SPECTRAL AND COLORIMETRIC CHARACTERIZATION OF PAINTED SURFACES: A SCANNING DEVICE FOR THE IMAGING ANALYSIS OF PAINTINGS

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ABSTRACT

In the last few years multispectral imaging has entered the field of painting diagnostics and conservation because of its effectiveness and safety. It provides spectral and colorimetric characterization of the whole paint layer, suitable to document the conservation state of the artwork and useful in the study for the identification of pigments.

Here we present a high-resolution scanning system for 32-band multispectral imaging of paintings in the 380÷800 nm spectral region. This system is based on a fast spectrometer for contact-less single-point measures mounted on two orthogonal XY translation stages. It can scan an area of 1 m² with a spatial resolution of 4 dots/mm and a spectral resolution of 10 nm.

Spectral reflection factor and tristimulus value measurements were carried out on coloured ceramic tiles and the results were compared with the corresponding certified values.

Multispectral analysis was performed on a few ancient paintings and spectrophotometric results are shown.

Keywords: Painting analysis, multispectral imaging, colorimetric characterization, spectral reflectance factor.

1. INTRODUCTION

Imaging techniques produce, by measuring one or more physical parameters (spectral reflectance factor, colorimetric coordinates, quote, …), a set of data that can be represented and visualized as a set of images each concerning one of the above mentioned parameters. The acquisition resolution depends on the sampling step, on the intrinsic characteristics of the sensor and on the geometry of the setup.

In particular, for multispectral imaging we intend the spectral reflectance factor (R) characterization of a surface in several bands of the visible (VIS) and near infrared (NIR) spectral range.

Spectral reflectance characterization of the paint layer has received a great attention in recent years because of its several applications ranging from diagnostics (monitoring of conservation state and recognition of pigments) to digital documentation, in an absolutely non-destructive way.

The technique is based on irradiating the painting surface with broadband continuous sources, such as halogen lamps, and detecting with a suitable detector the back-scattered radiation within narrow spectral intervals.

Up to now, either CCD or Vidicon cameras have been used as a detector. In order to select suitable spectral bands in the spectral range of interest, the sensor is coupled with filters (a filter wheel or a LCD tunable filter) or is equipped with an imaging spectrograph.

These systems entail calibration procedures to correct the non-uniform irradiation of the investigated area as well as the chromatic and geometrical aberrations and the prospective distortions due to the camera lens. Moreover, as the spatial resolution is related to the measured area, in case of large panels several images must be acquired and combined into a mosaic.

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To overcome the above mentioned problems, related to the use of spatially-extended sensors, we propose an innovative device based on a fast single-point spectrophotometer, specifically developed for multispectral imaging in the 380-800 nm spectral region, opportunely combined with an high-resolution scanning system. We report on the characteristics of our instrument and the relative adjustment and calibration procedures, based on a set of reference ceramic tiles, certified by the National Physical Laboratory (NPL) of UK.

2. THE MULTISPECTRAL SCANNER

The block diagram of the scanner is shown in Fig.1: the scanning system (XY motorized translation stages) moves the lighting system (source) and the collecting optics (optical head). The collecting optics images the sampling point on the entrance of a multimode optical fiber connected to the fast spectrophotometer (detector).

![Figure 1: Block diagram of the multispectral scanner](image)

The lighting system is composed of two low-voltage current-stabilized halogen lamps (20 W) irradiating a 5 cm² area. The lamp reflectors have a dichroic coating transmitting backwards large part of IR radiation, thus minimizing the heating of the painting surface. The beam divergence is 10°, according to CIE specifications for the 45°/0° illumination/observation geometry.

The collecting optics (Fig.2), in order to avoid chromatic aberration, is composed of two faced spherical mirrors. The working entrance $f_i$ is 2.4, corresponding to an acceptance angle of 24°. The working exit $f_o$ is 3.6 to obtain best matching with the multimode optical fiber (N.A. = 0.22, $\Phi_{core} = 200 \mu m$). The collecting optics magnification is 1.5, so entailing a sampling point diameter of about 130 µm. The working distance of the collecting optics is near 16 cm with a depth of field of ± 275 µm.

The spectrophotometer is constituted by a 32-elements array multi-anode photomultiplier tube (H7260-01 Hamamatsu) equipped with a 32-elements array interference filter, so to each element corresponds a different 10 nm wide (FWHM) spectral band in the 380-800 nm spectral range. High tonal dynamics is guaranteed by the 12-bit A/D conversion electronics.

