Multispectral Imaging and Digital Restoration for Paintings Documentation

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Abstract. Spectral imaging for radiation wavelengths different from the visible ones, namely in the infrared (IR) and ultraviolet (UV) ranges provides useful information about the actual preservation state and past conditions of paintings. As a consequence, it is possible to combine this information with that obtained in the usual RGB visible basis and to propose digital or 'virtual' restoration of a painting, taking into account its history, modifications and repaintings done in the past. As an example, a work of Pietro Lianori is discussed and analysed.

Keywords: Multispectral analysis, IR and UV images, virtual restoration, painting.

1 Introduction

The virtual restoration is now a good opportunity for analyses to be performed by restorers, conservators and art historians. Many works often can not be restored, sometimes for lack of valid techniques or because of bad previous operations, sometimes due to deficiency of precise records allowing us to understand how the work had been rebuilt.

As an example, when the paintings show successive repaintings, - a well-known case is represented by the painting of Caravaggio, *The good luck*, conserved in Capitolini Museums of Rome – one should not intervene with the removal of the second painting since itself is an artistic work to be preserved, but in digital you have the freedom to remove or divide the two paintings by techniques that allow retouching, with higher magnification, to restore the original features, without the work suffering a loss.

Within a digital framework, there is a large freedom of action to create hypotheses for restoration of paintings, frescoes, but also photographs, architecture and three-dimensional objects. Today, the digital (or virtual) restoration is considered an accepted technique for the restoration of old photographs, but it is also an excellent opportunity to develop possible interventions on paintings, sculptures and archaeological artefacts.

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Fig. 1. Pietro Lianori, *Virgin with the Child,* Cappuccinis' Museum, Bologna, XV century, 171 x 124 cm, before restoration (on the left) and during the restoration (on the right)

2 The Virgin with Child of Pietro Lianori

In this paper we consider a very controversial and partial restoration carried out on a painting by Pietro di Giovanni Lianori, representing the Virgin and the Child (fig. 1), an artist active in the fifteenth century. This work is conserved in the Museum of Cappuccini in Bologna, Italy, since 1928. In the provincial archives of the Cappuccini Friars of Bologna the photographs are preserved, documenting the status of the work before and during the restoration that has been interrupted because of the discovery of the original painting below a successive remaking (fig. 2).

These images confirmed a very difficult situation for restorers and conservators, due to a complex overlapping of layers both original and repainted in order to refresh the painting and to highlight the identity of a new donor. In fact, the comparison between data recorded from multispectral images in various spectral bands has allowed the identification of quantitative and qualitative differences subsequent to the drafting of the original (fig. 3).

The comparison of the recovery image of this panel in visible light before, during and after the restoration of the seventies of the twentieth century clearly shows that the work had been almost entirely repainted. If the choice to remove, in some areas, repaintings arising from the seventeenth century modifications made it possible to uncover the original paint surface that is still preserved in the underlying layers, although very impoverished in terms of material, it has also compromised the ability to read all work in a consistent manner.

Fig. 2. Pietro Lianori, Virgin with the Child, image in visible light, current issue

Fig. 3. Pietro Lianori, *Virgin with the Child*, IR image (on the left) and image in UV fluorescence (on the right)

Fig. 4. Pietro Lianori, Virgin with the Child, details showing the two coats of arms in visible light (left) and IR reflectography (right) with different symbols

The dynamic composition of the painting is monumental, a feature typical of the artist, where the Virgin is represented seated on the throne with his right arm raised and holding the Child, and in her left hand there is a white rose, symbol of purity. Above the shelves aside of the throne, one can see two coats of arms that may lead back to bidders, smaller paintings in the lower part of the work, the sides of the central throne (fig. 4).

In the latter there is a scroll with the following inscription:
"PETRUS IOHANIS DE LIANORIS PXT ANO 236 GABRIEL DARDUS MED. DOCTOR DONAVIT ANNO DNI 1611", written in gothic letters in the first row and in the second one in Roman letters.

