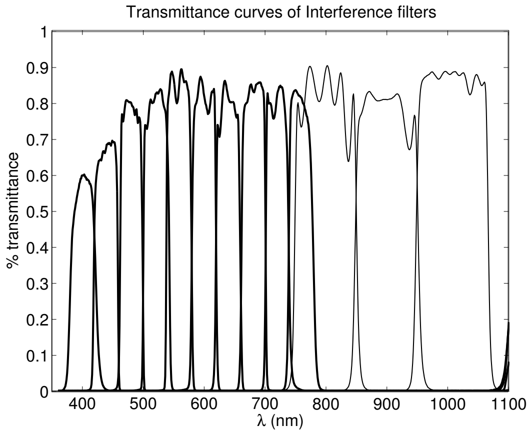

Figure 2: *Measured visible and infrared filter responses.*

For the purpose of this paper, the CCD was used at its lowest resolution, i.e. without micro-scanning. The response of the CCD was found to be linear over almost the entire range (Fig. 4), and the mean dark current was found to be constant with exposure time. Each series of a dozen dark frames was taken at the same exposure, to produce master dark frames to be subtracted from target frames taken with the same exposure time.

A white Teflon (PTFE) board was used for flat-fielding, and a Spectralon white from LabSphere was used as a white spectral target. An ideal flat-field frame compensates for both the inhomogeneity of the illumination and the variation in pixel-to-pixel response of the detector for each filter. However, these effects are normally coupled with the small-scale inhomogeneity of the calibration target, unless the surface is perfectly smooth. A common way of separating the small-scale inhomogeneity of the surface from the effects of illumination and detector response is by defocusing slightly. We present here a robust and more accurate flat-fielding technique, that avoids the need to defocus, and has less strict requirements for surface smoothness and cleanliness of the white target. For each filter, a series of eleven images of the white Teflon board was taken at various random positions on the board. The median image obtained, gives a true flatfield image that represents only the product of the lighting inhomogeneity and variation of the CCD pixel-to-pixel response; it is devoid of the small-scale inhomogeneities of the board. A normalised master flat-field produced for each filter in this way, was used to correct the target frames made with the same filter.

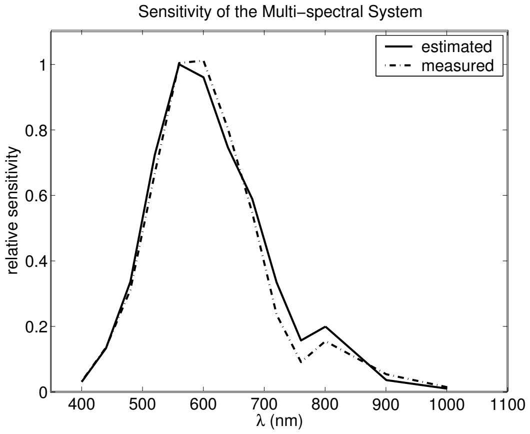

Figure 3: *Relative efficiency of the system. A comparison of the estimated efficiency from the sensitivity of the individual system components and those measured directly from a spectral white target.*

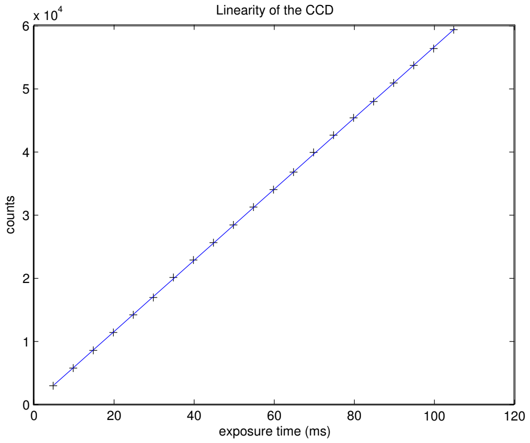

Figure 4: *Median counts of images of a target versus exposure time: the crosses are the measured median counts and the solid line is a straight line fit to the data.*

The central area of the dark subtracted and flatfielded image of the spectral white target was then used to white balance the target frames.

