Towards the Definition of a Low-Cost Toolbox for Qualitative Inspection of Painted Historical Vaults by Means of Modified DSLR Cameras, Open Source Programs and Signal Processing Techniques

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Abstract. Historical architecture is a primary element containing the identity values of a society. The wide diffusion of many ancient buildings gathering part of these values on painting walls over territories often characterized by poor technological or economic resources brings to consider the development of low-cost protocols to inspect valued surfaces and to give the authorities in charge of preservation and restoration adequate technical information. Here we present the preliminary results of a recent application of remote sensing micro-geophysical techniques to typical architectural targets such as vaults. A modified commercial Digital Single-Lens Reflex (DSLR) camera was used to acquire multispectral datasets on portions of a painted vault. Multispectral datasets were used raw or after the application of a pre-processing step with a Multi Images Stacking (MIS) algorithm. Multispectral images were then processed with spatial wavelet decomposition, histogram enhancing, thresholds application, image fusion, false colors compositing and Principal Component Analysis (PCA) techniques. Software used have been GNU Image Manipulation Program (GIMP) and Mathworks MATLAB (which can be substituted for the processing steps proposed by the built-in functions of GNU OCTAVE open-source software). Processed images were able to highlight features on vault paintings revealing details of the surface or its very shallow layers which were impossible or very difficult to distinguish in raw data. In fact, they emphasized low-visible details, differences in apparently similar finishes or pigments, cracks and probably details of surface preparation.

Keywords: Multispectral analysis · Digital image processing · PCA · Cultural heritage · Historical architecture · Painted walls inspection · Low cost diagnostics

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O. Gervasi et al. (Eds.): ICCSA 2020, LNCS 12255, pp. 971–991, 2020.
https://doi.org/10.1007/978-3-030-58820-5_70

1 Introduction

In this paper, we present a recent multispectral survey carried out within a monumental building in the historical center of Cagliari, Italy: the church of San Giuseppe Calasanzio (Fig. 1a). Built between XVII and XVIII centuries in a baroque style, like other Italian churches of the Piarists' Order [1], together with the adjacent college. The church has a barrel-vaulted nave with three chapels intercommunicating on the sides and a deep presbytery, covered with a dome on an octagonal drum from which it is possible to laterally reach the sacristy and the building of the college (Fig. 1b); The complex is currently close because of long-lasting and incomplete restoration works with a general state of decay of the inner finishes. At ground level, the vault of the sacristy, indicated with red region in Fig. 1b and geometrically reconstructed in Fig. 2, has painting finishes with pictures of religious themes on the inner side, with decayed parts (Fig. 3a, b). First floor level over the sacristy is communicating with the college.

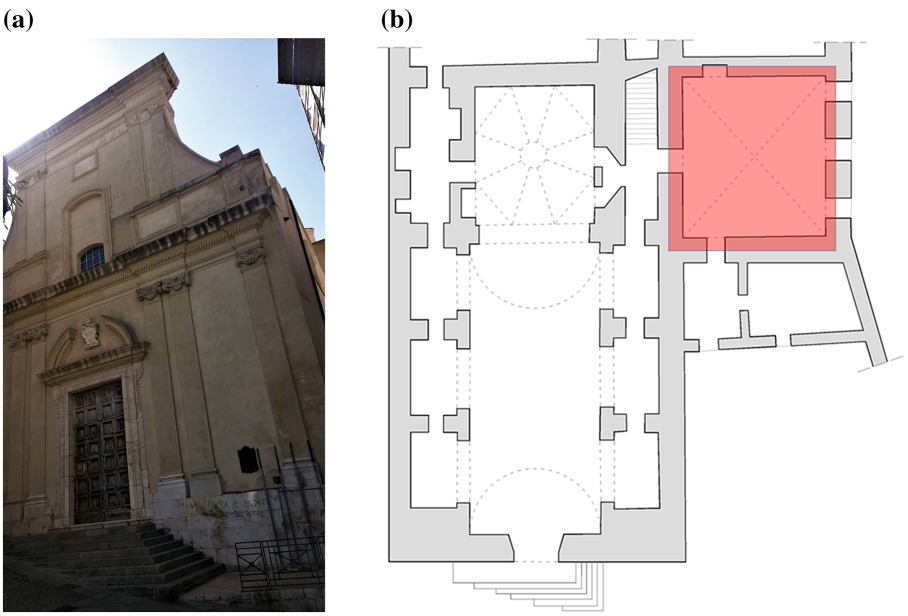

Fig. 1. Façade of the church of San Giuseppe Calasanzio **(a)** and plan of the ground level of the church with the connected sacristy indicated with a red region **(b).** (Color figure online)