The XY scanning system (Fig. 3), composed by two high-precision motorized translation stages mounted orthogonally, allows to measure continuously areas up to 1.5 m² with a spatial resolution of 16 dots/mm². The acquisition time for 1 m² area is of about 10 hours at typical acquisition rate of 500 Hz.
The high sensitivity of the detector allows to measure low reflectance values (less than 5%) in spite of the small area of the sampling point and a typical integration time of about 200 μs. The lighting system, current-stabilized and firmly settled with the collecting optics, and the single-point measurement ensure uniform illumination for all the sampling points. Moreover, single-point detection avoids off-axis aberrations and the mechanical scanning entails distortions free images.

The whole system is computer controlled: acquisition parameters (scanned area, integration time, detector gain, sampling frequency, …) are adjustable depending on the sampled surface characteristics.
3. CALIBRATION AND ADJUSTMENT

For a specific illumination/observation geometry, the spectral reflection factor \( R_{\lambda} \) is calculated according to the following expression:

\[
Eq. (1) \quad R_{\lambda} = \rho_{\lambda}^{\text{ref}} \frac{V_{\lambda}^{\text{dark}} - V_{\lambda}^{\text{ref}}}{V_{\lambda}^{\text{ref}} - V_{\lambda}^{\text{dark}}}
\]

where \( \rho_{\lambda}^{\text{ref}} \) is the certified spectral reflectance of a neutral diffuser in the specified geometry, \( V_{\lambda}^{\text{ref}} \) and \( V_{\lambda}^{\text{dark}} \) are the detector signals respectively related to the sample and the neutral diffuser and \( V_{\lambda}^{\text{dark}} \) is the detector signal when the collecting optics entrance is darkened. We use a neutral diffuser with mean spectral reflectance of 66%, certified by the National Physical Laboratory (NPL), UK. \( V_{\lambda}^{\text{ref}} \) and \( V_{\lambda}^{\text{dark}} \) measurement correspond to the instrument adjustment procedure, that has to be repeated before starting each measurement session.

The calibration procedure, as determination of the instrument accuracy, was accomplished by measuring the spectral reflection factor of seven coloured ceramic tiles of NPL and comparing the results to the corresponding certified values. Each acquisition was repeated 100 times to evaluate measurement repeatability. In order to obtain a quantitative estimate of instrument accuracy, the mean absolute deviation \( \Delta R \) was calculated for each tile after 1 nm interpolation of the corresponding measured and certified spectra (Table 1).

<table>
<thead>
<tr>
<th>Orange [%]</th>
<th>Blue [%]</th>
<th>Cyan [%]</th>
<th>Yellow [%]</th>
<th>Red [%]</th>
<th>Green [%]</th>
<th>Pink [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta R )</td>
<td>2.1</td>
<td>1.4</td>
<td>1.0</td>
<td>1.7</td>
<td>1.1</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Table 1: Mean absolute deviation between measured and certified spectral reflection factor \( R \).

In figure 4 the measured spectral reflection factors (colour circles) and the respective certified values (black squares) are shown on the same graph. Experimental points are associated with the standard deviation of the mean. Good agreement between the two data sets is present even in case of low spectral reflection factor and spectrum slope variation.

Colorimetric calculations were also carried out in accordance with:

\[
Eq. (2) \quad X = K \sum_{\lambda=380}^{780} S_{\lambda} R_{\lambda} x_{\lambda} \Delta \lambda \\
Y = K \sum_{\lambda=380}^{780} S_{\lambda} R_{\lambda} y_{\lambda} \Delta \lambda \\
Z = K \sum_{\lambda=380}^{780} S_{\lambda} R_{\lambda} z_{\lambda} \Delta \lambda \\
K = \frac{100}{\sum_{\lambda=380}^{780} S_{\lambda} y_{\lambda} \Delta \lambda}
\]

where \( S_{\lambda} \) is the spectral distribution of the standard D65 illuminant, \( x_{\lambda} \), \( y_{\lambda} \), \( z_{\lambda} \) are the colorimetric functions for the standard observer CIE 1931 and \( R_{\lambda} \) is the 1 nm interpolated experimental spectral reflectance factor.

