When It Is Not Only About Color: The Importance of Hyperspectral Imaging Applied to the Investigation of Paintings

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Abstract. This paper illustrates some of the developments achieved in the field of non-contact analytical tools for two-dimensional polychrome artworks. It reports significant advantages within the application of hyperspectral imaging for high-quality documentation, accurate color reproduction, study of artists' materials and techniques, and identification of past conservation treatments. In particular, Dürer's oil painting on panel, Adoration of the Magi (1504), was analyzed with a pushbroom hyperspectral imaging system in the visible-near-infrared range (Vis-NIR, 400–900 nm). The results obtained, including high-resolution color-accurate and false-color images, as well as high-resolution reflectance spectra, are reported and discussed, and the importance of hyperspectral imaging applied to the investigation of paintings is shown.

Keywords: Color-accurate image · False-color image · Hyperspectral imaging · Oil painting · Reflectance spectroscopy

1 Introduction

Since the 2000s imaging spectroscopy, also known as spectral imaging, has presented promising advances in the field of non-contact analytical tools for cultural heritage [1]. Reflectance hyperspectral imaging (HSI) systems in particular, consist of the collection of images in hundreds of contiguous narrow spectral bands (bandwidth <10 nm), offering high spatial and spectral resolution. The data set obtained, often referred to as an image-cube, includes a unique collection of spatial and spectral information of the imaged object, which can be processed and analyzed by several sophisticated tools. These tools can be used and adapted according to the specific purposes of the scan. The exploration of the image-cube, including the possibility to view, superimpose and compare high-resolution images at different wavelengths, as well as to extract a reflectance spectrum from each spatial pixel, can bring essential insight into the study and conservation of two-dimensional polychrome artworks. Some important advantages of

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the application of HSI to these cultural heritage objects are the possibility to document them with high-quality, to accurately reproduce color, to distinguish and map artists' materials and study their techniques, and to identify non-original areas containing inpaints.

The usefulness of applying HSI to polychrome artworks is illustrated in the present paper through a case-study investigated with a HSI scanner, Albrecht Dürer's oil painting on panel, Adoration of the Magi (1504) at the Uffizi Gallery, Florence, Italy. This painting is one of the most beautiful works by the German painter, printmaker and theorist Albrecht Dürer (1471–1528), who was born in the Franconian city of Nuremberg, one of the strongest artistic and commercial centers in Europe during the fifteenth and sixteenth centuries. Dürer was particularly engaged by the artistic practices and theoretical interests of Italy, which he visited twice between 1494 and 1507. During these periods, the artist was fascinated by some of the great works of the Italian Renaissance, as well as by the classical heritage and theoretical writings of the region. Dürer's talent, ambition, and sharp, wide-ranging intellect earned him the attention and friendship of some of the most prominent figures in the German society [2]. Dürer's Adoration of the Magi is an altar-piece, which was commissioned by the king Friedrich III, who came to be known as Frederick the Wise, for the Schlosskirche at Wittenberg, Germany. The painting has an unusual setting and the fact that Joseph is missing from the scene is unconventional. The magi are richly clothed and their offerings impressive. On the right side, a servant appears to be taking more gifts from a bag. Some of Dürer's scholars consider that the magus with the green mantle possibly is the self-portrait of the painter himself.

The painting was scanned during a restoration process in 2006 at the former Restoration Laboratory of the *Soprintendenza Speciale per il Patrimonio Storico, Artistico ed Etnoantropologico e per il Polo Museale della città di Firenze* with the "Nello Carrara" Institute of Applied Physics of the National Research Council (IFAC-CNR) hyperspectral imaging camera in the visible-near-infrared range (Vis-NIR, 400–900 nm). The scan yielded high-resolution color-accurate and false-color images, as well as high-resolution reflectance spectra, which allowed to create an accurate record of the painting, get insight into the painting's colored materials, and identify areas that underwent past conservation treatments.

2 Hyperspectral Imaging System

Measurement of the Adoration of the Magi was carried out in the 400–900 nm range with the hyperspectral imaging scanner designed and assembled at IFAC-CNR, which was optimized for acquiring data on paintings with high spatial and spectral sampling (Fig. 1). The system has been thoroughly described by the authors in previous publications [1, 3–5]. It is based on a prism-grating-prism line-spectrograph, which is connected to a high sensitivity camera. Data acquisition is made following the pushbroom approach, also known as line scanning, in which a complete spectrum of each point along a line is formed on one column of the 2D detector array and the area of interest has to be scanned one line at a time. Illumination of the line-segment with a QTH lamp is made by two fiber-optic line-lights equipped with focusing lenses that are fixed to the scanner and symmetrically project their beams at 45° angles with respect to the normal direction at the imaged surface (0°/2 × 45° observation/illumination geometry). To calibrate the system and to compensate for the variation of emission of the QTH lamp, before each vertical scan the scan-head is positioned on a certified standard target of diffuse reflectance (99% Spectralon® Diffuse Reflectance Standard, Labsphere INC., North Sutton, NH, USA).

