Acquisition of spectral images of paintings by means of a spectrophotometric scanner

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The settlement of archives of reference images useful for the diagnosis of the preservation state of paintings and restorer actions can be obtained using a spectrophotometric scanner capturing spectral images. This scanner is built arranging a spectrometer between the objective lens and a black and white digital matrix camera. The paper describes the working principles of the scanner, its technical properties, the fidelity of both the color acquisition and reproduction, and the spatial resolution. Practical works carried out using the scanner are shortly presented.

1. Introduction

Archives of reference images are necessary for both the diagnostic of the preservation state and the faithful restoration of paintings and other works of art.

A reference image is a long-term image, which features do not depend of the properties of the instrumentation used for its capture and which colors are specified in the CIE Standard Observer space: i.e. the color space of the human vision system (CIE color space).

Today, archives of reference images are lacking. The existing archives consist mainly of film pictures and digital images, taken either with a still camera or with a scanner. Such images are not useful for archives because their features depend on several non-controlled factors such as: optical geometry, power spectrum of the lighting source, lighting uniformity, spectral response of the optical components, non linear spectral responsivity of the devices, etc.. Furthermore, the colors of these images are strongly device dependent: i.e. images taken with different devices have different colors. In fact, if other measurement conditions are constant, the output colors of an imaging system depend on three light absorption bands (film emulsion) or three light transmission bands of optical filters (digital cameras) centered in the red, green, and blue spectral regions of the visible light. Generally, these spectral bands are not linear combination of the spectral bands of another device and then their numerical specification of the colors will be different, but the case of metamerism. The same considerations apply between a color device and the human vision system. In this case, the linear combinations of the device spectral bands do not match the Color Matching Functions (CMFs) of the CIE Standard Observer: i.e. the average psychometric spectral color response of the human vision system. These observations and the known non-uniformity of the color spaces for both a device and the CIE Standard Observer, allow saying that it is quite difficult, almost impossible, to find a transformation converting the color specification of a device into the CIE color space. In practice, this kind of conversion is obtained inserting a standard color checker in the picture taken with a device allowing setting out a conversion Look up Table (LUT). This procedure is really an unsatisfactory trick; therefore, images taken with color devices do not fit the CIE color space.

It is now clear, that color images taken with different devices or seen by the CIE Standard Observer will look different. This is also true for images taken with the same device at different time due both to the unlikely repetition of the optical geometry and to the aging of the light source and of the device. For these reasons the images taken with a color device are not reference images.

The acquisition of a reference image must involve a physical quantity of the surface layer also useful for the calculation of its tristimulus color values in the color space of the CIE Standard Observer [1]. A pertinent physical quantity is the spectral reflectance factor of the surface layer, measured under defined optical geometry. It depends on both the mechanical and the physical-chemical properties of the surface layer but not on the measuring system. If these properties change with time, the spectral reflectance factor changes showing the rise of problems on the layer. Therefore, the periodic measurement of the spectral reflectance factor of a painting is able to monitor its preservation state.

The efficient control of the preservation state of a painting requires the measurement of the spectral reflectance factor of the whole surface on a pixel basis. This means to take a spectral image of the whole painting: i.e. the ordered collection of the spectral reflectance factor of its pixels. The spectral image allows both the calculation of the color image in the CIE color space and to monitor the preservation state of a painting by comparison with a previous spectral image, therefore it has the properties of a reference image suitable for archive purposes. The spectral images have several advantages with respect to the usual images because they allow:

1. the control of the metamerism;
2. the reconstruction of the color images with choice of both illuminants and CMFs;
3. the color encoding in any color space;
4. the arrangement of data in any type of format;
5. the use of the images also with the future development of the colorimetry;
6. the reproduction of the images on a spectral basis.

2. How to take spectral images

Actually, the main techniques able to acquire spectral images are the multispectral [2-10] and the spectrophotometric techniques [11][12]. Other techniques are under development [13][14].