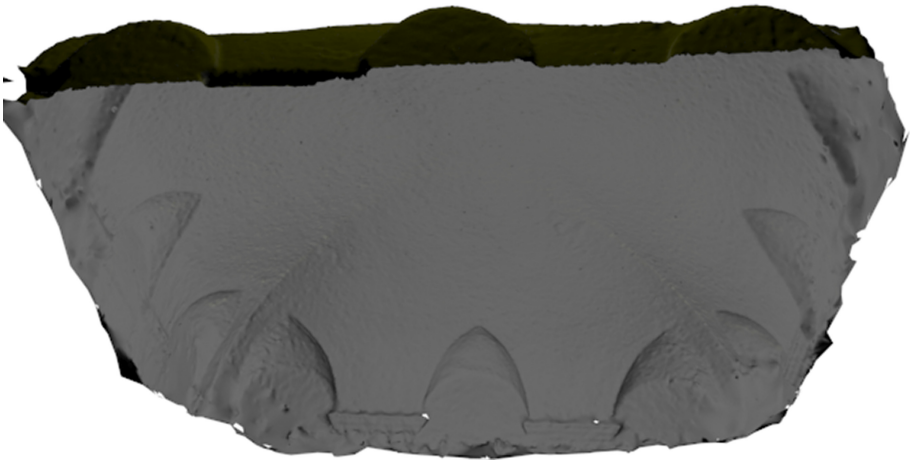

Fig. 2. 3D model of the inner surface of the sacristy vault, reconstructed with Structure from Motion techniques.

Instrumental miniaturization has recently focused the interest of geophysical community to the application of micro-geophysics to also architectural elements [2–16].

The growing attention of our society to cultural heritage assets made possible an extension of traditional disciplinary limits to new methods and technology which, even with strong contribution from consolidated geophysical techniques, are developing aiming to resolve specific issues linked to the new diagnostic targets [17, 18].

In this context, an important role is being played by remote sensing techniques. Nowadays, remote sensing methods are an evolving research field taking advantage of the knowledge contamination from many specializations related to surveys and technology [19].

The most immediate demand for historical architecture documentation is the reconstruction of detailed and reliable 3D models of the monuments or their elements, that can be achieved with geomatic technologies such as photogrammetry through image-based modelling and Terrestrial Laser Scanner [20–26]. Structural analysis of cultural heritage assets is also possible by means of motion video magnification [27] or other photogrammetric techniques [28].

The experimental dynamic behavior of valuable historical slender structures, such as bridges, bell towers or other structures with one dimension prevailing on the others, can be assessed with ground-based remote sensing instruments simultaneously measuring structural vibrations of multiple backscattering points by means of Real Aperture Radar (RAR) interferometry [29–33].

Based on the radar interferometry, even slow movements of more complex building elements or parts of historical centers and Cultural Heritage sites are monitored using satellite Synthetic Aperture Radar [34–37].

Another emerging remote sensing technique in the field of Cultural Heritage inspection is the so called Teraherz (THz) technology, which, based on the recording of

(a)



(b)



Fig. 3. Details of the sacristy vault paintings on a corner at the set level **(a)** and in the middle at the keystone level **(b).**

electromagnetic (EM) waves of that bands, is used on various kinds of archaeological or historical items allowing, under specific experimental setups, to image studies bodies at various depths [38, 39].

Thermal infrared acquisitions allow the assessment of various issues linked to monuments studies, like detection of moisture presence, cracks, voids and anomalous elements in historical walls [21, 40–45]. The application of infrared thermography to small objects reliably identified hidden defects or invisible restoration works [38, 46–49].

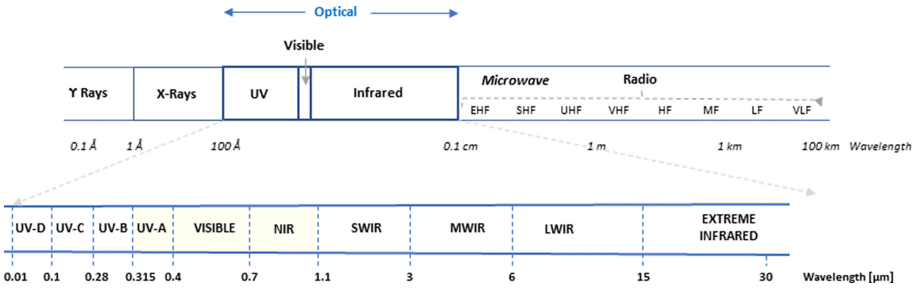

Fig. 4. Schematic representation of the most important EM bands for remote sensing applications [50, 51]. The bands involved in this study are highlighted in yellow. (Color figure online)

Multispectral (MS) remote sensing mostly investigates the surface finishes through their interaction with the radiation from a range of wavelengths, both visible and invisible to the human eye, across the EM spectrum. Acquisition setup include camera, light sources, and filters parameters.

Multispectral images are usually composed by different monochrome images collected by filtering the electromagnetic signals reflected and/or emitted by the objects through narrow spectral bands (Fig. 4). In most cases, the images are acquired:

- at the spectral interval of the ultraviolet light, at wavelengths lower than 400 nm;
- at the visible frequencies, corresponding to the wavelength interval comprised between about 400 nm and 700 nm;
- and at several frequency bands of the infrared signals, typically in the spectral bands of
  - Near Infrared (NIR), between 700 nm and 1100 nm,
  - Short Wavelength Infrared (SWIR), between 1100 and 3000 nm,
  - Mid Wavelength Infrared (MWIR), from 3000 nm to 6000 nm,
  - Long Wavelength Infrared (LWIR), from 6000 to 15000 nm,
  - and Far/Extreme Infrared (TIR), from 15000 nm to 1000000 nm.

These EM bands sensing is also known as optical remote sensing and is sensitive to a wide range of applications [19].

We have already mentioned THz and thermographic techniques, which often constitute part of the multispectral protocols extended to all or most parts of the optical remote sensing bands [38, 45, 49].