By means of multispectral investigation it was possible to examine non-destructively the entire surface of the painting and find some significant areas where the different penetration of the radiation used has highlighted the differences between the drafts and the fifteenth-seventeenth century modified version as in the case of the two coats of arms.

3 Multispectral Imaging and Processing

Multispectral images have been obtained by means of a portable equipment, MUSIS 2007, provided with CCD camera that acquires images with 558 x 370 pixels, recorded at the wavelengths of RGB components of visible light, near-infrared and UV fluorescence. The spatial resolution in the acquisition phase has been chosen in such a way that the digital images could reproduce the *craquelures* of the painted surface; this result has been obtained with a sampling frequency corresponding to 6 pixels/mm.

Therefore, the whole painting has been digitized by capturing partial images referring to an area of 9 x 6 cm and, in order to improve the signal noise ratio, each image consists of an average image of 16 acquired frames for the following recomposition of the whole digital image. The complete final digital images of the painting have been obtained by means of suitable algorithms of reassembly and are shown in figs. 2 and 3.

In order to improve the image contrast, all images have been made uniform radiometrically by means of an equalization procedure and a mean-centering scaling algorithm was adopted [1]. As shown in our previous works [2-5], the multispectral image of figs. 2 and 3 can be summed up in a three-way array, G(IxJxK), with I and J indexes labelling row and column, respectively, of each image, while K refers to the wavelengths. The results of standard PCA (Principal Component Analysis) [6-11] applied to G matrix are summarized by the simple expression:

$$\underline{G} = \sum_{a=1}^{A} T_a * p_a \quad (1)$$

where A is the rank of a two-way G(IxJ)xK matrix resulting from the rearrangement of G, and each term in the summation is multivariate product, T_a*p_a, between the score images, T_a , and the corresponding loading vectors, p_a. Only three PCs explain with "sufficient accuracy" the multivariate image G, and the correspondent score images, T_a, as proved by the structure of the loading vectors. As evident by the loading plots, the first component, T_1, summarizes the information common to all the wavelength with some emphasis on RGB ones. As a consequence, the physical features of the figures and details such as the coats are well outlined. Second and third score images, T_2 e T_3, mainly resume IR and/or UV wavelength concerning the preparatory drawings as well as tonalities present both in the figure of the Virgin and on the background. Moreover, in these score images the restoration areas are clearly identified. T_4 e T_5 images are responsible of a small amount of the whole multispectral variability, whose importance must be evaluated time by time.

This case study shows that the detection of photon spectra combined with the *x-y* scanning procedure is a multivariate measurement. Indeed, *I* scannings of *J* voxels each are performed in order to detect the corresponding scattering spectrum; furthermore, each spectrum is functionally divided in *K* energy intervals, so that a three-way (three-mode) data array follows. In these terms, the layer density evaluation may be considered a spectroscopic imaging technique like satellite and microscopic imaging, where the spatial and spectral data expressed in a *multivariate image* are used to extract significant information [6].

In fig.5A, the three-way data matrix is shown as a stack of congruent images viewing the same field-of-view, measured for a series of different 'variables'. The k= 1, …, K frontal slices are two-way images resulting from the integral of the corresponding energy interval computed for all the IxJ voxels. As a consequence, the pixel density distribution comes from the collapse of the multiple images into a single one. The three-way data array shown in fig.5A is denoted by an underlined bold-face matrix, $\underline{\mathbf{G}}^{(IxJxK)}$, and its elements as g_{ijk}, where indices i=1, …, I, and j=1, …, J, indicate voxels and k=1, …, K the energy intervals. Following the terminology used in [9] for the *N*-way image analysis, arrays of three-way data can be characterized by a categorical object/variable (O/V) mode convention, and a multivariate image as an object-object-variable (OOV) array; in these terms voxels in mode A) and B) in fig.5A are the objects, and energy intervals in mode C are variables.The three-way array $\underline{\mathbf{G}}$ may be unfolded into a two-way data matrix and examined with ordinary principal component analysis (PCA). This approach is termed *unfold*-PCA and is summarized in fig.5B, where the stack of images $\underline{\mathbf{G}}^{(IxJxK)}$ is firstly unfolded into a two-way matrix, $\mathbf{G}^{(IJxK)}$, and then represented by means of structure and noise terms.