The multispectral technique, developed in the last ten years, use a black and white digital matrix camera and a set of 6 to 12 optical filters with bandwidth higher than 10 nm and peak transmissions distributed in the 380-1000 nm wavelength range. Using the optical filters in a sequence, this technique acquire from 6 to 12 points of reflectance averaged by the filter bandwidths, for any pixels of the image. These points are not exact values of the spectral reflectance factor, therefore it must be recovered by a deconvolution process based on a previous calibration of the measuring system carried out using a color checker image. The last evolution of this technique is due to the recently concluded CRISATEL european project. The details of the CRISATEL project can be found in [15][16]. It seems that some features of this technique wait for a solution.

The spectrophotometric technique [11] is the base of the scanner we have developed. This technique uses a black and white digital matrix camera and a spectrometer transforming the measuring system in a single beam multichannel spectrophotometer. Fig.1 shows the arrangement of the main components of the measuring system.

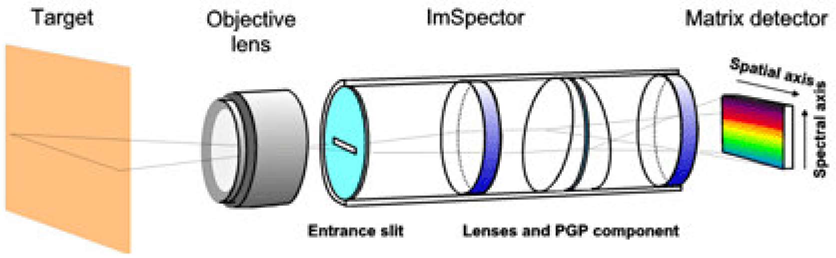

Fig. 1 - Diagram of the measuring system showing the arrangement of the main optical components (figure taken from the website www.specim.fi). The target is the painting.

The scanner works as follows. The objective lens focalizes the image of the painting on the plane of the entrance slit of the spectrometer but only the light coming from the points of the painting stripe conjugated with the points of the entrance slit enters the spectrometer. The spectrometer disperses the light in a plane normal to its optical axis and focalize the dispersed light on the sensor area with the red light on the top and the blue light on the bottom of the sensor. Now, because the image magnification of the spectrometer is 1:1, the entrance slit of the spectrometer will be focalized on the pixel rows of the camera sensor if the spectrometer slit is well aligned with the pixel rows. In other words, the spectrometer takes the polychromatic image of the entrance slit producing monochromatic images of the slit dispersed on the sensor area along the pixel rows as exemplified in Fig.2. Remembering that the points of the entrance slit are conjugated with the points of a stripe of the painting, the monochromatic images of the slit dispersed on the sensor area, are really the monochromatic images of the painting stripe which pixels are defined by the pixels of the rows of the camera sensor as shown schematically in Fig.2.

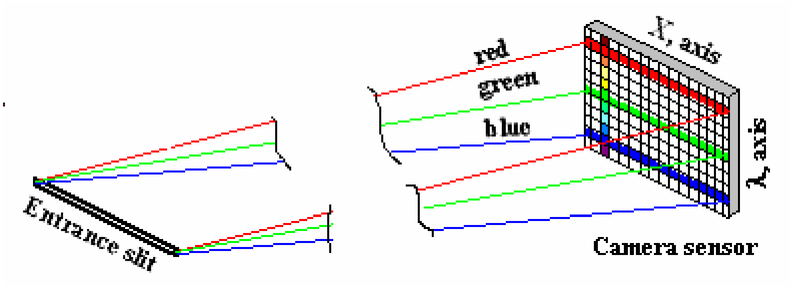

Fig. 2 – Schematic representation of the working principle of the spectrometer inserted between the lens and the digital camera.

The light signals detected by the pixels of a column of the sensor constitute the spectrum of the light reflected by a pixel of the painting stripe. The spectrometer associates to the rows and the columns of the camera sensor, spatial and spectral axes respectively.

The acquisition of a camera frame allows the simultaneous detection of the light spectra reflected by the pixels of a painting stripe, therefore we call our system a multichannel spectrophotometer. For example, a matrix sensor with 1280×1024 pixels is a spectrophotometer with 1280 spatial channels and 1024 spectral channel. Of course, the independent channels of both the spatial and the spectral axes depend on the pixel size of the sensor, on the entrance slit width, on the spread point of the optics, and on other measurement conditions [11].