Fig. 1. IFAC-CNR HSI scanner during the measurement of the panel Adoration of the Magi (1504) by Albrecht Dürer at the former Restoration Laboratory of the *Soprintendenza Speciale per il Patrimonio Storico, Artistico ed Etnoantropologico e per il Polo Museale della città di Firenze*

3 Results and Discussion

Figure 2 shows the overall calibrated accurate RGB image of the oil painting on panel (100 cm × 114 cm) extracted from the image-cube. The RGB values are calculated following the standard IEC 61966-2-1:1999, originally proposed by Hewlett-Packard hp® and Microsoft® in 1996 for the exploitation of the gamut of computer display devices (with gamma 2.2). In summary, a linear transformation is applied to the XYZ values obtained by integration of each reflectance spectrum weighted with the CIE 1931 2° Standard Observer coordinates and the D65 illuminant curve. An exponential function is then applied to the three "RGB-linear" results to obtain the sRGB components, usually scaled as integer values between 0 to 255. If needed, other color components can be readily calculated, such as in the Adobe D50 illuminant color space or in the CIE L*a*b* (CIELAB), more suitable for accurate evaluation of colorimetric differences [6].

The high-resolution images (11.4 line/mm) obtained from the image-cube allow to view very small details, as can be seen by the magnified details of the RGB image reported in Fig. 3. Images can also be extracted from the image-cube at specific wavelengths. An image was extracted at 880 nm to complement the information obtained with the visible image and get further knowledge about the painting's materials and techniques (Fig. 4). This image revealed that some materials, which appear to be the same in the RGB image, have different behavior in the near-infrared, for example, the blue sky in the top right corner and the green mantle of one of the magi. Following this result, the infrared false-color (IRFC) image, in which infrared and visible bands are selected to create a pseudo-color image, was also reconstructed from the image-cube and evidenced the presence of non-original areas of paint (Fig. 5). This image is an average of the following wavelengths: R, 751–900 nm; G, 581–750 nm; B, 520–580 nm. For its reconstruction, the 99% Spectralon® Diffuse Reflectance Standard is used to verify and calibrate the procedure since after the IRFC process the reflectance standard has to appear as a perfect white surface. It should also be noted that the digitally reconstructed IRFC image is fully comparable to the traditional IRFC photo obtained by using IRFC Kodak films [7].

Fig. 2. RGB color image of the oil painting on panel Adoration of the Magi reconstructed from the image-cube (the dark shadow in the bottom center corresponds to the easel holding the painting during the measurement with the HSI scanner) (Color figure online)

Fig. 3. Magnified details of the RGB color image of the oil painting on panel Adoration of the Magi reconstructed from the image-cube (*left:* butterfly in the bottom left corner of the painting; *right:* castle on top of the green mountain in the background of the painting) (Color figure online)

Fig. 4. 880 nm image of the oil painting on panel Adoration of the Magi reconstructed from the image-cube

Materials with similar color, which means that they have similar absorbance spectra in the visible, but different infrared behavior, can be distinguished in the painting by their false color. In other words, since the information from the infrared region is presented in the IRFC image with color, different pigments can have a specific false-color appearance according to their reflectance in the infrared, which can be used for their identification [7]. An example of the utility of IRFC is shown by the magnified detail of the blue sky in Fig. 6. Here, the same area shows two different IRFC behaviors:

Fig. 5. Infrared false-color image of the oil painting on panel Adoration of the Magi reconstructed from the image-cube (Color figure online)

most of the sky is reported with a dark purple-bluish color while the non-original areas of paint are presented in a pale pink-reddish color, despite their similar appearance in the visible. The average CIELAB76 color values for both areas are L* = 34.7, a* = −15.2, b* = −7.5 and L* = 34.8, a* = −12.8, b* = −6.0 for the original and the inpainted areas, respectively. These values, calculated from the reflectance spectrum extracted from the respective pixels, mean that the color parameters of both areas are very close to each other. It can be concluded that the conservator was successful in creating the inpainted areas starting from the surrounding original colors even if the blue pigments used were different from the original one. In this case, by looking at the IRFC image it can be suggested that the original sky was painted with azurite while blue ultramarine, smalt, or cobalt blue might have been used in the inpainted areas.