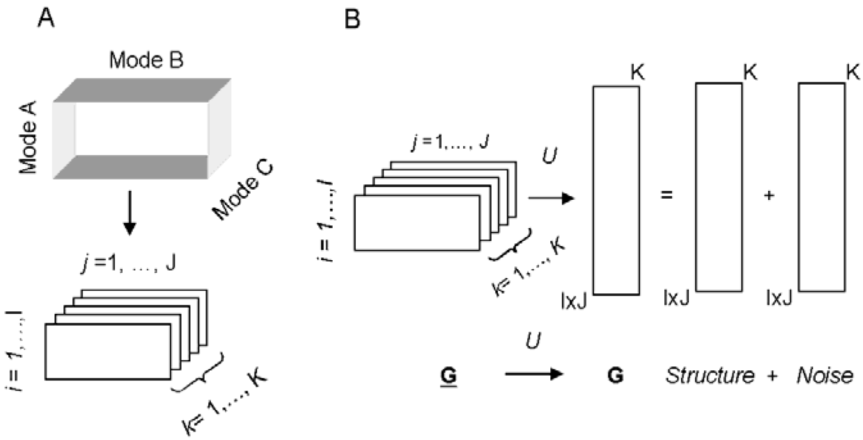


Fig. 5. A) Three-way array, G(IxJxK).. B) Unfold-PCA (see text), U denotes the unfolding operator

The two-way data matrix, **G,** has *IJ* objects corresponding to the spectra detected at each voxel, and *K* homogeneous variables – the number of photons in each energy interval – ranging between tens to tens-of-thousand. In order to take into account the differences between variables, **G** was variable-wise scaled by dividing each vector $\mathbf{g}_k$ by the square root of its mean value, and then centered to obtain a new matrix, **X.** This scaling gives the right weight to every variable in **G** matrix, and makes it possible to obtain the appropriate linear model that describes the data variability.

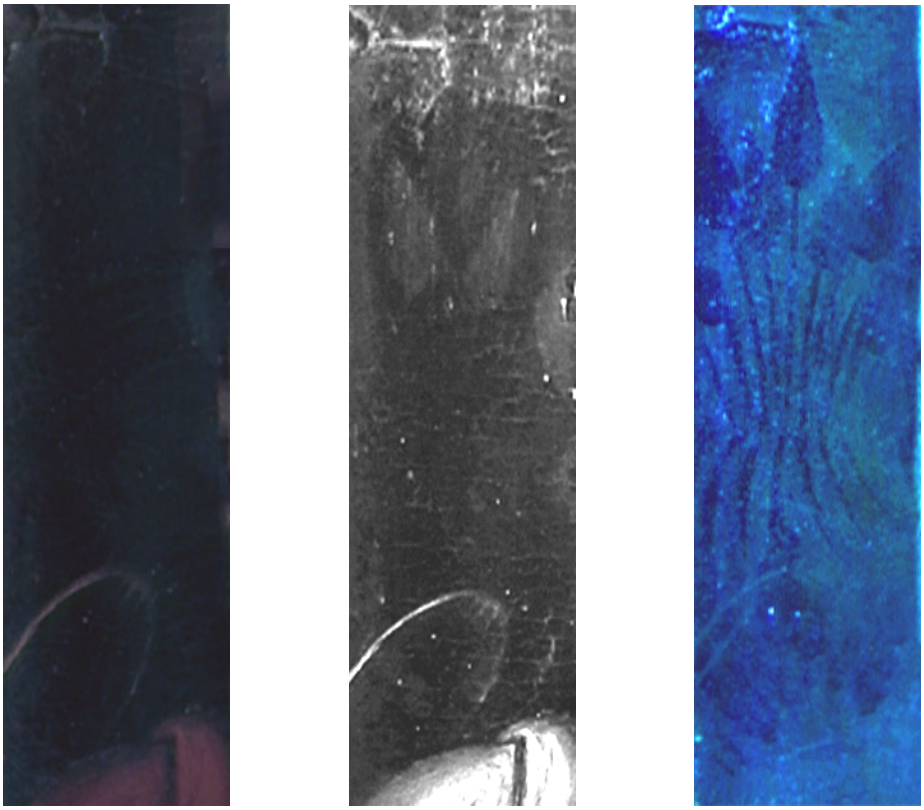
To reduce matrix **X** into principal components, the singular value decomposition (SVD) was computed,

