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Multispectral Hypercolorimetry and automatic guided pigment identification: some masterpieces case studies

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ABSTRACT

A couple of years ago we proposed, in this same session, an extension to the standard colorimetry (CIE '31) that we called Hypercolorimetry. It was based on an even sampling of the 300-1000nm wavelength range, with the definition of 7 hypercolor matching functions optimally shaped to minimize the methamerism. Since then we consolidated the approach through a large number of multispectral analysis and specialized the system to the non invasive diagnosis for paintings and frescos. In this paper we describe the whole process, from the multispectral image acquisition to the final 7 bands computation and we show the results on paintings from Masters of the colour.

We describe and propose in this paper a systematic approach to the non invasive diagnosis that is able to change a subjective analysis into a repeatable measure indipendent from the specific lighting conditions and from the specific acquisition system. Along with the Hypercolorimetry and its consolidation in the field of non invasive diagnosis, we developed also a standard spectral reflectance database of pure pigments and pigments painted with different bindings. As we will see, this database could be compared to the reflectances of the painting to help the diagnostician in identifing the proper matter

We used a Nikon D800FR (Full Range) camera. This is a 36megapixel reflex camera modified under a Nikon/Profilocolore common project, to achieve a 300-1000nm range sensitivity. The large amount of data allowed us to perform very accurate pixels comparisions, based on their spectral reflectance.

All the original pigments and their binding have been provided by the Opificio delle Pietre Dure, Firenze, Italy, while the analyzed masterpieces belong to the collection of the Pinacoteca Nazionale of Bologna, Italy.

Keywords: Multispectral Imaging, Hypercolorimetry, UV and IR non invasive analysis, conservation, restoration, PCA principal components analysis, portable system, spectral reflectances database.

1. INTRODUCTION

The activities of restoration and conservation of art masterpieces in the world of cultural heritage make use of ever more sophisticated and less invasive methods in compliance with the principles of respect for the artwork as a whole and for the details found in the trace of the author . Particular attention is given to preparatory phase of the restoration itself, those that investigate the actual state of conservation of the work, the materials used, the conservation status of the media, any previous interventions of restoration, specific surface or volume diseases, and the effects of environment and time.

In this important and delicate phase, the ideal would be to ach ieve a perfect and complete knowledge both of all materials used in the original work, and of all the substances that have been added over time by age or artificially. But such knowledge would require sooner or later some invasive intervention on paintings, through, for example, extraction of micro samples followed by chemical analysis, mass spectrometric analysis, analysis at the scanning microscope. It is obvious that rarely one has the possibility of making such micro samples, so improvement or innovation in the field of non-invasive analysis represents a step forward in the diagnosis. The theoretical and practical methodology that we describe in this work is exactly in this direction, both by improvements in techniques already used, an by introducing standard and innovative non-invasive techniques.

2. ELECTROMAGNETIC INTERACTIONS BASED ANALYSIS

Having ruled out chemical-physical interactions with the artworks, the non-invasive analysis can all be grouped into the family of electromagnetic interactions, i.e. those analyzes where the extraction of information about artwork materials is performed through the study of the reaction of matter to electromagnetic waves at various wavelengths.

2.1 Terahertz

The analysis of the terahertz is a relatively new resource in the field of paintings diagnostic and still little exploited. This analysis is able to provide some physical parameters such as thickness of a layer and density of the medium.

2.2 Infrared

The family of infrared analysis could divided into:

FIR (far infrared) Measurement of temperature (typically 3000 to 15000nm);

MIR (mid infrared) Reflectography in the medium infrared (1200 to 3000nm) which allows to obtain images of drawings and underlying structures consisting of layers of color;

NIR (near infrared) band of visible closest infrared (700 to 1000nm) which allows to view high resolution of underlying drawings and glazes.

2.3 Visible

This is the band where our eyes are sensitive. It perfectly fits to the band of maximum emission from the Sun, ranging blue to red (as the rainbow) including also what we call “white” as the mix of wavelengths similar to Sun itself. This is the all about Colorimetry band. Furthermore, every photometric measurement lays in this band and is weighted by the so called V(lambda), i.e. the photopic black&white eye sensitivity function.

2.4 Ultraviolet

Even the ultraviolet, such as infrared, occupy a bandwidth large enough, and a way to classify them is the division into UVA (315-400nm), UVB (280-315nm) and UVC (100-280nm). The band of our interest is mainly the UVA, used both in reflection and fluorescence.