Results: Spectral Reflectance

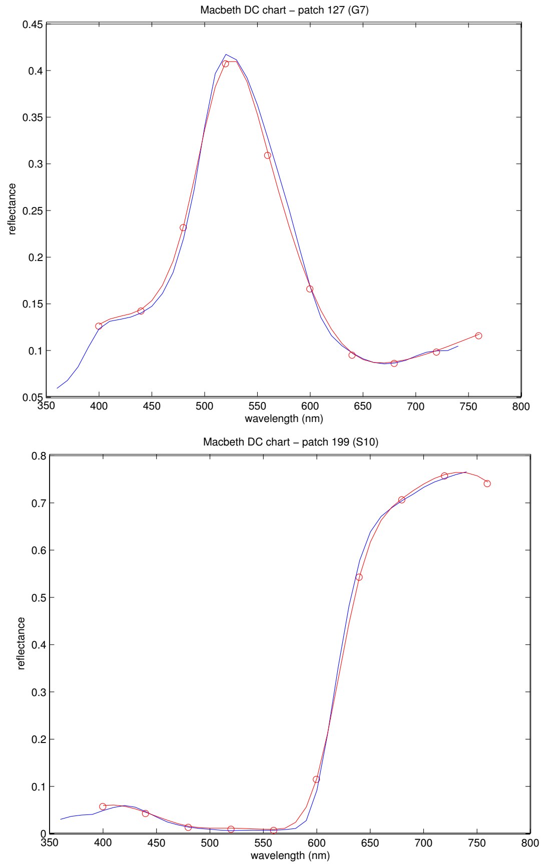

Figure 5: Two example spectra measured with the current multi-spectral system compared with those measured with a Minolta spectrophotometer. Spectra measured with the Minolta are shown as full lines, and the reconstructed spectra from a simple cubic spline interpolation between data points (circles) corresponding to each filter are shown as faint lines.

Quality of Spectra

A simple cubic spline or piecewise cubic Hermite fit was found to be sufficient to recover the spectral reflectance from multi-spectral images. To check the accuracy of the measured spectra, we imaged two kinds of pigment-based colour chart: the Macbeth ColorChecker DC chart with 240 colour and grey scale patches, and the Pebéo chart[9] with 117 colour and grey patches duplicated in both a varnished (glossy) and an unvarnished version. While the commercially-available Machbeth ColorChecker DC chart is a pigment-based chart with a wide colour gamut, it was thought to be unrepresentative of the spectral reflectance of pigments found in old master paintings. A special chart that is more representative of artists' pigments was developed in the CRISATEL project by Pebéo.

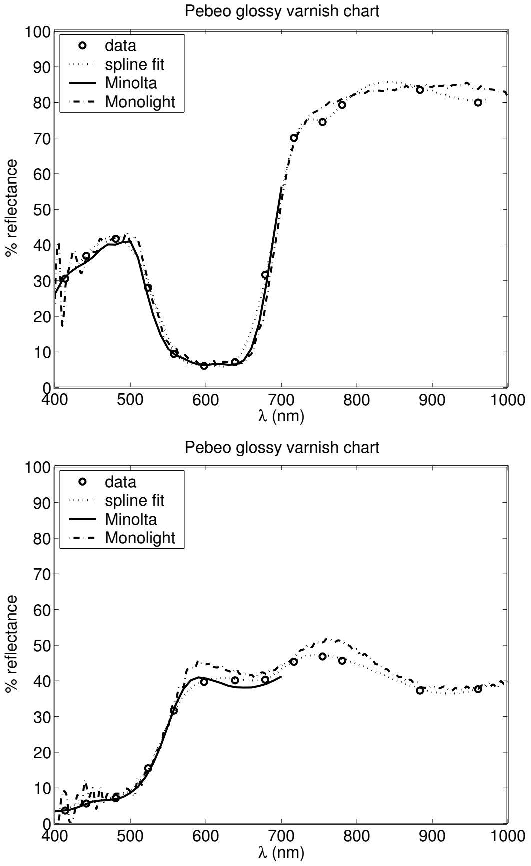

Figure 6: Two spectra from the glossy Pebéo chart obtained from the multi-spectral system compared with measurements made with the Minolta and Monolight spectrometers: upper spectra, cobalt blue; lower spectra, yellow ochre.