The acquisition of a camera frame allows the acquisition of the spectral image of a stripe of the painting, therefore to acquire the full images, it is necessary to scan the painting. This requires a mechanical structure driven by control electronics moving the optical system at some speed along the painting capturing subsequent stripes. Moreover, because the measurements of the spectral images need a well-defined optical geometry, it is necessary to associate a lighting system to the scanner, moving rigidly with the optical system.

The last question concern the spatial resolution of the digital images. The archived images serve for several purposes, some of them requiring high spatial resolution: i.e. the fine details of the painting. Usually, the spatial resolution satisfying all the needs is ≅20 lp/degree. This means the resolution of spatial details with radius of about 200 µm seen at a distance of 50 cm. This high resolution is not achieved in a single scan because of the little dimensions of the camera sensors, and then it is necessary to take several strips of the painting and to compose the mosaic later.

3. Description of the scanner

To describe the arrangement of the mechanical and the optical parts of the scanner [17] we refer to Fig. 3. The scanner consists of three mechanical parts: a base to displace a vertical mechanical stem supporting a shorter mechanical stem equipped with a rigid plate carrying the optical components and moving finely on two rails. The picture shows also the fiber optics for blade lighting of the subject (a book in the picture). The vertical stem is displaces manually on the base with a movement of 140 cm. A numerical display allows controlling its position. The shorter stem can be moved up and down along the vertical stem, with a stepper motor manually driven. It can also rotate finely with respect to the vertical column to allow the scanner moving parallel to the surface of the painting. This possibility is very helpful taking “in situ” images, particularly for arched frescos in a church. The rigid plate finely shifts along the short stem driven by a stepping motor controlled by the acquisition software. Its movement is of about 60 cm but owing to the displacement of the short stem along the vertical stem, it is possible to scan a vertical area of 140×120 cm.

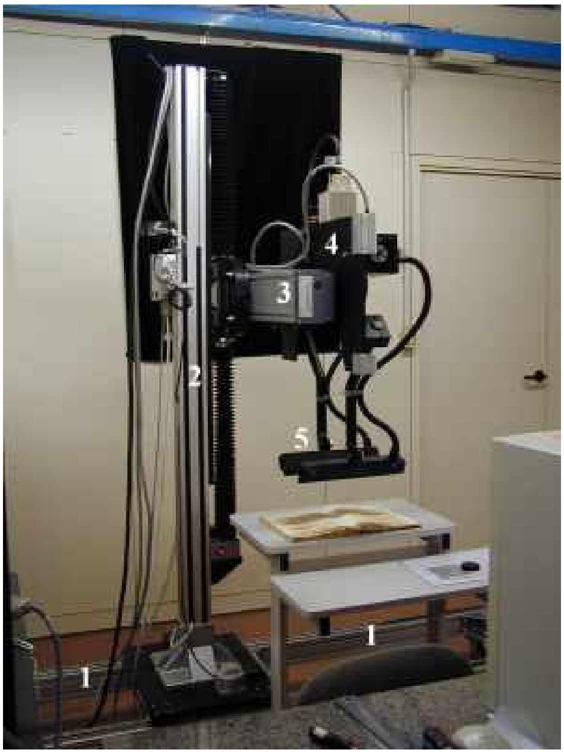

Fig. 3 - The picture shows the more significant mechanical parts of the scanner. 1. base; 2. vertical stem; 3. shorter stem; 4. rigid plate; 5. fiber optics for blade lighting.

