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MULTISPECTRAL UV FLUORESCENCE ANALYSIS OF PAINTED SURFACES

A. Pelagotti[1]*, L. Pezzati*[1]*, A. Piva*[2]*, and A. Del Mastio*[2]

[1]Istituto Nazionale di Ottica Applicata
Largo E.Fermi 6, 50125 Firenze, Italy
phone: +(0039) 055 2308238
e-mail: anna@ino.it

[2] MICC – Media Integration and Communication Center
Viale Morgagni 65, 50100 Florence, Italy
phone: + (0039) 055 4237404, fax: + (0039) 055 4237400
e-mail: delmastio@lci.det.unifi.it

ABSTRACT

A novel system has been developed to acquire digital multispectral ultraviolet (UV) induced visible fluorescence images of paintings. We present here the image processing needed to understand and further process the acquired multispectral UV fluorescence images.

1. INTRODUCTION

Observations of an artwork under UV light have been carried on since the end of the twenties. Traditionally this diagnostic method is used mainly to reveal the presence of old varnish layers, and to observe whether the fluorescent haze due to it is even or not, where a lack of fluorescence may indicate retouched or newly repainted areas. However, UV fluorescence imaging potentialities go beyond this, although they have never, until recently, been fully explored and exploited. As a matter of fact, traditional imaging systems such as photographic cameras, considerably limit the possibility to collect reliable data and quantify the fluorescence emission, making it difficult to compare results obtained at different times, with other devices or on other artworks.

We realised a new UV imaging system which is able to overcome some of the present limitations and to pave the way to new applications for UV fluorescence imaging in art diagnostics. The system and the results obtained will be described in the following sections.

2. UV FLUORESCENCE APPLICATIONS FOR CONSERVATION: STATE OF THE ART AND OPPORTUNITIES

Traditionally, fluorescence photographs are mostly used to identify different varnishes and overpainting. Occasionally, their colours are considered to give some indications of the pigments used, but are seen as a supplementary rather than primary technique for identifying materials. This is also because the photographic acquisition and reproduction of fluorescence images does not allow a correct colorimetric reproduction nor a quantitatively correct radiometric or photometric evaluation, and therefore also not meaningful and reliable further data processing and analysis. This is due to the limited data set that the system is able to reveal and to several irreproducibility factors in phase of acquisition, developing, and printing. Summarising this method only gives qualitative, as opposed to quantitative, indications. One more limit of the traditional system is that Wood lamps are not pure UV sources. They present a residual visible emission that superimpose on the fluorescence emission, and may compromise the correct acquisition and reproduction of the intensities and colours of the fluorescence images. The only kind of reliable documentation of fluorescence currently applied is the acquisition of fluorescence spectra on selected spots, or, more often of samples in a spectrofluorometer. However this last one is an invasive technique. Moreover, with “spot” techniques, i.e. investigating single small areas on the painting, it is only possible to measure a limited number of points. This means that measurement places have to be selected very carefully, trying to guess which areas of the painting are expected to carry relevant information. Imaging techniques avoid this difficulty by measuring the entire surface. Moreover their results retain the visual aspects of the investigated objects, and this makes them more easily readable and accessible.

3. THE NOVEL MULTISPECTRAL UV FLUORESCENCE IMAGE ACQUISITION SYSTEM

A new system for the acquisition of digital multispectral fluorescence images was designed, built and tested. The system is essentially composed by an ad hoc designed UV light source, filtered in order to block the radiation in the visible range, a high sensitivity cooled scientific digital CCD camera with a 14 bit A/D Converter, 7 interferential filters and multivariate analysis software. The system allows to digitally characterise the fluorescence emission both radiometrically and colorimetrically and to further process it.

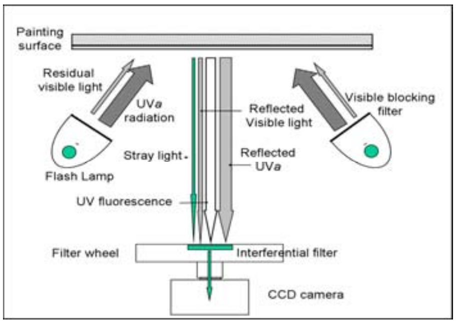

Fig. 1 Acquisition system

4. THE IMAGE PROCESSING

With the system described seven monochrome images of 1024x1024 pixels, each in a different spectral band, may be captured and stored in a 14 bit digital format. Therefore they may be corrected, calibrated and processed in order to combine their information.