Finally (Table 2) the chromaticity coordinates \( x, y \), defined by Eq. (3), and the luminance \( Y \) (Eq. (2)) were compared to the NPL certified values.

\[
Eq. (3) \quad x = \frac{X}{X + Y + Z} \\
y = \frac{Y}{X + Y + Z}
\]
Figure 4: Spectral reflection factors measured with the developed device (colour circle) and certificated by NPL in UK (black square) for a set coloured ceramic tiles.
Table 2: Comparison between measured and certified values of luminance and chromaticity coordinates.

<table>
<thead>
<tr>
<th></th>
<th>Y</th>
<th>Yref</th>
<th>ΔY</th>
<th>X</th>
<th>Xref</th>
<th>ΔX</th>
<th>Y</th>
<th>Yref</th>
<th>ΔY</th>
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<tr>
<td>Orange</td>
<td>41.6</td>
<td>38.8</td>
<td>2.8</td>
<td>0.48</td>
<td>0.49</td>
<td>0.01</td>
<td>0.39</td>
<td>0.38</td>
<td>0.01</td>
</tr>
<tr>
<td>Blue</td>
<td>6.99</td>
<td>6.58</td>
<td>0.41</td>
<td>0.27</td>
<td>0.26</td>
<td>0.01</td>
<td>0.26</td>
<td>0.25</td>
<td>0.01</td>
</tr>
<tr>
<td>Cyan</td>
<td>24.3</td>
<td>24.2</td>
<td>0.10</td>
<td>0.22</td>
<td>0.22</td>
<td>0.00</td>
<td>0.26</td>
<td>0.26</td>
<td>0.00</td>
</tr>
<tr>
<td>Yellow</td>
<td>64.3</td>
<td>64.6</td>
<td>0.3</td>
<td>0.42</td>
<td>0.43</td>
<td>0.01</td>
<td>0.46</td>
<td>0.46</td>
<td>0.00</td>
</tr>
<tr>
<td>Red</td>
<td>18.0</td>
<td>17.8</td>
<td>0.2</td>
<td>0.46</td>
<td>0.45</td>
<td>0.01</td>
<td>0.33</td>
<td>0.33</td>
<td>0.00</td>
</tr>
<tr>
<td>Green</td>
<td>27.1</td>
<td>26.6</td>
<td>0.50</td>
<td>0.28</td>
<td>0.28</td>
<td>0.00</td>
<td>0.39</td>
<td>0.39</td>
<td>0.00</td>
</tr>
<tr>
<td>Pink</td>
<td>17.7</td>
<td>17.1</td>
<td>0.6</td>
<td>0.37</td>
<td>0.37</td>
<td>0.00</td>
<td>0.31</td>
<td>0.31</td>
<td>0.00</td>
</tr>
</tbody>
</table>

4. APPLICATIONS

The scanning spectrophotometer was tested on different ancient paintings: the panel “San Nicola” by an anonymous Florentine, “Portrait of Lionello d’Este” by Pisanello, “Croce di Rosano” by Maestro di Rosano, a fresco dated between the VI and the VIII century at “Santa Maria Antiqua” Church in Rome and some details of the painting “Madonna in gloria tra Santi” by Andrea Mantegna, located at Pinacoteca delle Civiche Raccolte del Castello Sforzesco in Milano. Here we show a few results relative to these measurements.

The imaging analysis of “Madonna in gloria con Santi”, a canvas painting dated 1497, was carried out on some details of the painting, including the face of a cherub (100x130 mm$^2$) and the Madonna’s left arm (60x70 mm$^2$). The results of an acquisition can be visualized as 32 monochromatic pictures, one for each spectral band; some of these, which show the face of the cherub, are depicted in figure 5.

![Figure 5: A few small scale digital images selected among the 32 monochrome images acquired with the developed multispectral scanner. The images depict details of the painting “Madonna in gloria con Santi”. The output of the shown channels corresponds to the following wavelengths: 420nm, 460nm, 500nm, 540nm, 560nm, 660nm, 740nm, 800nm.](image-url)
Colorimetric coordinates in the XYZ colour space were computed for each pixel of the sampled area, and than they were converted into the RGB coordinates. After normalization to the highest of the RGB values, the resulting data were stored as standard format 8-bit images and finally the three images, R-G-B were combined to get the colour image (figure 6) of the sampled area.