Over the time, the multispectral analysis has been improved to study paintings, frescoes and historical documents [52]. Advances in this field of study allow the identification of the kind of material utilized by the artists and the detection of overlays, drawing additions, defects and past pictures not clearly readable by means of the visible light. Depending on the comparison of the energizing and the recorded spectrum, we can distinguish fluorescence or reflectometric surveys.

The most common experimental configurations are based on recording the reflection of a natural or artificial energizing flux, in bands from ultraviolet (UV) to near-infrared (NIR), (Fig. 5). Their use allows to study the most superficial layers of paintings and writings [53–57]. As predictable, the penetration depth of the different signals mainly depends on their wavelength. As shown in the scheme of Fig. 5, the investigation depth increases as the frequency of the electromagnetic wave decreases.

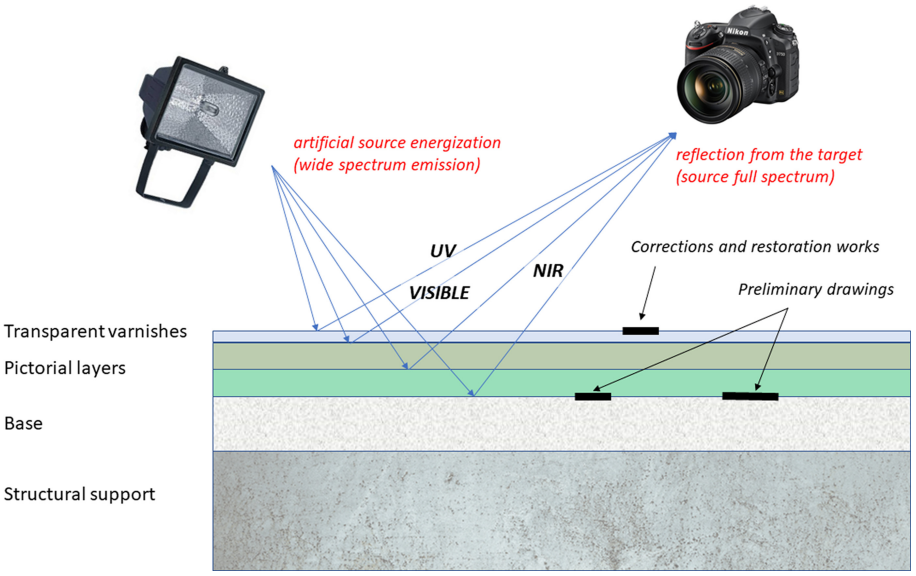

Fig. 5. Artistic representation of a typical reflectometric survey.

MS surveys are characterized by several parameters that influence the quality and the features of the experimental images. In the scientific literature different resolutions are defined. In particular, the spatial resolution indicates the size of a single pixel of the acquired data. The spectral resolution describes the width of the spectral bands that the sensor is suitable to record. The radiometric resolution defines the ability of the sensor to differentiate among small variations in the sensor incoming EM signal. In addition, the time resolution represents the time interval between two consecutive acquisitions [19].

In November and December 2017, the complex of San Giuseppe Calasanzio was the object of geophysical measurements as a preliminary step to develop a diagnostic protocol for the integrated knowledge of historical architectonic elements [11].

To test the usefulness of multispectral reflectometric methods for the inspection of precious inaccessible surfaces, this proximal sensing technique was applied to the sacristy painted vault. A set of low-cost hardware constitutes the acquisition instrumental fleet. Some processing steps are developed and proposed that can be easily implemented with open-source tools. Their preliminary application to the multispectral datasets is described to verify potentialities in detail enhancing, joint information retrieving and rough differentiation of apparently very similar pigments.

2 Data Acquisition and Preprocessing

2.1 Data Acquisition

The multispectral images were collected in raw format using a digital single-lens reflex (DSLR) camera, Nikon D750, modified by removal of the internal bandpass EM original filter. This, permanent, operation allows the camera sensor to receive and record EM energy for a spectrum wider than the only visible band for which it was designed. To perform the multispectral over multiple narrower bands, five external optical filters were mounted, one by one, over the camera lenses (Fig. 6):

- an UV bandpass filter, with acquisition in the range 320–390 nm;
- a visible bandpass filter, in the range 390–700 nm;
- an IR high pass filter at 720 nm;
- an IR high pass filter at 850 nm;
- an IR high pass filter at 950 nm.

The camera setup was remotely controlled with a commercial acquisition software package distributed by the same manufacturer, the Nikon Camera Control Pro 2 (Fig. 7a). Raw images had been acquired at a resolution of 6016 by 4016 pixels, with the following acquisition setup:

- Bit range: 14 bit
- F-stop: f/8
- Sensitivity: ISO-800
- Focal distance: 42 mm
- Exposition time: variable

To make more uniform the target lighting and to guarantee an energization over the camera recording bands, four artificial halogen lights were utilized (960 W, in total), and natural light was reduced as much as possible.

The MS datasets were collected shots through four shots across the painted vault of the sacristy (Fig. 7b): the camera was positioned approximately at one meter from ground, with direction mostly perpendicular to the vault inspected regions.