$$\mathbf{X} = \mathbf{U}\mathbf{D}\mathbf{V}^T = \sum_{k=1}^{K} d_k \mathbf{u}_k \mathbf{v}_k^T = \sum_{k=1}^{K} \mathbf{t}_k \mathbf{p}_k^T \qquad (2)$$

where vectors $\mathbf{t}_k = d_k\mathbf{u}_k$ and $\mathbf{p}_k = \mathbf{v}_k$ are the scores and loadings vectors, respectively, of the structure term in fig.5B, and K is the full rank of **X** matrix. Scores and loadings vectors in eq.(2) are, respectively, orthogonal and orthonormal.It is found that a two PCs model, accounting for about 92% and 6% of the total variance, respectively, describes with a “sufficient accuracy” the **X** matrix; i.e., the effective rank of **X** is A = 2, and the remaining PCs account for the noise term only of fig.5B. These results were further confirmed by the Bartlett sphericity test with p = 0.9 [10]. The model with two principal components is given by

$$\mathbf{X} = \hat{\mathbf{X}} + \mathbf{E} = \mathbf{t}_1\mathbf{p}_1^T + \mathbf{t}_2\mathbf{p}_2^T + \mathbf{E} \qquad (3)$$

where $\hat{\mathbf{X}}$ and **E** matrices are the structure and noise terms, respectively, and the outer products between loadings and score vectors, $\mathbf{t}_k\mathbf{p}_k^T$, univocally identify the structure term.



a b c

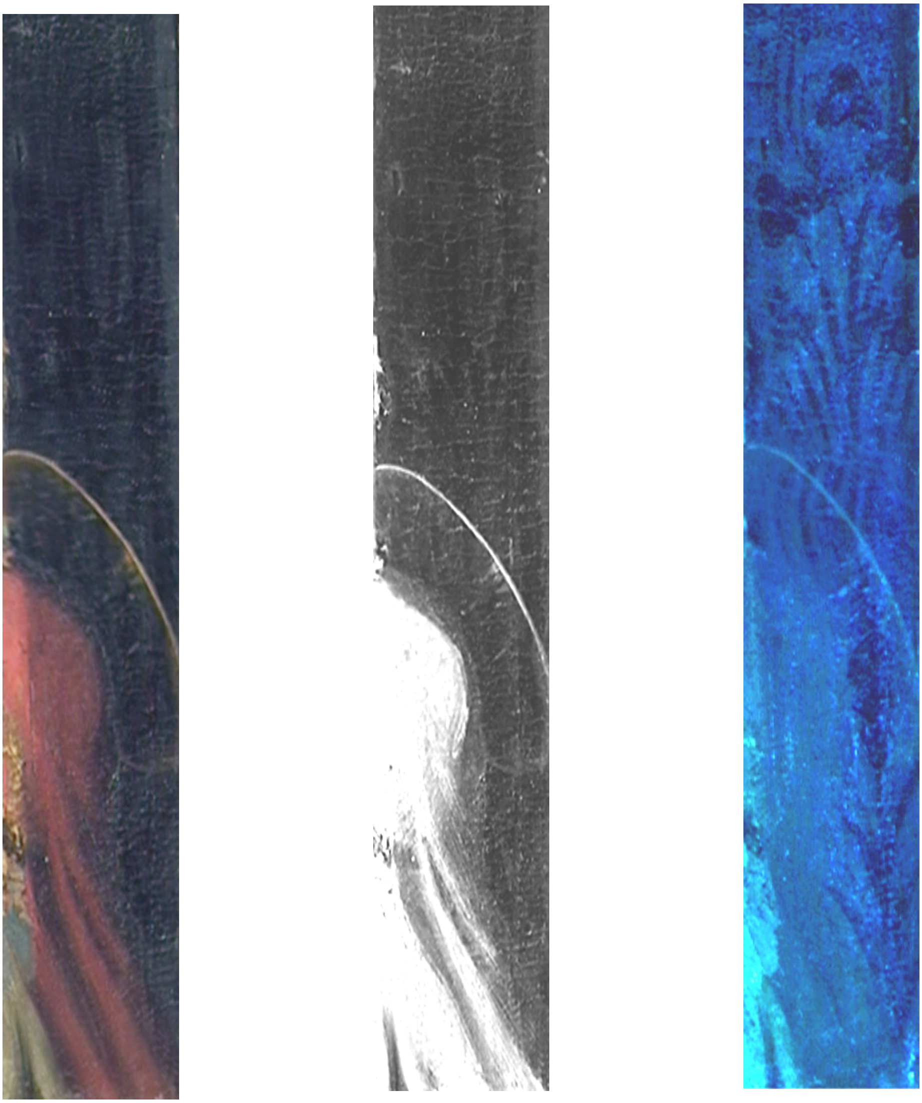
Fig. 6. Pietro Lianori, Virgin with the Child, details in visible light (a), infrared reflectography (b) and ultraviolet fluorescence (c)