Figure 7: Madonna in Gloria con Santi: a) RGB colour image, b) IR@800 nm and c) false colour image.
Fig 7 displays the RGB colour image (figure 7a), the IR@800 nm image (figure 7b) and a false colour image of the detail Madonna’s left arm (figure 7c). The first one was obtained by properly mixing the 31 monochromatic images; the second one is the IR reflectogram collected on the 32nd channel (which, although it is characterised by lesser legibility than the Vidicon or IR scanner by INOA reflectography, provides an information equal to that obtained with the photographic technique) and the last one is the false colour image obtained through the combination of the IR, R, G images attributed to the R, G, B channels, respectively.

The latter image allows to highlight the difference between mixture pigments having the same chromatic yield and being thus indistinguishable at sight; this is the case of the two red and blue areas shown in figure 7c. This difference is confirmed by the spectra (average value of the spectral reflection factors of the points framed by the white squares) shown in figure 8 (right).

![Figure 8: Detail of the “Madonna in gloria con Santi”: (left) RGB colour image, (right) average value of the spectral reflection factors of the points framed in the white squares.]

Another important application concerns “Croce di Rosano”, a wooden crucifix dated XII century, now under repair at the “Opificio delle Pietre Dure”; the imaging analysis was carried out on a detail (60x16 cm²) of the painting.

Figure 9 shows a detail, representing the three Mary's at Christ's sepulchre; from top to bottom are displayed the RGB colour image, the IR@800 nm image and a false colour image obtained through the combination of the IR@800nm, R, G images attributed to the R, G, B channels, respectively.

In this case, e.g., the latter image allows to discriminate the lapis lazuli and azurite; actually these pigments are identifiable only through the false colour image, with the lapis lazuli appearing red. Considering the RGB image (top) and the false colour (bottom), the veil of the two outer women is probably lapis lazuli. In order to confirm this data, spectral characterization of the detail has been useful.

The spectral reflection factor reported in fig. 9 is an average value over 1000 adjacent points, in order to consider spectra that would be representative of the measured area. The spectra were then compared with spectral reflection factors of samples, purposely prepared at the Opificio delle Pietre Dure restoration laboratory in Florence, whose composition reproduces ancient painting materials. The R values of the samples were measured with a commercial contact spectrometer characterized by the same illumination/observation geometry as ours. The comparison of painting and reference spectral reflection factors showed a good agreement between the veil’s pigment and lapis lazuli-carmine mixture.

These preliminary results show how multispectral analysis can be an effective tool not only for painting documentation and monitoring but also for pigment identification.
Finally we present the results obtained with the multispectral analysis on the Pisanello’s “Portrait of Lionello d’Este”. The portrait of Lionello d’Este is one of the most famous paintings of the Italian Renaissance because of its dynastic and profane imagery. It was painted in a very particular and rich technique, using many glazes and metal leaves and probably an oil medium for the flesh tones (which is very unusual in Italy in the period). The results obtained with the multispectral scanner are displayed in figure 10 where on the same picture were combined (from left to right), the multispectral colour imaging, the IR reflectography (acquired with IR reflectography scanner by INOA), and the false colour image.

Figure 9: Croce di Rosano: (left) from top to bottom, RGB colour image, IR@800 nm image and false colour image; (right) spectral reflection factor of the area identified by a white square on the image. The black square are an average over raw data on different adjacent points; the blue dots are the values measured by a contact spectrometer on a set of reference samples prepared at OPD laboratories.

Figure 10: Pisanello’s “Portrait of Lionello d’Este: (from left to right) combinaton of multispectral colour image, IR reflectography, and false colour image.
5. CONCLUSIONS

A scanning spectrophotometer for multispectral and colorimetric characterization of painting surfaces was developed. The device enables multispectral imaging in the 380-800 nm spectral region of surfaces up to 1.5 m$^2$ with spatial resolution of 4 dots/mm and spectral resolution of 10 nm. The spectrometer accuracy was determined by measuring spectral reflection factor and colorimetric coordinates on a set of coloured ceramic tiles, certified by the NPL in UK. We have presented the results of measurements performed on different ancient paintings: “Madonna in Gloria con Santi”“Croce di Rosano” by Maestro di Rosano, “Portrait of Lionello d’Este” by Pisanello. These results showed the usefulness of the developed instrument for monitoring and digital documentation of the conservation state of works of art. Multispectral imaging application to ease pigment identification was also shown. Our next goals are the extension of spectral sensitivity up to 2400 nm and the introduction of an autofocus system that, besides keeping the painting surface focussed during the scan even in case of surface irregularities, will allow the simultaneous acquisition of the painting shape proceedings a more uniform look.

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