2.5 X-Ray

Finally we find the X-ray band, used both in transmission (x-ray) to obtain images of the internal structure of the work, and fluorescence, to obtain information on chemical elements present in the pigments and substrates. Actually, following all the techniques developed in medicine, using the X-Ray it is possible to thoroughly investigate the inner structures of an artwork, with a stratigraphic imaging, for example, or even a CT.

2.6 Hypercolorimetry wavelength range

Multyspectral Hypercolorimetric Imaging analysis is based on the simultaneous exploitation of the UVA to NIR bands. Once the acquisition is done under a standard metric, as we defined, this is the way of characterize surfaces in a more detailed way than using the standard colorimetry.

3. SPECTRAL REFLECTANCE

As it is known, the spectral reflectance of a surface is the relationship between the incident radiation and the reflected radiation, as a function of wavelength, with an angle of incidence of 45 ° and reading angle 0 ° from normal. When we look at an illuminated surface, the radiation that reaches our eyes brings a spectral emission information combined with information of the spectral reflectance of the surface.

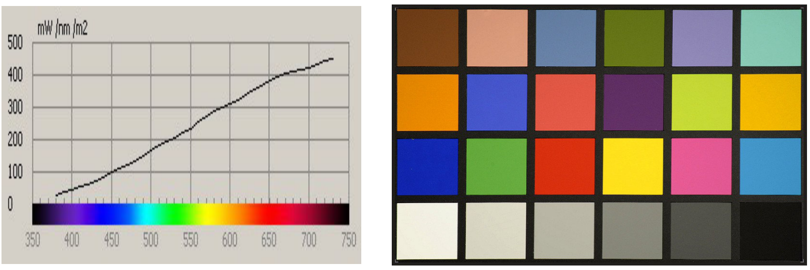

Figure 1. Spectral emission (left) and illuminated surface (right)

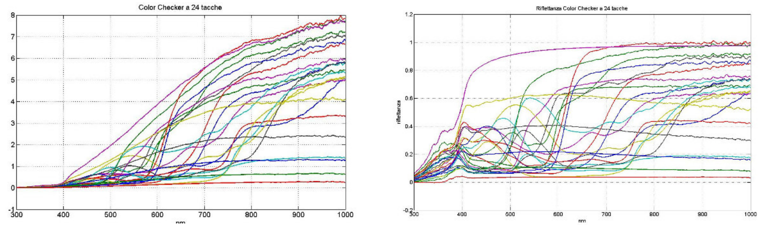

Figure 2. Reflected radiation (left) and spectral reflectance (right)

But our eye is not able to resolve the spectrum of the received radiation with great detail, rather it makes a coarse sampling weighed through the sensitivity curves of the cones of the retina, transforming the received radiation into three nervous stimula: the ones coming from cones sensitive at short wavelengths (blue), from cones sensitive to medium wavelengths (green) and from cones sensitive to long wavelengths (red).

Since 1931 the CIE (Commission Internationale de l'Eclairage, http://www.cie.co.at), starting from the physiology of the eye has established three weighting functions, the Color Matching Functions, to convert a spectral radiation into a set of XYZ values. The represented values are the so-called XYZ colorimetric coordinates of a spectrum of radiation (in the visible). In the space of the XYZ coordinates, a spectrum of radiation will then be represented by a point Q (XYZ). The vector OQ intersects a plane passing through (001, 010, 100) at a point q of normalized coordinates x = X / (X + Y + Z), y = Y / (X + Y + Z) z = Z / (X + Y + Z). The figures x, y and z are called chromaticity coordinates.

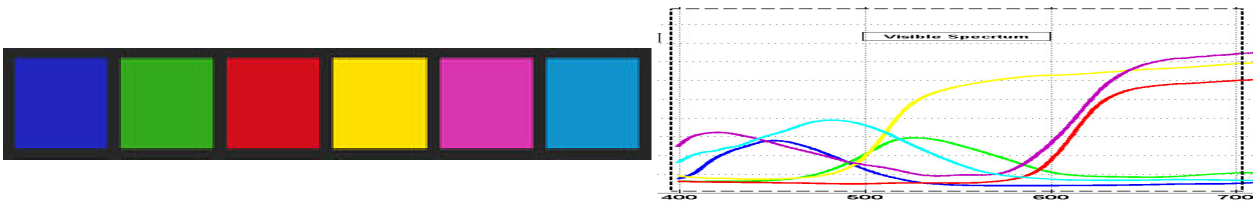

Figure 3. Colored surface (left) and corresponding spectral reflectances (right)

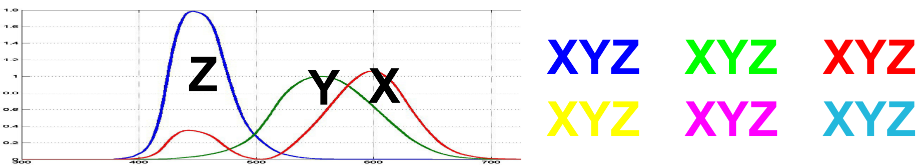

Figure 4. Color Matching Functions (left) and colored surfaces Colorimetric Coordinates (right).