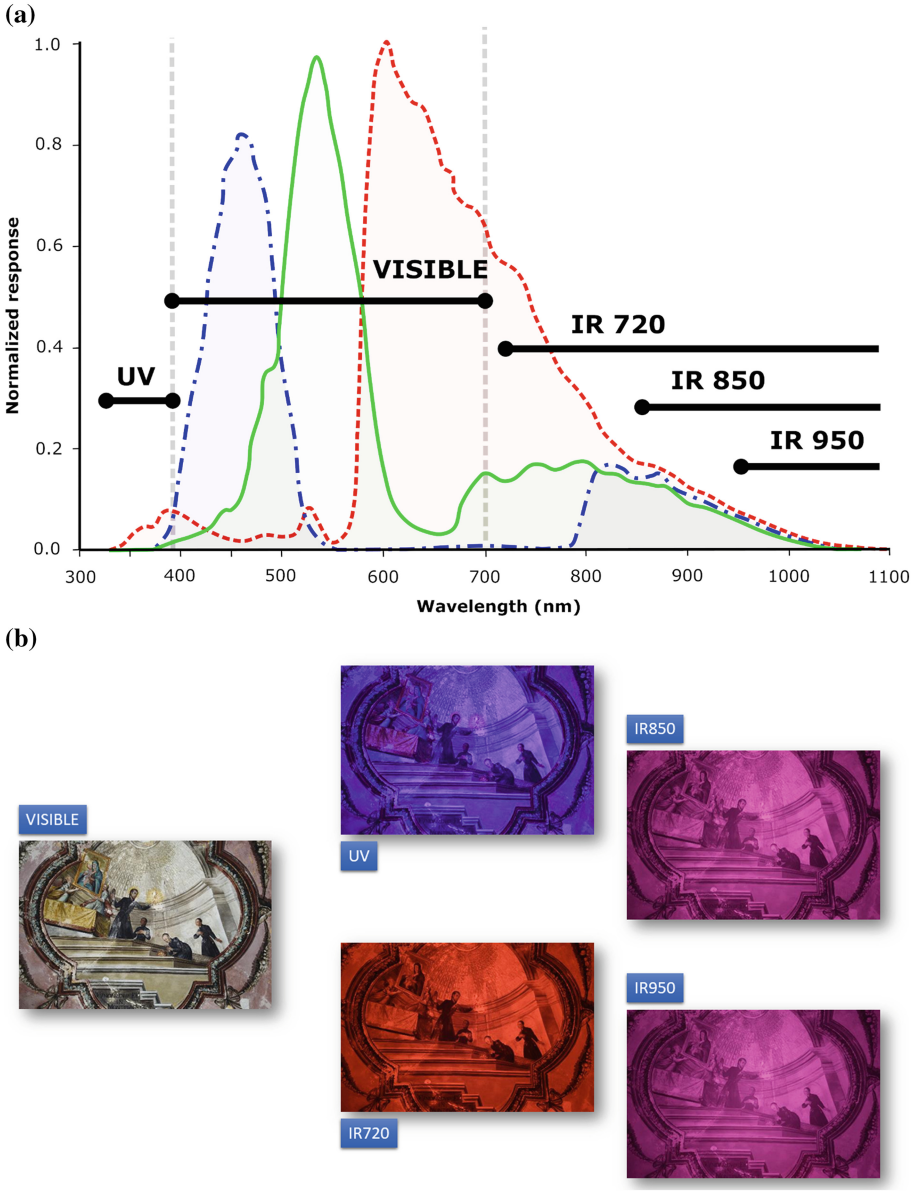

Fig. 6. **(a)** Representation of multispectral bands configurations (black lines indicate the fives EM filters), plotted over the sensitivity curves of the three RGB channels of a camera, the Nikon D200, similar to the one used during MS acquisition (RGB channels sensitivity from [42]. **(b)** Raw data example acquired within the multispectral survey.