Visualization of model parameters, loading and score vectors, has an important role in interpreting the results of multivariate spectroscopy data analysis. Moreover, by the difference between the **X** matrix evaluated from the visible image before the partial restoration and that obtained from the multispectral analysis of the painting in its present status, we derive a quantitative estimate allowing a well-grounded digital restoration to be performed pixel-by-pixel in each region of interest.

4 Results and Conclusions

Figs. 6-8 show a few details of Lianori's painting where digital images have been captured in visible RGB basis, in IR reflectography and UV fluorescence to be combined together according to the procedure summarized in the previous paragraph.

A PCA analysis has been performed for the whole panel, starting from these photon spectra, digitally recorded and processed, as in fig. 5 and eqs.(2,3). Once obtained the **X** matrix a pixel-by-pixel local operations have been carried out by subtracting the content of each pixel in the X matrix corresponding to the RGB image before the restoration.



a b c

Fig. 7. Pietro Lianori, *Virgin with the Child,* other details in visible light (a), infrared reflectography (b) and ultraviolet fluorescence (c)

Therefore, a digital or virtual restoration of the painting is recovered where the hidden original layer is brought back to pristine condition, as shown in figs. 9 and 10. The concept of 'virtual restoration', despite its introduction is recent enough, is not without ambiguity of use and meaning. Founded in the field of cultural heritage, it has gradually emancipated widening the scope of its application and getting to lick even the linguistic and literary studies, yet the term 'virtual restoration', even in its variant of 'digital restoration', continues to show just the technical means used rather than a clear instance of methodology. Recently, someone has seriously proposed abandonment of these expressions in favor of a more comprehensive definition, but still with a good degree of vagueness, such as, for example, 'iconological digital restoration'.

a b c d e

Fig. 8. Pietro Lianori, *Virgin with the Child,* details of the base of the throne with the inscription before restoration (a), during restoration (b), in visible light (c), infrared reflectography (d) and ultraviolet fluorescence (e)

Fig. 9. Two details of Lianori's painting during virtual restoration

Fig. 10. Preliminary results of virtual restoration

Our purpose was to prove that even a virtual restoration can be performed by respecting the principles stated by Cesare Brandi [13] for real restorations and overall in the world adopted, namely respect for the aesthetic and historical aspects, recognizability of the intervention, reversibility of the materials and minimal intervention, while the fourth one, compatibility of materials, is pertinent only to the real restoration.

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