4.1 Registration

The first step consists in a registration procedure which is intended to remove the geometrical misalignments of the images. These differences are mainly due to small changes in the optical path, between the object and the CCD sensor for the various filters. This is most probably caused by the different optical properties of each filter and a possible slightly different relative position of the various interferential filters in the filter wheel. An "*ad hoc*" software has been developed to automatically register the images acquired with the different filters (for each imaged area we need to register 21 images at a time, 3 images for each of the 7 bands, as described in the following section and shown in Fig. 3). The algorithm is based on mutual information maximisation [3]. Mutual information is a similarity measure coming from the information theory. It is a highly performing similarity measure, compared to traditional ones, such as cross-correlation, which can often fail when dealing with multi-source images for the inherently different image structures and tone dynamics (i.e. in case of images coming from different sensors or regarding different frequency bands).

4.2 Correction and un-mixing

Once the registration procedure has been successfully performed, we can digitally process the acquired images to correct for uneven illumination and stray light and to un-mix the relative contribution of fluorescence and reflectance, which is necessary since the light source cannot be totally filtered in the visible range by the filter on the UV source. For each filter, we acquired a "raw" fluorescence image ($\mathbf{I}_{R\_UV}$) of the painting using our UV lamp, and taking care of having a reflectance standard of known reflectance, next to the painting (this can be considered with a good approximation a Lambertian surface, i.e. the radiation that illuminates the sample is isotropically reflected by it). In this way, for each band, we record in a portion of the image, values directly proportional to a known percentage of the incident stray-light.

We acquired, with the same acquisition time used for the fluorescence image, also a "dark" image ($\mathbf{I}_{D\_UV}$), i.e. an image with the UV light source turned off, and a "flat" image ($\mathbf{I}_{F\_UV}$), i.e. an image of a white surface placed in the same position as the painting and with the UV light shined on it.

In the same way, for each filter we acquired a "raw" radiance image ($\mathbf{I}_{R\_R}$) of the painting using a halogen lamp ("white" lamp), and taking care of having the same reflectance standard in the same position as for the fluorescence image. In this way we would have, for each band, in a given position of the images, as described above in case of the UV light, pixels with values directly proportional to the light reflected by the reflectance standard i.e. directly proportional to known percentage of the incident light. We then acquired with the same acquisition time used for the reflectance image also a "dark" image ($\mathbf{I}_{D\_R}$), i.e. an image with no light source shined on the painting, and a "flat" image ($\mathbf{I}_{F\_R}$), i.e. an image of a white surface place in the same position as the painting with the "white light" shined on it.

We then performed what we called an "*a posteriori*" correction, i.e. we computed the Corrected Fluorescence+StrayLight Image ($\mathbf{I}_{C\_UV+S}$), and the Corrected Radiance Image ($\mathbf{I}_{C\_R}$) according to the following:

$$\mathbf{I}_{C\_UV+S} = (\boldsymbol{a}\_{F\_UV})*(\mathbf{I}_{R\_UV}-\mathbf{I}_{D\_UV})/(\mathbf{I}_{F\_UV})$$

$$\mathbf{I}_{C\_R} = (\boldsymbol{a}\_{F\_R})*(\mathbf{I}_{R\_R}-\mathbf{I}_{D\_R})/(\mathbf{I}_{F\_R})$$

where $\boldsymbol{a}\_{F\_UV}$ is the average value of $\mathbf{I}_{F\_UV}$ over the whole image, and $\boldsymbol{a}\_{F\_R}$ is the average value of $\mathbf{I}_{F\_R}$. over the whole image.

In this way, we removed the contribution of the environment light, and we compensated for a possible uneven illumination. The contribution given by the dark current was automatically compensated for by the CCD camera during the acquisition process.

The Reflectance Image ($\mathbf{I}_{Ref}$) can then be computed as the result of the division between the Corrected Radiance Image and the average of the pixels' values in the Corrected Radiance Image over the part where the reflectance standard was imaged ($\boldsymbol{s\_lr}$) by inverse of the reflectance percentage ($\boldsymbol{R}$) of the reflectance standard used.

$$\mathbf{I}_{Ref}=\mathbf{I}_{C\_R}/\boldsymbol{s\_lr} \times \boldsymbol{(100/R)}$$

The Corrected Fluorescence Image ($\mathbf{I}_{C\_UV}$) can be obtained subtracting the Stray-Light image ($\mathbf{I}_S$) from the $\mathbf{I}_{C\_UV+S}$ image.

$$\mathbf{I}_{C\_UV} = \mathbf{I}_{C\_UV+S} - \mathbf{I}_S$$

This last one ($\mathbf{I}_S$) can be computed as the product of the Corrected Reflectance Image by the average of the pixels' values in the Corrected Fluorescence+StrayLight Image over the part where the reflectance standard was imaged ($\boldsymbol{s\_luv}$) by inverse of the reflectance percentage ($\boldsymbol{R}$) of the reflectance standard used.

$$\mathbf{I}_S=\mathbf{I}_{Ref} \times \boldsymbol{s\_luv} \times (\boldsymbol{100/R})$$

4.3 Radiance calibration

The main components involved in an image acquisition process are depicted in Fig. 1 (Note that only one optical colour filter is represented, while, a set of filters is used for the complete acquisition).