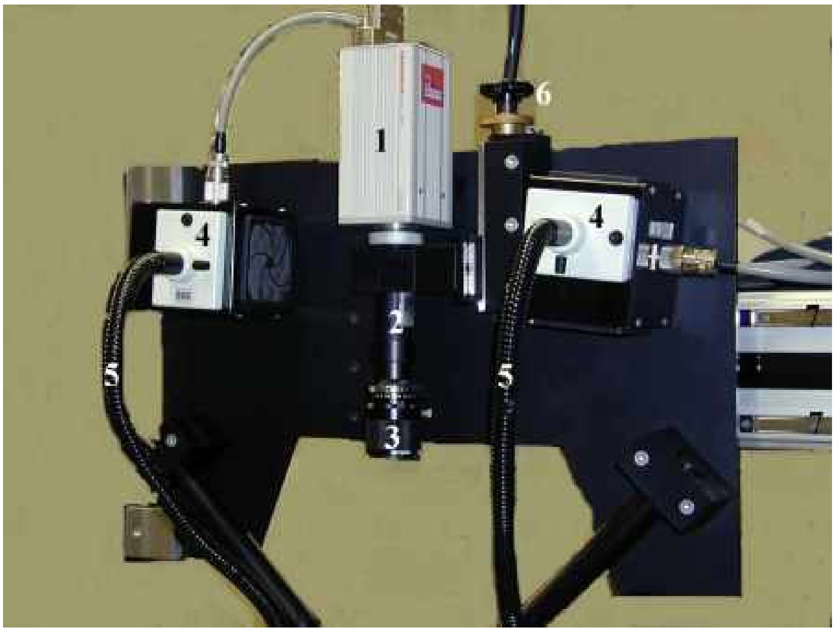

Fig.4 – Arrangement of the optical components on the rigid plate. 1. Camera; 2. Spectrometer; 3. Lens; 4. Halogen Lamps; 5. Optical Fibers; 6. Screw for the manual regulation of the lens to subject distance; 7. Rails.

Fig.4 shows the arrangement of the optical components on the rigid plate. The digital camera, the spectrometer and the lens, form an aligned optical group. A manual screw allows the regulation of the lens-subject distance. The halogen lamps housing are fixed on the rigid plate together with the glass fibers used for the lighting. The fiber blade terminations can be oriented with respect to the optical axis to set the incident angle of the light. The standard optical geometry used in our measurements is 45°/0°. Fig.4 shows also the rails required for the movement of the rigid plate. The scan speed of the acquisitions is usually software selected at 1 mm/sec to prevent the spatial integration along the scan direction that will reduce the spatial resolution. The scanner works with a 12-bit digital electronics.

4. The image acquisition

The general characterization of the scanner is a necessary step before its practical use. This characterization regards the spectral calibration, the geometrical alignment, the linearity of the spatial axis, the linearity of the spectral sensitivity, the color reproduction, the spatial resolution etc. as reported in [11][18] and it is performed when necessary. However, before to take images it is always a good thing to check the spectral axis and the spatial field of view. The first check follows the procedures used for the spectrophotometers; the second is carried out using a scientific ruler.

A standard white is necessary to acquire a spectral image: i.e. a white surface with spectral reflectance certified by a metrological laboratory under the optical geometry used for the image acquisition. The measurement procedure needs the preliminary combined choice of integration time of the digital camera and f /number of the lens and then the following steps:

1. Acquisition of a dark reference frame signals $D_n(\lambda_i)$ usually done by a black cap placed on the lens;
2. Acquisition of the white reference frame signals $W_n(\lambda_i)$ using the standard white.

The spectral image is taken with the acquisition of frame signals $S_n^S(\lambda_i)$ of the light reflected by the stripes of the subject during the scan. The software program calculate the spectral reflectance factor on a pixel basis, following the equation:

$$R_n^S(\lambda_i) = R_{WC}(\lambda_i)\frac{S_n^S(\lambda_i) - D_n(\lambda_i)}{W_n(\lambda_i) - D_n(\lambda_i)} \tag{1}$$

where index *S* indicate the stripe, *n* the pixel number in the stripe and *i* indicate the wavelength value. With *S* and n constant and *i* is running the spectral reflectance factor $R_n^S(\lambda)$ of pixel n in the stripe *S* is obtained, therefore, the spectral image is made by the ordered collection of the stripes as follows:

$$\begin{pmatrix} R_1^1(\lambda) & \dots & R_N^1(\lambda) \\ \vdots & \ddots & \vdots \\ R_1^M(\lambda) & \cdots & R_N^M(\lambda) \end{pmatrix} \tag{2}$$

To see such image it is necessary to calculate the color tristimulus values of its pixels as recommended by CIE [1]:

$$\begin{aligned} X_n^S &= K\sum_i \bar{x}(\lambda_i)R_n^S(\lambda_i)S_{\lambda_i}\Delta\lambda_i \\ Y_n^S &= K\sum_i \bar{y}(\lambda_i)R_n^S(\lambda_i)S_{\lambda_i}\Delta\lambda_i \\ Z_n^S &= K\sum_i \bar{z}(\lambda_i)R_n^S(\lambda_i)S_{\lambda_i}\Delta\lambda_i \end{aligned} \tag{3}$$

where

$$K = \frac{100}{\sum_i \bar{y}(\lambda_i)S_{\lambda_i}\Delta\lambda_i} \tag{4}$$