The average rms spectral differences between the spectra measured with the multi-spectral system and those measured with a Minolta CM 2600d spectrophotometer were between 0.3% and 6.1%, with an average of 1.7% in the visible range for the Macbeth ColorChecker DC chart. Similar values were found for the varnished (glossy) and unvarnished Pebéo chart. However, the average rms spectral difference between the measurements with a Minolta spectrophotometer, which has a diffuse / 8° geometry, and a Monolight spectrophotometer with 45°/ 0° geometry was 2.7%, indicating that the uncertainties in the reconstructed spectra were within the errors expected from the difference in illumination/viewing geometry between the multi-spectral system and a particular spectrophotometer. The Monolight is rather noisy in the blue spectral region, hence for a fair comparison we chose the spectral range between 500 and 700 nm.

Table 1 summarises the differences in terms of rms spectral differences and ΔE_{00} under illuminant D65 between the spectral reflectances obtained from the multi-spectral system and those from the Minolta spectrophotometer for various test charts in the spectral range of 400 to 700 nm with a step size of 10 nm. In this case, the Minolta measurements were made by collecting reflected light from a circular area of 5 mm in diameter, and the multi-spectral measurements were averaged over an area of $3.5 \times 3.5\,\mathrm{mm}^2$. It is important to note here that the spectra obtained from the multi-spectral system were simple cubic interpolations between the measured data, and were not reconstructed using any spectral reconstruction method, linear or non-linear, which minimises either the spectral difference, or the ΔE between the reconstructed spectra and those of a spectrophotometer, for a test chart. The differences listed in Table 1 are the result of the measurement errors which include scattering effects from the surrounding, interpolation errors, as well as the intrinsic geometric difference between the multi-spectral system and the Minolta spectrometer. In other words, the true spectral accuracy is better than that listed in Table 1.

Table 1. Spectral Accuracy

Chart	Spectral rms diff. mean [min-max]	ΔE_{00}^{D65} mean [min-max]
Macbeth	0.014 [0.002-0.042]	1.2 [0.2-3.7]
Macbeth DC	0.017 [0.003-0.061]	1.6 [0.4-7.4]
Pebéo (unvarnished)	0.015 [0.003-0.052]	1.9 [0.3-6.4]
Pebéo (gloss varnish)	0.017 [0.002-0.050]	1.8 [0.3-4.4]

Image Rendering

The system was next used to image paintings in the National Gallery Collection, providing per-pixel spectral information that allows the simulation of the colour appearance of the same painting under different illuminants. The example given here derives from the data collected by the multi-spectral system for a painting of *St Mary Magdalene* by the Venetian artist Carlo Crivelli [National Gallery, London No. 907.2]. The painting was scanned in 32 individual images per filter, 1300 × 1030 in size, with an overlap between successive images of 100 pixels. At this imaging distance, the change in image scale between filters was less than 1 pixel. Hence, it was not necessary to resample the images onto the same scale. The corresponding images through different filters were aligned automatically using a cross-correlation routine in VIPS,[10] and the 32 images thus aligned were mosaiced together automatically for one reference channel; the other channels were then mosaiced in exactly the same fashion as the reference channel using the automatic mosaic routines in VIPS.

The spectral reflectance for each pixel obtained though a cubic spline interpolation between the 13 data points from 400 to 1000 nm, was then multiplied by the spectral power distribution of the chosen illuminant and the results rendered using the 1931 2° CIE standard observer weighting functions to give a colour image of the painting under a specific illuminant. Figure 9 on the colour plate shows a rendered colour image of the painting under D50. An enlarged detail showing some craquelure is also shown in the colour plate (Fig. 10 on the colour plate) to demonstrate that the image registration between the channels was accurate, since no colour fringing was seen at the edge of the cracks.

For quality control, a small Macbeth chart of 24 patches was scanned at the same time as the painting, and the spectral difference compared with those measured with the Minolta CM 2600d is listed in Table 1.