The detection of the signal is performed by a CCD array. Solid state sensors like the CCD of our camera generally have a linear response to the received radiation even for low intensities, and this allows us to perform highly accurate radiometric and photometric measurements. However the CCD response depends not only on the signal energy but also on the system behaviour for each filter.

If we denote the spectral fluorescence emission by ***f(λ)***, the spectral transmittance of the optical systems in front of the detector array by ***o(λ)***, the spectral transmittance of the ***k***-th optical colour filter by $\boldsymbol{\Phi_k(\lambda)}$ and the spectral sensitivity of the CCD array by ***α(λ)*** and supposing a linear optoelectronic transfer function of the acquisition system, the camera response $\boldsymbol{I_k}$ for an image pixel is then equal to:

$$I_k = \int_{\lambda_{\min}}^{\lambda_{ma}} \mathrm{f}(\lambda) o(\lambda) \Phi_K(\lambda) \alpha(\lambda) d(\lambda) = \int_{\lambda_{\min}}^{\lambda_{ma}} \mathrm{f}(\lambda)\, \mathrm{w}_{\mathrm{k}}(\lambda) d(\lambda)$$

where $\boldsymbol{w_k(\lambda)}$ denotes the spectral sensitivity of the ***k-th*** channel. Hence, to be able to quantify and analyse ***f(λ)***, a radiance system calibration needs to be performed to know $\boldsymbol{w_k(\lambda)}$.

Substituting ***f(λ)*** with an approximating function $\boldsymbol{F_k(\lambda)}$ and $\boldsymbol{w_k(\lambda)}$ with an approximating function $\boldsymbol{W_k(\lambda)}$, where the new functions assume one average value in each of the transmittance wavebands of the interferential filters:

$$I_k \approx F_k(\lambda) W_k(\lambda) \quad \text{(eq. 1)}$$

$$F_k \approx I_k(\lambda) / W_k(\lambda) \quad \text{(eq. 2)}$$

In order to estimate $\boldsymbol{F_k(\lambda)}$, we need to estimate $\boldsymbol{W_k(\lambda)}$. To do so, we proceeded with an indirect method as follows. An incandescence lamp was shined on a sample of reflectance calibration standard by means of an optical fibre, which formed an angle of 45 degrees with the reflectance standard surface, so to minimise the specular reflectance. The reflected light spectrum of a spot was acquired using a spectroradiometer. In the same geometrical configuration, we then acquired the images of the reflectance standard with the novel experimental set-up and with each of the 7 interference filters.

For every image acquired with each of the interferential filter, we took the average over the pixels' values ($\boldsymbol{V_k}$) of the above mentioned spot. We then calculated the 7 calibration factors $\boldsymbol{W_k}$ (k=1,2...7) defined as $\boldsymbol{W_k=R_k/V_k}$, where $\boldsymbol{R_i}$ are the average values of the reflected light in each of the interferential filter band as achieved with the spectroradiometer. The calibration in radiance, performed as described, is affected by a large inaccuracy; nevertheless, this procedure allows estimating the visible spectrum of the radiation detected by the imaging system, with a spectral resolution that depends on the FWHM of the interference filters (around 40 nm).

At the moment different *standard* calibration procedures for the radiometric and photometric calibration of multispectral fluorescence images do not exist. The CIE standards, used for standard imaging, are not directly applicable.

4.4 Fluorescence spectra estimation

Although there are no comprehensive studies over fluorescence spectra of painting materials, we assume that there could be abrupt or very narrow spectral features (ref.[4,7]), thus we cannot claim to be able, with our system to reproduce the fluorescence spectral signature across the entire surface of the painting, and supply a definitive record of the fluorescence emission at a given time. However, we could provide estimation of the fluorescence spectra and of the colour co-ordinates in a standard colour space. This can be especially useful to monitor changes that would occur to the fluorescence emission of the painting. Moreover, since we acquire also 7 reflectance images we could estimate the reflectance spectra as well. With the 14 values for each picture element, 7 relative to the fluorescence emission and 7 relative to the reflectance behaviour, first trials to discriminate materials show quite promising results (ref.[7]).