By varying the wavelength of a monochromatic source from the far red to the extreme visible blue, its chromaticity coordinates would draw a counterclockwise arc inside the triangle (001, 010, 100). Connecting the ends of the arc with a segment on the xy plane we obtain the Chromaticity Diagram.

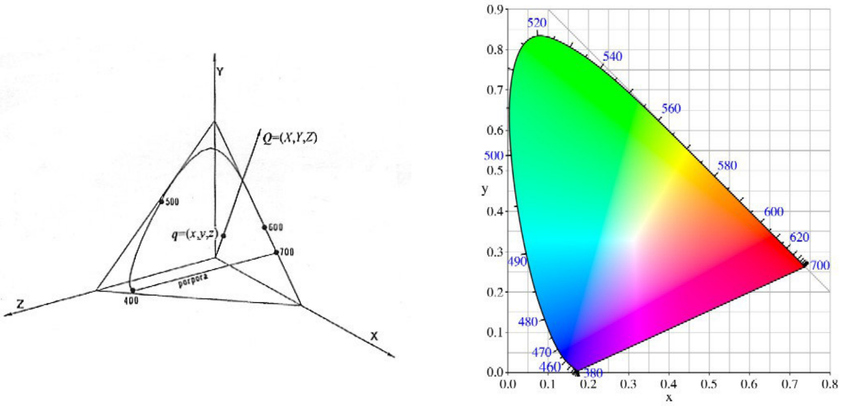

Figure 5. XYZ space and normalized xyz plane (left). Cromaticity Diagram (right).

Naturally synthesizing a continuous spectrum with only three values, from the information theory point of view, means losing much of the original data. In fact, it is extremely common that more spectra give rise to the same colorimetric backhoe, this phenomenon is known as metamerism. All manmade imaging is based on metamerism, namely on the simulation of almost any color through the mixture of few sources with fixed radiation spectra (or pigments with fixed spectral reflectances).

Actually, the CMF curves are not very good, they do not minimize the metamerism and fail to properly represent a source at maximum saturation (monochrome) except in some areas of the xy plane. The "ideal CMF" should have a linear behavior and a triangle shape. This is well know manufacturers of sensors and digital cameras so that they tend to approximate the ideal curves with the spectral sensitivity of the Sensor / Bayer matrix pair.

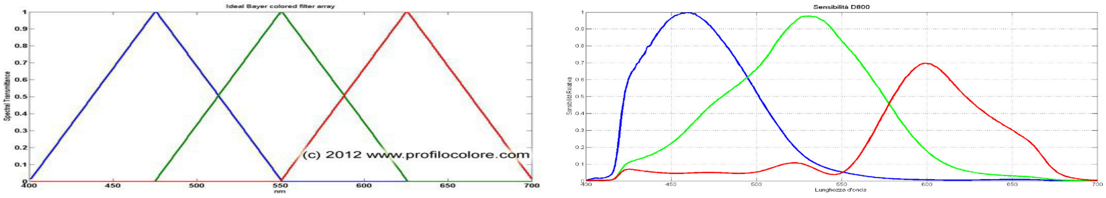

Figure 6. Ideal Colorimetric Functions (left), standard Nikon D800 RGB Sensitivity functions (right).

These ideal curves have some characteristics similar to those of CMF (there are three, and are equienergy) and also other features superior to CMF (they are equally spaced allowing a better sampling of the spectra, are linear and have constant ability to discriminate colors on the whole 'axis of the wavelengths, and, within the limits of Nyquist, allow the reconstruction of the spectrum with minimal errors).

To close the chapter on Spectral Reflectance and Colorimetry we compare the performance of the CMF Vs the Nikon D800 when exposed to quite saturated colors, generated with an arc Xenon lamp followed by a 50nm bandwidth monochromator.