The functions $\bar{x}(\lambda_i)$, $\bar{y}(\lambda_i)$, $\bar{z}(\lambda_i)$ are the CMFs of the CIE Standard Observer, $R_n^S(\lambda_i)$ is the spectral reflectance factor of pixel *n* of stipe *S*, S_{λ_i} is a CIE standard illuminant, $\Delta\lambda_i$ is the spectral resolution of the spectrometer at wavelength λ_i. The *K* factor normalizes the luminance factor *Y* to 100. The sums are carried out in the spectral range 400÷730 nm. An important observation is that the spectral images allow to compute color images with the free choice of CMFs and illuminant. This offer a tool to study problems concerning the technical lighting.

Lastly, we put in evidence that the spectral image acquired by the scanner are at present saved in a proprietary [17] SIF format or in ENVI format. On the other hand, it is possible to save the images as BMP, TIFF and TXT formats. However, there is not difficulty to arrange the acquired data in other types of formats.

5. Fidelity of color acquisition and reproduction

The fidelity of the color acquisition has been evaluated in the CIELAB space by taking the spectral image of 14 grey and color gloss tiles certified by the National Physical Laboratory (UK), covering a wide color gamut.

The obtained average color distance is ΔE_{94}=0.46 with a $\Delta E_{\max}$=0.90 [11] that is a very good performance considering that ΔE=1 is the threashold of color discrimination.

The reproduction of the color images is carried out using a monitor, a display, a printer or a projector. The tristimulus values *XYZ* calculated by equation (3) cannot be directly used to drive these devices requiring their specific *RGB* digital signals. The transformation converting the *XYZ* tristimulus values to *RGB* signals is not obvious. The device selected for the reproduction of the images taken by the scanner is a CRT monitor, probably the most simple and accurate reproduction device at present. In this case the *RGB* driving signals are obtained by a linear transformation using the set of the measured calibration data carried out on the monitor. The color fidelity of the reproduced images has been checked by evaluating the color of the reproduced the NPL certified tiles by measuring the spectral emission of the monitor. The obtained color difference between the colors reproduced by the monitor and the NPL certified colors has an average value ΔE_{64}=2.8 with a $\Delta E_{\max}$=4.2. This can be considered a good result.

6. Spatial resolution

The spatial resolution of the scanner allows appreciating the minimum spatial detail of a scene. It depends on the lens magnification, on the spatial light spread due to the optical components, on the dimensions of the sensor pixels, on the mechanical vibrations, on the lighting non-uniformities, on the scan speed, and on other parameters associated to the measurements. To account for all these parameters it is necessary to acquire the image of some test chart specifically designed for this task. The spatial resolution has been studied using the FBI SIQT Scanner Test Chart, supplied by Sine Patterns (USA). Its image, scanned at a speed of 1 mm/sec, has a resolution of about 20 lp/degree: i.e. a spatial resolution close to that of the human vision system [11][18].

7. Practical works

High-resolution images of paintings by Leonardo, Parmigianino, Annibale Carracci, Filippo Mazzola, Jan Provost, Van Dyck, and other painters, acquired at the National Gallery of Parma, allow to test the quality of the scanner. The restorers of the museum analyzed the images to put in evidence artifacts and color fidelity. They concluded that images have not artifact and was exceptionally good concerning the color. This is a satisfactory conclusion considering that quantitative evaluation methods concerning the quality of color images do not exist at our knowledge. However, a quantitative conclusion is welcome.

The virtual restoration of a sixteen-century manuscript, the index book of the important library of doctor Demetrio Canevari preserved at the Berio Library in Genoa, is the second practical work done with the scanner. The preservation state of the manuscript was very bad therefore it was impossible to read many of its pages because of the acidification of the paper due to the iron-gall ink used at that time. Here, the main exploited property of the scanner is the high spatial resolution. The detailed images of the pages of the manuscript taken by the scanner allow making brighter the pixels near the original writing, until to obtain its recovery. This has been done processing the images by a sequence of mathematical filters.

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