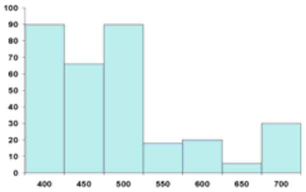

Fig. 2: Spectral profiling achievable with the current acquisition system

4.5 RGB true colour fluorescence image

For conservation purposes the first useful image processing is to recombine the 7 monochrome bands into a true colour image, where this means that the picture shows objects in the same colours that your eyes would normally see.

The colour image reproduction performed through multispectral imaging allows matching more precisely the response of the human visual system, because this can be described more precisely by combining the sensitivity functions of a multispectral camera than by using RGB camera sensitivities, which are moreover strongly device-dependent. This can clearly be done both for the reflectance and for the fluorescence images.

The first unsolved problem to achieve a correct reproduction of these last ones, is that the general paintings fluorescence emissions have intensities in the mesopic range, often close to the photopic range, i.e. present low intensities for which the CIE still needs to define optimal colour matching functions. If we disregard this matter, we could compute an RGB image using the following procedure:

$$R = R_{\max}\left[F_1(\lambda)\bar{r}_1(\lambda) + F_2(\lambda)\bar{r}_2(\lambda) + \ldots + F_7(\lambda)\bar{r}_7(\lambda)\right]$$

$$G = G_{\max}\left[F_1(\lambda)\bar{g}_1(\lambda) + F_2(\lambda)\bar{g}_2(\lambda) + . + F_7(\lambda)\bar{g}_7(\lambda)\right]$$

$$B = G_{\max}\left[F_1(\lambda)\bar{b}_1(\lambda) + F_2(\lambda)\bar{b}_2(\lambda) + \ldots + F_7(\lambda)\bar{b}_7(\lambda)\right]$$

where $\boldsymbol{F_k(\lambda)}$ is the approximating function of the spectral fluorescence emission (see eq.1 and eq.2), and $\bar{r}(\lambda)$, $\bar{g}(\lambda)$ and $\bar{b}(\lambda)$ are the 10-deg colour matching functions of Stiles and Burch (1959):

$$\bar{r}_k(\lambda)=\int_{\Delta k}\bar{r}(\lambda)d(\lambda) \quad \text{for } \boldsymbol{k}=1,...,7$$

$$\bar{g}_k(\lambda)=\int_{\Delta k}\bar{g}(\lambda)d(\lambda) \quad \text{for } \boldsymbol{k}=1,...,7$$

$$\bar{b}_k(\lambda)=\int_{\Delta k}\bar{b}(\lambda)d(\lambda) \quad \text{for } \boldsymbol{k}=1,...,7$$

eq.(3)

5. APPLICATIONS

We applied the RGB composition described in (eq.3), to the 7 monochrome images of a detail of the painting, after the corrections as described in the previous section. Figure 4 shows the image of the painting, in the 450 nm band, under UV light, as after the acquisition only. It is possible to notice how the visible components of the source light which are transmitted by filter on the lamp, reflect on the reflectance standard surface (top right), and onto the gilded background. Fig. 5 reproduces the fluorescence emission of the painting after removing stray light. In this case there is no visible light reflected neither on the reflectance standard nor on the background, apart from where the assumption of a diffusing surface is not valid. The image intensity is here only due to the fluorescence of painting surface. The same detail of the painting is shown in Fig 6, where the image is relative to the 600 nm band. Here substantial differences in emission are visible in many parts. The bright areas correspond to materials having a peak emission around 600 nm.