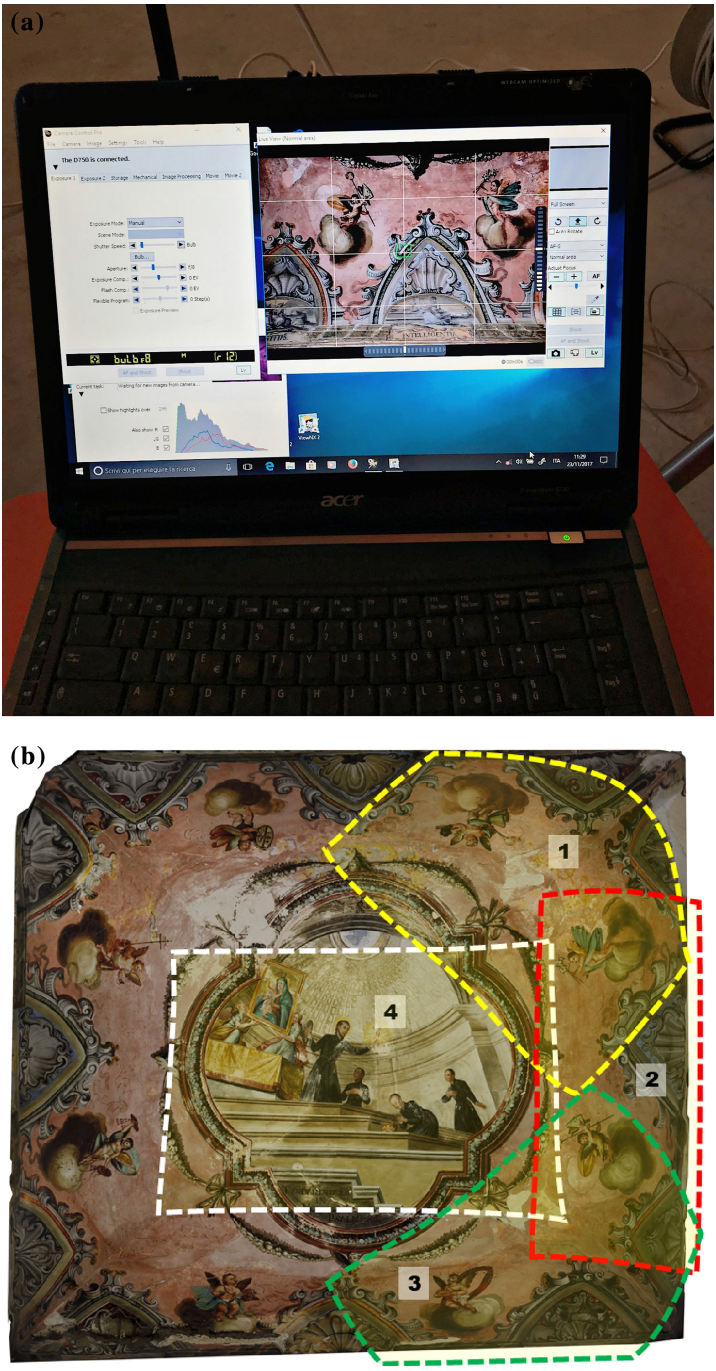

Fig. 7. **(a)** Setting up parameters and data preview through the acquisition software environment (courtesy F. Mura). **(b)** Regions of the painted vault surveyed by the four MS shots.

2.2 Pre-processing

Preliminarily to most processing steps, acquires datasets have been pre-processed with a Multi-Image Stacking (MIS) approach [45, 55–57]. Following this technique, raw MS images are acquired setting multiple camera exposition times for each combination of the other acquisition parameters (shot, optical filters, camera and light setups). Each RGB image, recorder with the given exposure, is then converted to a 16 bit grayscale image and then stacked with others at varying exposition time to produce an image (representative of the full stack images) which maintains a high level of details, optimized over each region of expositions (Fig. 8). This procedure is repeated for each spectral gathering of acquisitions (each EM passband filter) and for each shot, using free image conversion and common mathematical processing tools.

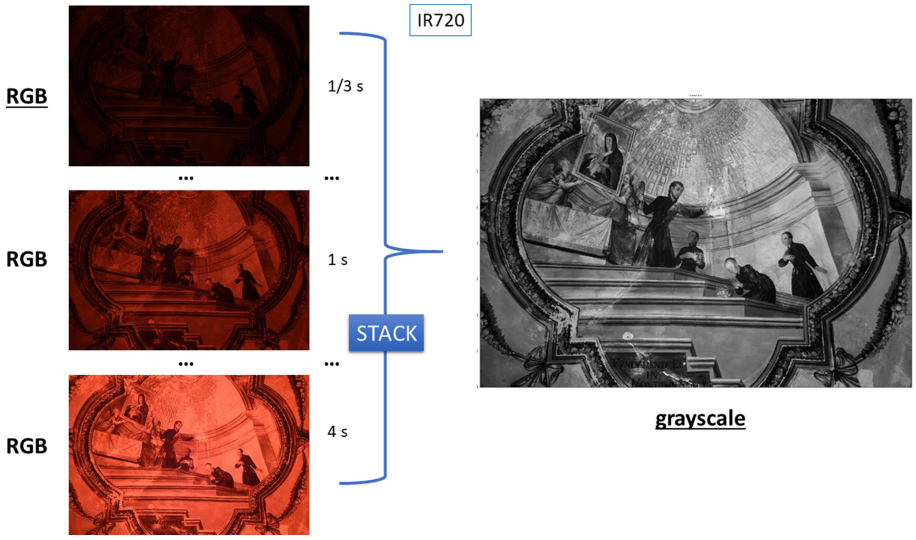

Fig. 8. The Multi Images Stacking (MIS) procedure: raw data (at varying exposure times of acquisition) on the left are the input to produce the stacked grayscale image on the right.

3 Data Processing

MS data are essentially images that can be processed as images or matrices with most common software tools for image editing (like GIMP, GNU Image Manipulation Program, or Photoshop by Adobe) and mathematical processing (like GNU Octave or MATLAB, MATrix LABoratory, by MathWorks).

The processing proposed in this study are feasible with both free and proprietary software, even though they are realized through GIMP and MATLAB.

3.1 Digital Image Processing and Spatial Filtering

One set of the processing steps implemented to enhance the qualitative interpretation of the MS datasets include most common functions in image editing, such as histogram enhancing, contrast magnification, color tuning, image fusion techniques, and others [58].

Furthermore, spatial signals in stacked grayscale images are evidenced using the Wavelet Decompose function [56], which is now included in the standard distribution of GIMP. The workflow for this processing step, illustrated in Fig. 9, can be summarized in:

- image spatial wavelet decomposition (6 levels), regional field removing (−1 level);
- histogram enhancing, contrast and brightness calibration, curve levels adjustments;
- merging of resulting high spatial frequency levels.