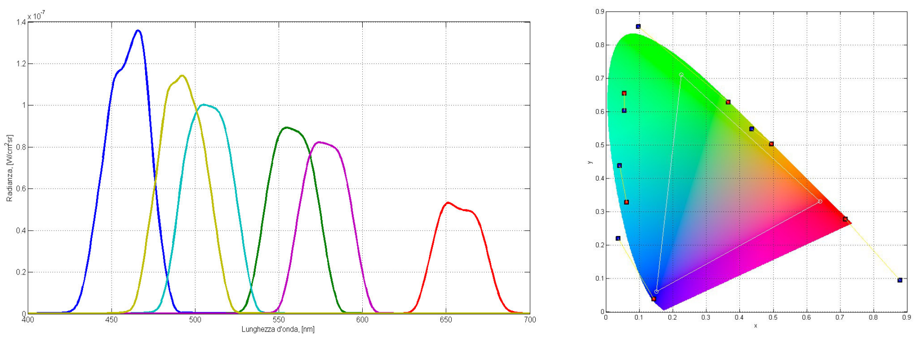

Figure 7 High saturation colors (left). Chromatic xy coordinates (red squares) and normalized rg coordinates (blue square).

As expected, due the shapes closer to the ideal ones, the normalized rgb coordinates range to a wider space approximating the 0, 01, 10, 0 triangle, exiting the Chromatic Diagram. Maximum differences are in the red area, where CMF and RGB functions show biggest differences.

4. EVOLUTION OF THE DIGITAL IMAGING IN THE FIELD OF CONSERVATION AND RESTORATION

As already said, in the field of conservation the visible band is only one among those that are used. Imaging in the UV and IR bands hve been already used since the analog photography, with the use of special film selectively sensitive to those bands. A film of particular interest has been that so-called "infrared false colors". This is a three layers film that instead of capturing RGB channels it capture IR, Red and Green bands. Once developed the film show IR intensity as red intensity, original red as green and original green as blue. Most of the the experienced diagnosticians are used to compare the real color and the false color images and to deduct, from the color shift, a good idea of the nature of the used pigments, or at least of some of them.

The advent of digital photography, along with the quality and reliability that the modern cameras show, opened the way for more and more sophisticated and accurate investigations. Furthermore, the cameras are equipped with a silicon sensor (CMOS in general) that in native mode has a wider spectral sensitivity than the visible band. This offers the world of diagnostics a very flexible tool with which to investigate a broad spectrum. Actually it is quite common practice today to shooting digital cameras not only in the visible but also in the ultraviolet (UVA) and in the infrared (NIR), as well as in mixed bands as UV/Vis with fluorescence images, and in Vis/NIR images in luminescence. Besides the availability of digital cameras modified for UV and IR, the availability of image editing programs in general and manipulation of digital images has allowed one to build a false color IR photo by performing two shots, one in the visible and one in the IR, rearranging RGB channels with the sequence IR-R-G. The same concept has then been applied to the UV, getting to a two images acquisition (UV+Vis) and shifting channels to achieve the G-B-UV sequence (false color UV).

Regarding the false colors (both IR and UV), however, while the film provided a corresponding constancy of exposure ratio between the three channels (intrinsic to the way of production of the film itself) and necessarily a perfect registration of the three channels, the acquisition of two images in two distinct instant of time is not by itself guarantee of perfect images overlapping and perfect exposure equilibrium. The double shoot in the visible and the IR (or UV) and their recombination does not guarantee any of these things, thus providing results whose goodness depends on the accuracy of the operator and on the software post processing tools.

Furthermore, up to this point in the development of photographic techniques of investigation, analysis has always been done visually, by comparing maximum three bands simultaneously, for intrinsic limit of the human eye.

On the other hand, the availability of increasingly sophisticated sensors in terms of available megapixel, linear behavior and high reliability, and quite high numerical dynamic (now easily to 14 bits, for over 16000 levels per color), along with increasingly fast computing, cheap bigger memory capacity, suggest that it is time to make a quantum leap and tu push into two directions: a standardization of the representation of this broader available band; the introduction of state-of-the -art algorithms to get to perfectly registered images, and to deeply exploit the new richness of simultaneous bands.