Applications

Pigment identification

Generally, pigment identification using visible spectra is not a particularly efficient method; the observed surface colour often gives as much information as the spectra themselves. In addition, a simple visual inspection of the surface of the painting under a binocular microscope can reveal particle size and shape, two characteristics that greatly assist pigment recognition. However, the addition of the three infrared channels may aid the identification of pigments through spectral reflectance, as the behaviour of the pigments in the near infrared region is not evident in their colour. A comparison of the reconstructed spectra with those measured with either spectrophotometer for the Pebéo chart and the Macbeth ColorChecker DC chart, shows that the new multi-spectral system is on the whole comparable to a spectrophotometer. This is not surprising, since the spectral reflectance curves of most pigments are smooth and only a few pigments, like cobalt blue and the red 'lakes', have fine spectral features on the 10–20 nm scale (see the spectra of cobalt blue in Fig. 6). The advantage of the multi-spectral system compared with a spectrophotometer is the greatly improved efficiency.

To assess the ability of the multi-spectral system to produce tentative pigment identifications, four regions were selected from the painting of *St Mary Magdalene*. These regions were the bright red of her cloak, the green lining of the cloak, the blue fabric of her robe, and the purple-red brocade on the sleeve. For each colour, the final averaged spectra were obtained from two separate regions, each comprising around 5,000 pixels ($3.5\times3.5\,\mathrm{mm}^2$). These spectra were then compared with a spectral library of 63 historic artists' pigments to find the best match. The logarithm of the absorption and scattering ratio, $\log(\mathrm{K}/\mathrm{S})$, as well as the spectral reflectance were used for the comparison. The $\log(\mathrm{K}/\mathrm{S})$ parameter is more invariant to changes in concentration (a constant shift in the Y-axis) compared with either K/S or the spectral reflectance.[11]

The blue pigment best matched the spectra of either azurite or Prussian blue mixed with white. Under the binocular microscope these two pigments are easily distinguished: the mineral azurite (present here) has large angular particles, while Prussian blue has much smaller, intensely coloured particles. Spectral matching alone is clearly not sufficient to rule out the presence of the anachronous Prussian blue, which was first synthesized in the early 18th century. Figure 7 shows the $\log(K/S)$ spectra of the blue region from the painting and azurite from the library both derived from spectral measurements obtained from the multi-spectral system. It is interesting to note that the spectrum from the painting shows a higher reflectance in the red and green regions than the library spectrum for pure azurite. Examination of a fragment of paint from the blue robe revealed high quality azurite mixed with small quantities of pale, yellowish green and red impurities (Fig. 11 on the colour plate).

The bright red cloak provided a spectrum that best matched the traditional red pigment vermilion. The quality of the match was improved by the addition of a black pigment using a Kubelka-Munk method of mixture.[12,13] Again, an examination of a sample taken from the painting showed that the modelling in the cloak had been achieved using thin lines of black paint over a body colour of vermilion (Fig. 12 on the colour plate). The green paint gave good matches for verdigris, Scheele's green, and emerald green mixed with white. As emerald and Scheele's green were synthesised in the early 19th and late 18th century respectively, the limitations of spectral matching are again emphasised. Other analytical methods would again be required to establish the nature of the pigment. The red brocade on the sleeve was consistent with the spectra of red lake pigments, although it was not possible to be more specific as the spectra of these lakes vary with method of preparation and are broadly very similar.

Interband Comparisons

Interesting comparisons can be made between the images captured at different wavebands. For example, the infrared image at 900nm clearly shows the underdrawing on the palm of the hand, which is not seen in the 560nm image (Fig 8). Similarly, the 900nm image reveals a number of circular areas on the wall around the hand which are old damages that have been repaired by a conservator. The colour of these retouchings was well matched to the original paint in the surroundings, so that it is not easily discernable under visible light (see colour plate Fig. 9). However, the spectral reflectances of the retouchings and the original paint are clearly different in the infrared.