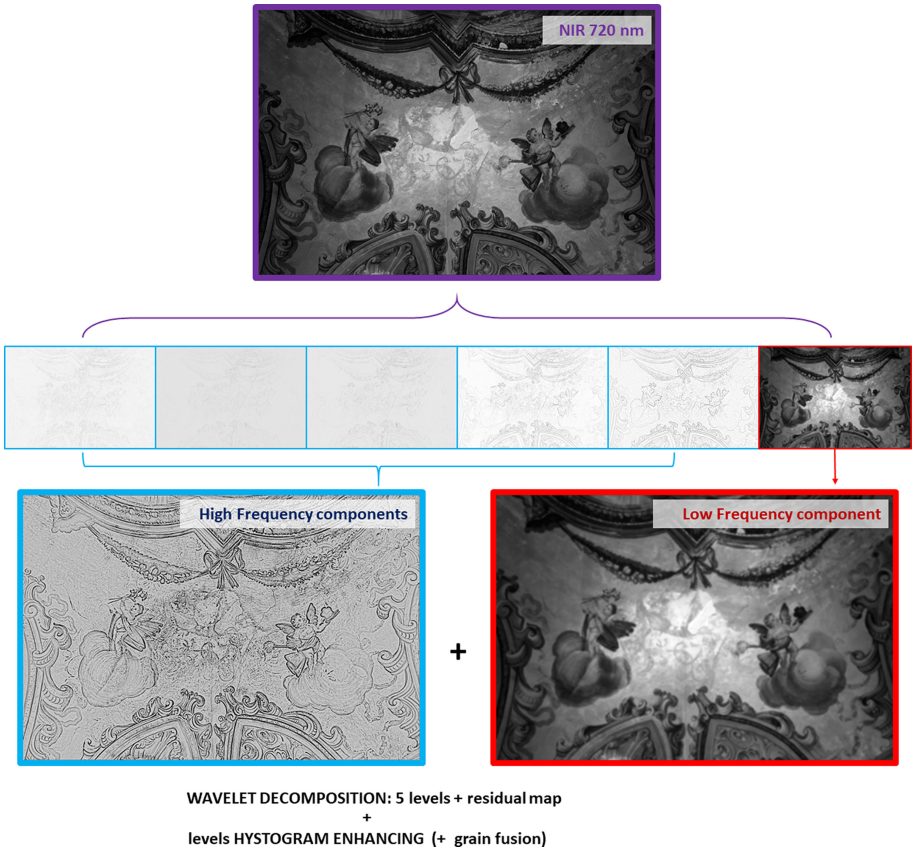

Fig. 9. Spatial wavelet decomposition of a stacked NIR image (bordered with violet) into low (red) and high (cyan) frequency components, with the application of histogram enhancing and grain fusion over high frequency levels. (Color figure online)

Finally, spectral dimension of experimental datasets can be explored, inside image editing environment, using popular tools like RGB channel combination or levels merging with the possibility to set up many parameters.

3.2 Principal Component Analysis of the MS Datasets

The second set of experimented processing steps was realized inside less user friendly but more powerful and flexible platforms, like the mathematical programming environments which however maintain a certain easy to use with respect to programming languages.

Most of the processing developed inside GIMP can be repeated even inside MATLAB environment, and some were, but with a little bigger difficulty due to the substantial absence of a graphical interface to tune many of the processing parameters. At least for beginners. Nevertheless, mathematical processing platforms flexibly allow to implement most complex processing like Principal Component Analysis, which is quite common in multispectral and hyperspectral remote sensing protocols so much that is available in specialized environmental remote sensing software (e.g. the open source SNAP by ESA).

The Principal Component Analysis (PCA) is a linear transformation implemented with the purpose to reduce multidimensional data in a few dimensions data set. The principle at the base of this technique considers that in many cases the data show correlations between their different dimensions. Through the PCA, the data are projected in a new set of axes. The new reference system is composed by the fewest possible dimensions. Therefore, this procedure consists of a coordinate transformation that allows to plot the original data in a new reference system of orthogonal axes with a minimum correlation between the variables. The first axis, derived from the PCA process, is oriented in the direction of the most variation, the second, in the direction of the new-most variation, etc. In order to calculate the new set of axes, the eigenvalues-eigenvectors decomposition is utilized. The eigenvectors are unit vectors pointing in the direction of the new axes of the reference system. The axis with the highest eigenvalue corresponds to the axis explaining the most variation of data set [59].

4 Results

4.1 Digital Image Processing and Spatial Filtering

Various sets of digital image processing were applied to the sample datasets, revealing great potentialities on their use to have a quick access to interpretable data through free software of generalist use. Images in Fig. 10 and their magnification in Fig. 11 show how is possible to quite simply obtain enhanced images where many details previously unrecognizable are revealed and interpretation of the inspected surfaces is aided.