5. HYPERCOLORIMETRY

Let's start from basics of colorimetry and our last comments on how good the CMF are in sampling a spectrum. As we have seen the CMF are the best approximation to the behavior of the human eye, but they are not optimized against maximum spectra distinction and metamerism. On the other hand, limited to the visible band, we have seen how linear triangle shaped functions are optimized and offer the best color space sampling. Considering that the sensor we are going to use is a piece of silicon, with almost linear response and much wider sensitivity band, the most natural enhancement to implement is to substitute the classic colorimetry with a new more uniform and wider one. The result is a 7 band colorimetry with functions centered at 350, 450, 550, 650, 750 , 850 and 950nm.

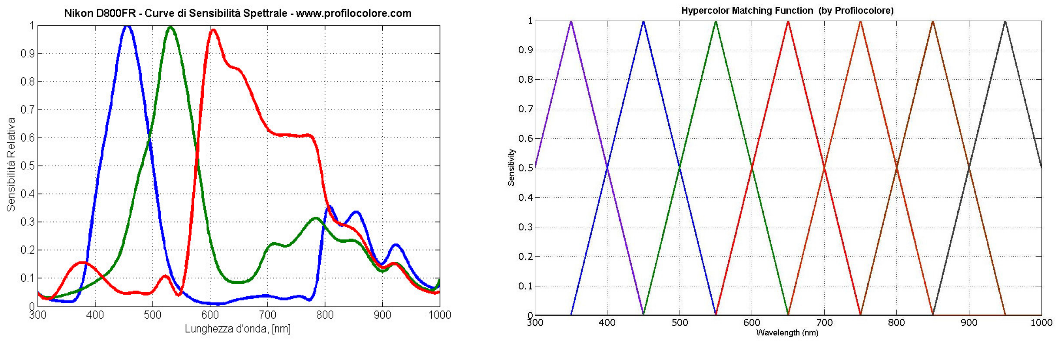

Figure 8. Nikon D800FR Sensitivity curves (left), Hypercolor Matching Functions - HMF (right).

This is a system of sensitivity or weighting functions, which transforms any spectra in the range of 300 to 1000nm wavelength into a sevenfold hypercolorimetric coordinates (H1.. H7).

This system includes and make consistent all bands of interest to the non-invasive diagnosis, providing a exact metric, a benchmark against which you can compare results from different operators and conditions and various equipment, as it is already done in the field of standard colorimetry.

As in colorimetry the connection between the sensitivity curves of the camera and the color coordinates is through the color profiles (with the limitation of the chosen color space Gamut), whose format is standardized by the International Color Consortium (www.color.org). As per analogy in the use of hypercolorimetry we have developed the necessary software to convert the spectrum recorded from a series of bandpass filtered shoots to a standard target, into a sevenfold H1 .. H7 hypercolorimetry.

The procedure for the characterization of the hypercolorimetric camera is analogous to that which is done to build the ICC color profile.

It starts with a color target whose spectral reflectance on each notch is carefully measured. All measurements have been performed with a traceable Instrument Systems CAS 140CT spectroradiometer. The obtained reflectance values have been weighed with the Hypercolor Matching Functions and transformed into 7 hypercolorimetric coordinates. The same target has been acquired in imaging mode through the camera in RAW format. In the RAW / Tiff transformation lens chromatic, spherical geometric and vignetting aberrations and distortions are corrected.

The hypercolor profile itself consist of a 7 input/7 output non linear conversion function automatically synthesized by a Profilocolore proprietary genetic algorithm.

The hypercolorimetric coordinates coincide with the continuous spectral reflectance sampled at 350, 450, 550, 650, 750, 850 and 950nm. In the following figure we show our custom target with a pair of measurement points highlighted by the blue and pink little circles. The top right diagram show the 7 hypercoordinates of the two points as have been measured through the modified camera and filter set, while right bottom are shown continuous spectral reflectances and corresponding theoretic HMF coordinates, as they come from the instrument measurements. As it can be seen the differences between the camera and the spectroradiometer measurements differ by less than 2 or 3 percentage units.