The possibility to extract from the image-cube a high-resolution reflectance spectrum from each spatial pixel allows to go further in the suggestion of the original artist's materials and those used in the inpainted areas. In this sense, it is possible to make a more accurate suggestion of the identification of materials. Reflectance spectra with a spectral resolution of approximately 2.5 nm were extracted from averaged 2.3 mm × 2.3 mm areas (25 px × 25 px) of the original blue in the sky and the inpainted blue areas (Fig. 7). Spectra of the original blue areas confirmed the use of the pigment azurite (basic copper carbonate), with its characteristic high absorbance from 600 nm to 900 nm [8, 9]. On the other hand, the spectral shape of the inpainted blue areas, with the presence of an absorption band around 620 nm, reveals that a mixture of pigments was likely used. In particular, the presence of the modern pigment cerulean blue or phthalocyanine blue can be suggested [10, 11].

Fig. 6. Magnified details of the RGB color image (*left*) and IRFC image (*right*) of the oil painting on panel Adoration of the Magi reconstructed from the image-cube (*top row:* blue sky in the top right corner of the painting; *bottom row:* green mantle of one of the magi). The yellow circles mark the areas from where the reflectance spectra were extracted (Color figure online)

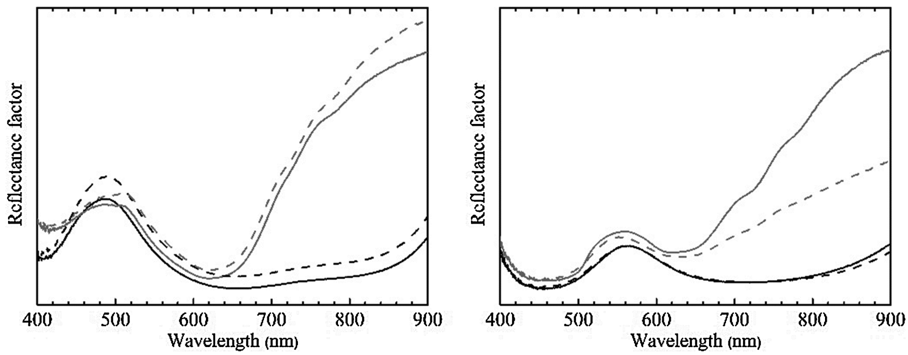

Fig. 7. Reflectance spectra of the oil painting on panel Adoration of the Magi extracted from the image-cube (*left:* blue sky; *right:* green mantle). Black lines = original areas; grey lines = inpainted areas

As previously stated, a similar situation is observed for the green color of one of the magi's mantle, which presents different IRFC behavior (the average CIELAB76 color values are L* = 18.1, a* = −3.2, b* = 13.8 and L* = 20.9, a* = −2.8, b* = 13.3 for the original and inpainted areas, respectively). The original green, which appears dark blue in the IRFC image (see the magnified detail in Fig. 6), is probably a copper-based green pigment, such as malachite or verdigris. The reflectance spectra extracted from these areas (Fig. 7) confirm the presence of a basic copper carbonate due to the wide absorption from 600 nm to 900 nm [9, 12]. The green color used for the inpainted areas has not been identified through its reflectance spectra. Complementary analytical techniques, commonly used for the study of artists' materials such as X-ray fluorescence, and Raman and infrared spectroscopies, would be required to make a positive identification.

Apart from the blue and green colors of the Adoration of the Magi, the reddish and pinkish colors were also investigated with HSI. This study was the subject of a previous publication by the authors [13].

4 Conclusions

This paper presents the use of an HSI scanner, which operates in the visible-near-infrared range (400–900 nm) and is based on a prism-grating-prism line-spectrograph, for the analysis of paintings. The system provides images with high spatial resolution and accurate color reproducibility. It is also able to acquire spectroscopic data with a very high resolution, making it possible to distinguish between different materials and to map them. However, despite this possibility, HSI does not provide by itself a straightforward or complete identification of the materials and complementary techniques such as X-ray fluorescence, and Raman and infrared spectroscopies were proved to be needed.

The investigation of Dürer's oil painting on panel, Adoration of the Magi, through its high-resolution color-accurate and false-color images, as well as high-resolution reflectance spectra extracted from the image-cube, revealed blue and green inpainted areas which were successfully masked with the original colors painted with azurite and a copper-based green (respectively). However, a positive identification of the inpainting materials could not be made solely based on their Vis-NIR reflectance spectra. This work illustrates some of the potentialities of non-contact hyperspectral imaging for investigating two-dimensional polychrome artworks.

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