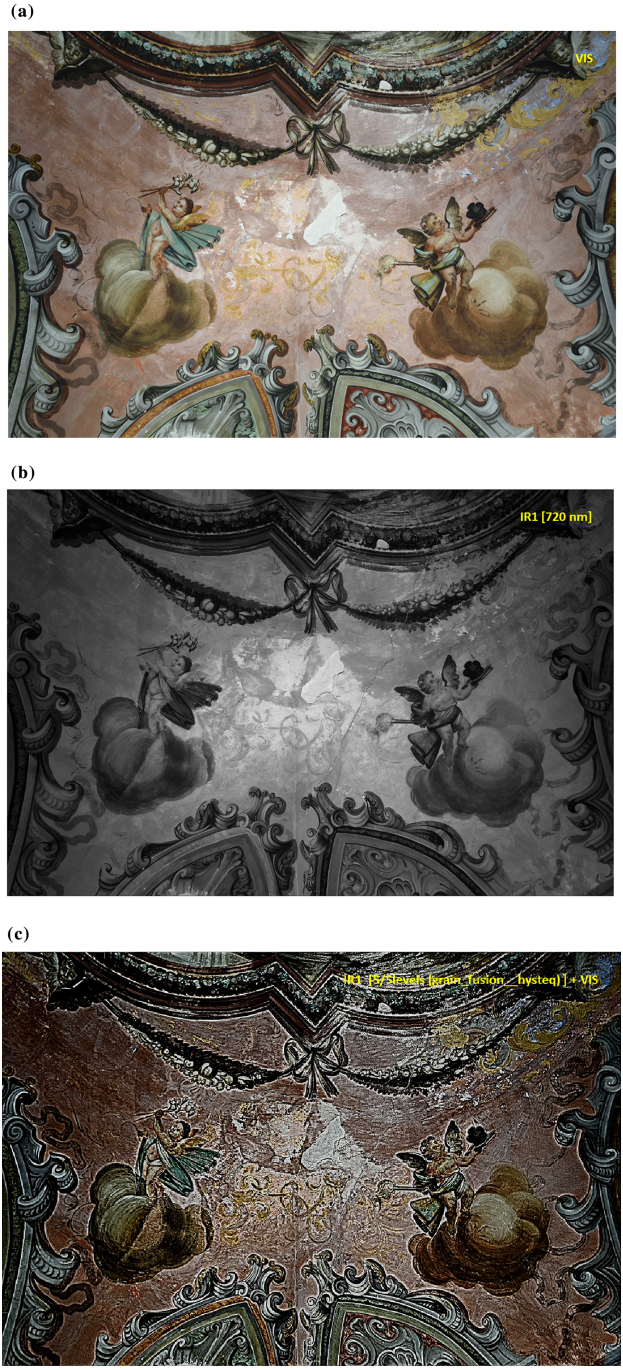

Fig. 10. Example of Digital Image Processing results on shot 1 dataset: visible **(a)** and NIR 720 nm **(b)** stacked data on the top images, and enhanced image **(c)** obtained by visible merging with the isolated and emphasized high spatial frequency signals of NIR image, on the bottom.



Fig. 11. Enlarged example of Digital Image Processing results on shot 1 dataset, at the bottom corner on the left: visible **(a)** and enhanced image **(b)**, showing a larger amount of details recognizable in the latter and the possibility to read painted subjects previously erroneously interpretable as noise or dirt on the paints.

Global view of Fig. 10 allows to evaluate the great quantity of informative data that appear to the watcher in terms of color lost drawings, minor cracks, surface roughness, to name some. Looking at a sample magnification, in Fig. 11, it is possible to notice a lot of the features of the original paints, revealing many details of leaves and decorations or evidencing an element previously imperceptible like the tape indicated by the white arrow.

4.2 Principal Component Analysis of the MS Datasets

Principal Component Analyses were applied to the four shots MS data, both raw, stacked and their combination. Here are presented some results from the processing of mixed datasets, with raw RGB visible images converted to bit depth homogeneous to grayscale UV and NIR data. In these conditions, we have input multidimensional matrices consisting in three layers for each acquisition at visible band for varying exposure times, plus one stacked UV layer and three stacked NIR layers (720, 850 and 950 nm filters). The layers identities are the vector base to which the eigenvectors proposed by the PCA are projected in the coordinates contained in the coefficient vectors matrix. For each eigenvector or Principal Component (PC), the dataset has a new coordinate per pixel, the eigenvalue or score matrix, consisting in the eigenvalues of the PCA transformation.



Fig. 12. Visible band raw image of the shot 4.