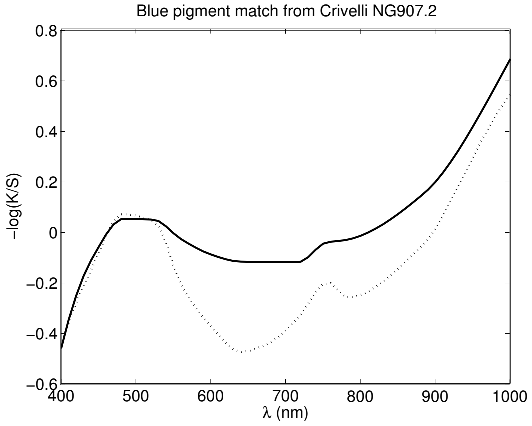

Figure 7: *The best match for the blue pigment in the Crivelli painting NG 907.2. The solid curve shows the measured spectrum from the blue region on the painting and the dotted curve shows the spectrum of an azurite, also measured with the multi-spectral system.*

Conclusions

We have shown that the new multi-spectral system described in this paper is capable of producing accurate spectral reflectance curves for paintings without any spectral reconstruction other than a simple cubic spline fit to the measured data in the 13 channels from 400 to 1000 nm. The new multi-spectral system can be used like a low resolution spectrophotometer where only standard calibrations such as dark subtraction, white balancing and flatfielding are need. There is no need to use colour calibration charts for spectral or colourimetric reconstruction. Only a small Macbeth chart is needed for quality control.

We have also demonstrated that with the addition of information from the near infrared, the multi-spectral system has some promise as a non-destructive and non-invasive method for pigment identification. The method is unlikely to replace other methods of examination, particularly microscopic examination of the surface; at present, pigment identification requires additional clarifying or corroborating information from other techniques. However, pigment identification will become more secure as more reference pigments are measured with the multi-spectral system and, as in this study, recorded spectra are correlated to pigment mixtures by examining the composition using microscopy or analytical methods. The multi-spectral images are also useful for identifying areas of retouching and revealing underdrawing. Finally, the multi-spectral images would form a useful database for 'spectral' printing.

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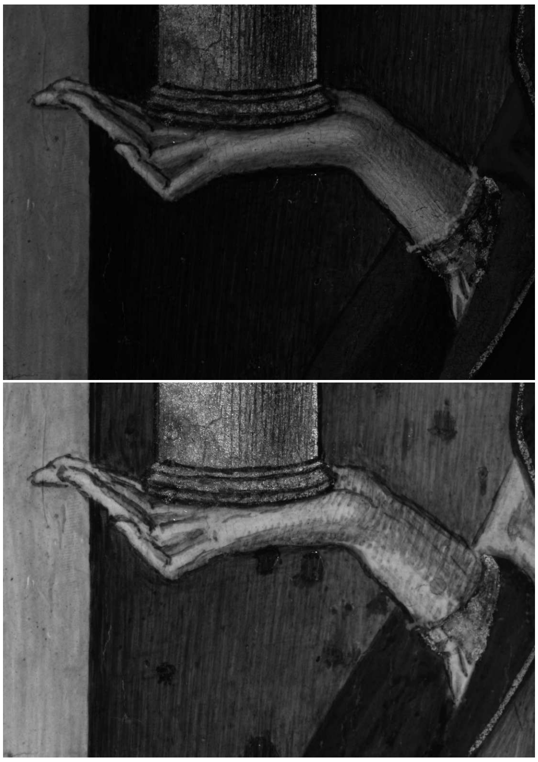

Figure 8: A comparison of a 560nm and a 900nm image of a detail from NG 907.2: the infrared image clearly shows the underdrawing and the retouchings.

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Acknowledgements

We would like to thank Marika Spring and Ashok Roy for examining and photographing the paint samples from *St Mary Magdalene*, and Clare Richardson for preparing the pigment library samples. This study was partly conducted within the EU-supported CRISATEL project (IST1999-20163): discussions with partners in the CRISATEL consortium are gratefully acknowledged.

Biography

Haida Liang received her B.Sc. in Physics from the University of Sydney, and her Ph.D. in Astronomy and Astrophysics from the Australian National University in 1995. Prior to joining the Scientific Dept. of the National Gallery in 2002, she worked on various astrophysics projects specialising on radio interferometry and multi-wavelength studies from radio, VIS, IR to X-rays of clusters of galaxies at the CEA (France) and the University of Bristol (England). She is currently working on the EU-funded CRISATEL project on multi-spectral imaging.