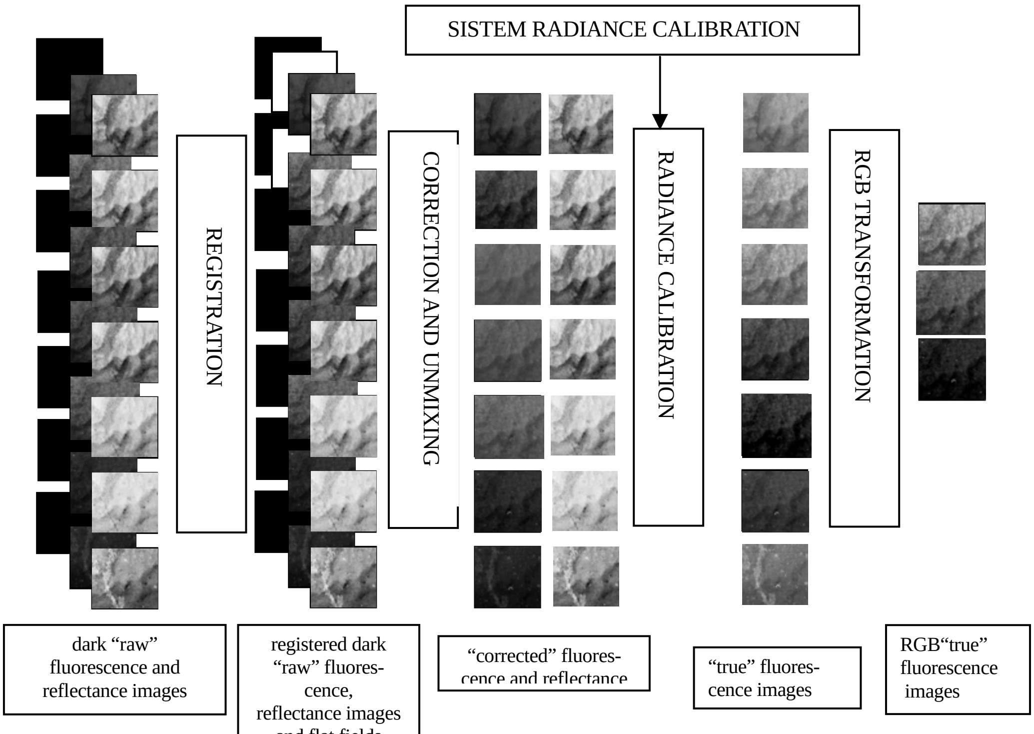

Fig. 3: Chain for image registration.

Using the 7 acquired and corrected images, we also performed an identification of the different coloured pigments, by applying the well known Spectral Angle Mapper algorithm. The preliminary results are shown in Fig. 8-11. In particular, in Fig. 8 and 9, results are shown when using the 7 fluorescence emission images, to search for the same pigment found on a spot of the Madonna’s cloak and arm, all over the painting, a binary mask is superimposed to the painting image to show where a similar spectral profile was identified. In Fig. 10 and 11, the cloak’s pigments are searched, respectively. only using the 7 reflectance sub-bands images and the 14 bands of the fluorescence and reflectance images together; note that in the latter case the upper part of the cloak over the Madonna’s head, is correctly discarded: this is because it belongs to a restored part of the art work, where other pigments have been used, compared to the original parts. Note that the best result is obtained combining the results of both the reflectance and the fluorescence imaging.

6. CONCLUSIONS

Fluorescence imaging has been used in the conservation field for more than 80 years to identify different varnishes and overpaintings. Only occasionally it has been also used as supplementary technique to recognise materials. Experienced conservators receive indications about pigments and dyes by direct observation of fluorescence intensity and hue. INOA developed a system to acquire and record digital multispectral (7 bands) fluorescence as well as reflectance images. This system is capable to provide quantitative rather than qualitative data, dramatically improving the traditional systems. The new system allows correcting captured images and calibrating them, recombining the 7 monochrome bands into a RGB image of a painting under UV light as perceived by an observer and separating the fluorescence component from the component due to the reflectance of visible stray light. Moreover it paves the way to the use of spectral profiling of fluorescence images to identify pigments and binding media.

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Fig. 4: image of the painting under UV light in the 450 nm. band.


Fig. 5: fluorescence emission image in the 450 nm band


Fig. 6: fluorescence emission in the 600 nm. band.


Fig. 7: re-composed RGB fluorescence emission image.


Fig. 8: attempt to identify a pigment by using the spectral profile of its fluorescence emission using using 7 images . A binary mask is superimposed to the RGB fluorescence image


Fig. 9: attempt to identify a pigment by using the spectral profile of its fluorescence emission., using 7 images A binary mask is superimposed to the fluorescence image


Fig. 10: attempt to identify a pigmens by using the spectral profile of its reflectance, using only 7 sub-bands in the visible range.

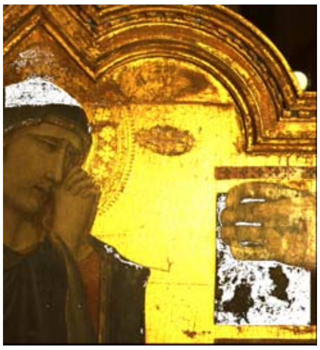
Fig. 11: attempt to identify a pigment by using its spectral profile, using 7 sub-bands for both reflectance and fluorescence. Please note how more accurate is the identification in this case