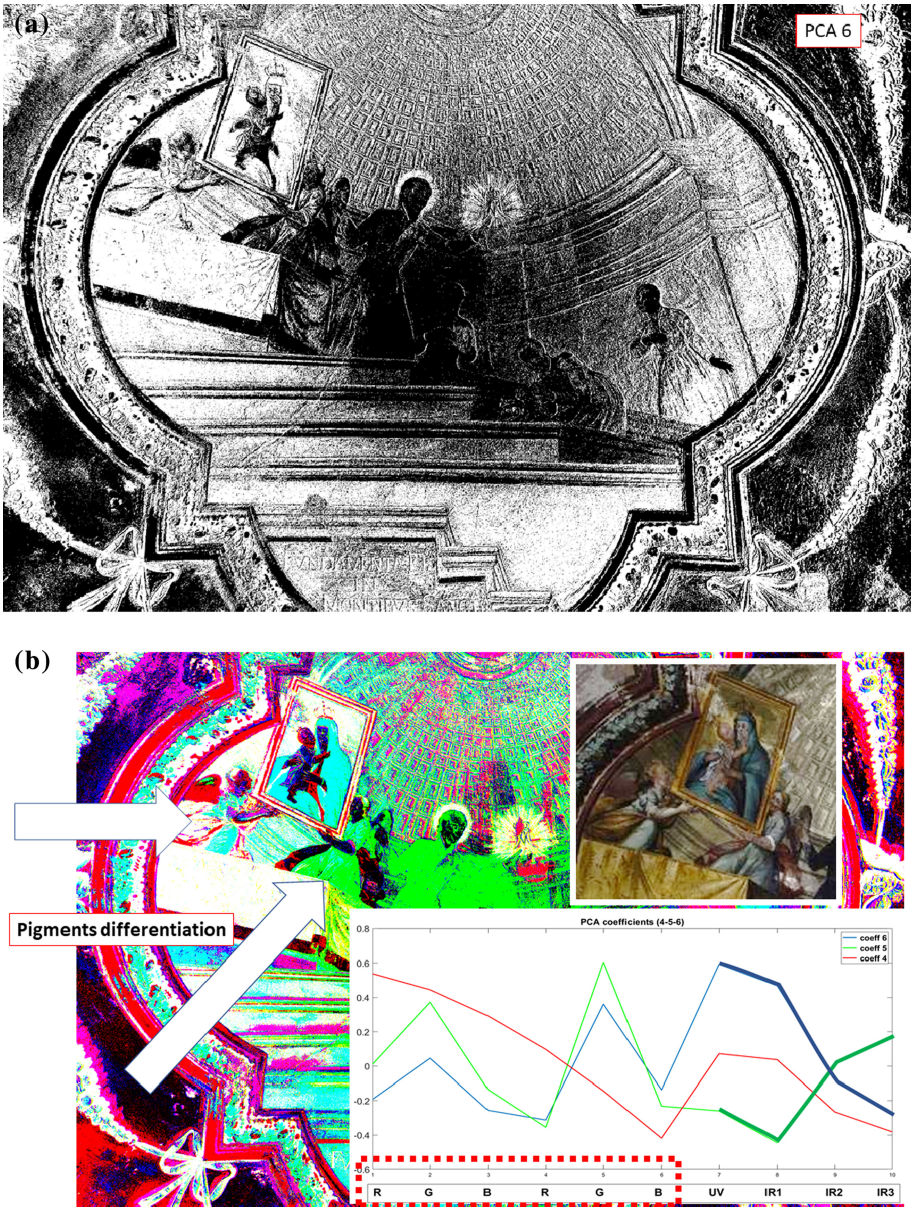

Fig. 13. PCA results on the shot 4 multispectral dataset: **(a)** 6-th principal component scores with the application of a visualization threshold aiming at contrast enhancement; **(b)** RGB false color combination of three principal components scores (R #4, G #5, B #6) with the superimposition of their coefficients (eigenvectors) plots: the white arrows indicate two angels' vests with quite similar color at visible wavelength but very different on PC5 (green) and PC6 (blue) projections. (Color figure online)

Figure 12 shows an RGB visible image acquired for shot 4. Figure 13 reports some results for the MS mixed dataset of the same shot. Figure 13a is the map of the 6-th PC score matrix, to which a threshold definition is applied to enhance the image contrast: many high frequency spatial features are evidenced, with respect to the RGB visible image, that can be reconducted to a subsurface roughness potentially related even to preparatory works. Figure 13b is an RGB false color combination of three principal components scores (R: PC #4; G: PC #5; B: PC #6) used here to differentiate two pigments with almost the same color, indicated by the white arrows. In the same figure, the coefficients of the three used PCs are plotted over part of the RGB false color image: the plot evidence that PC5 and PC6 have almost the same behavior over the original RBG axes constituted by two RGB acquisitions at visible band, but differ each other a lot for original coordinates corresponding to UV, NIR1 (720 nm) and NIR3 (950 nm) acquisitions. As a graphical validation we can see, in the map on the same figure, that the two angels' vests on the left of the image are represented with different behavior, being PC5 (green) prevalent for one and PC6 (blue) for the other. Despite of this, they are very similar in the visible band image (reported also inside Fig. 13b in the white bordered square on the top-right).

5 Conclusion

The paper presents a first approach towards the definition of a low-cost toolbox for qualitative inspection of valued painted surfaces. Most of the elements (low-cost modified DLSR cameras, pre-processing algorithms, digital image elaboration commands, signal processing techniques) were already existing before this application and are proposed here with the aim of a possible flexible integration in the context of the (qualitative) analysis of valued historical surfaced. The low-cost approach is essential to give a useful set of hardware and software tools which could be applied even to case studies of historical importance but with minor budget availability.

Processed images were able to highlight features on the vault paintings revealing details of the surface or its very shallow layers which were impossible or very difficult to distinguish in raw data. In fact, they emphasized low-visible details, differences in apparently similar finishes or pigments, cracks and probably details of surface preparation.

Acknowledgements. The authors gratefully acknowledge the essential help of L. Noli and M. Sitzia during data acquisition and instrumental setup. They also would like to thank F. Mura for the photo of Fig. 7.a. Finally, a special thanks to prof. D.R. Fiorino and the local prefecture for permitting the access to the San Giuseppe monumental structure.

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