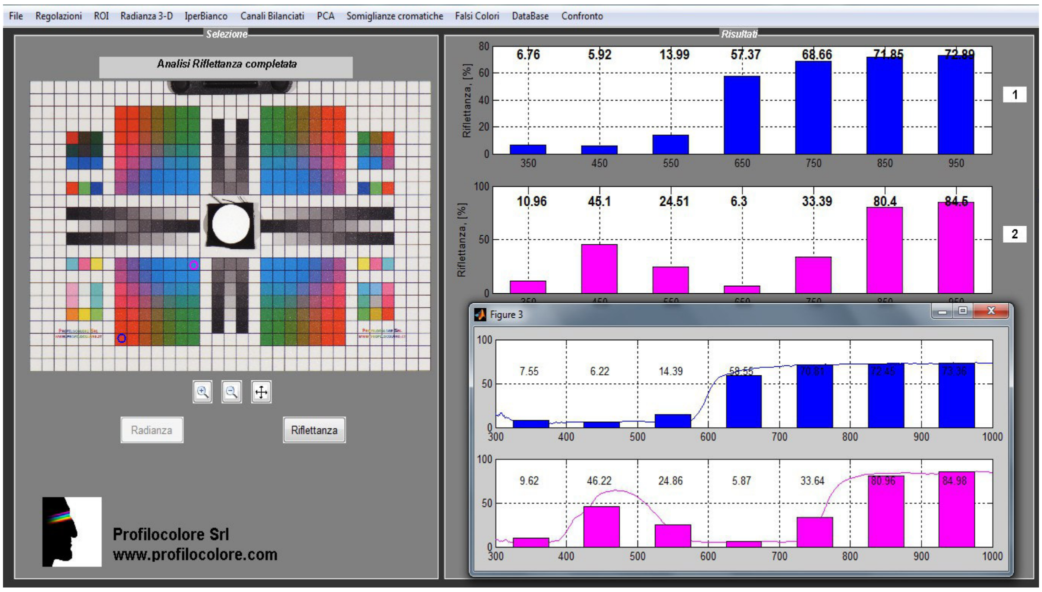

Figure 9. Comparison of modified camera and spectroradiometer measured hypercolorimetry (sampled spectral reflectance)

The achieved result has a great value in that it shows how it is possible to obtain a sampled spectral reflectance in imaging mode, i.e. pixel by pixel, and how this is equivalent to an instrumental local measurement.

All of the following case studies have been done with a Nikon D800FR modified digital SLR 36 Megapixel camera. Such a broadband spectral reflectance allows to distinguish the nature of a surface much better than one could achieve by only the visible band. Furthermore, as already shown, because the HMF functions perform better and include the CMF, it is quite easy to obtain from a multispectral image a high quality colorimetric image, i.e. to derive an image whose colour quality is even superior to a standard visible image.

6. STANDARD PIGMENTS AND DRAWING UP HYPERCOLORIMETRIC REFLECTANCES DATABASE

Thanks to the kind collaboration of the Opificio delle Pietre Dure in Florence, Italy, we had the opportunity measure and build a database of the spectral reflectance of large number of pigments and drawings with different bindings. Each item in the database is associated with the name of the pigment (with possible method of drawing and with binding), the spectral reflectance directly measured with the spectroradiometer, and the corresponding hypercoordinates.

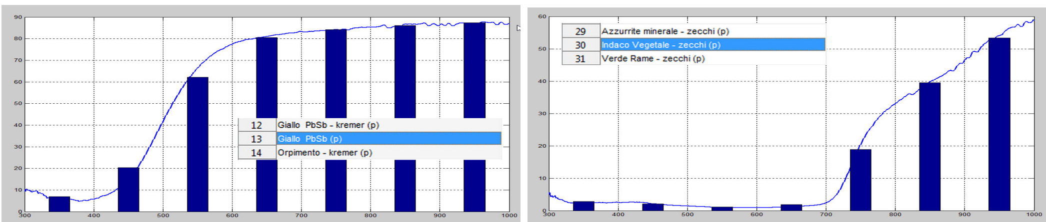

Figure 10. Two samples of the pigments and drawings database. Continuous spectral reflectance and Hypercoloriemtric coordinates.

As seen in Figure 9, a hypercolorimetric multispectral acquisition provide the user with an image where each pixel contains a 7 points sampled exact reflectance, with an error that is in the general less than 2 or 3%.

Having a large database of pigments and the possibility of extracting the reflectance at a point of the image (as discussed below) and through this search the database for the most similar pigment, would naturally let think of being able to immediately identify the pigments with a one step. In reality this is not true, however, almost the validation of the pigment identified requires an interpretation by the conservator / restorer. We'll see how it washes and pigment mixtures can bring out different spectral reflectance from the opera and partially mixed between them.

7. DOMENICO THEOTOKÒPULOS DETTO EL GRECO - ULTIMA CENA

Figure 11. 7. Domenico Theotokòpulos detto El Greco - Ultima cena. Pinacoteca Nazionale di Bologna

7.1 Spectral reflectance

Following interrogation of the system on two points: a yellow (blue circle) and a red drapery (pink circle). Illustration shows the two spectral reflectances and compared on a radar chart.

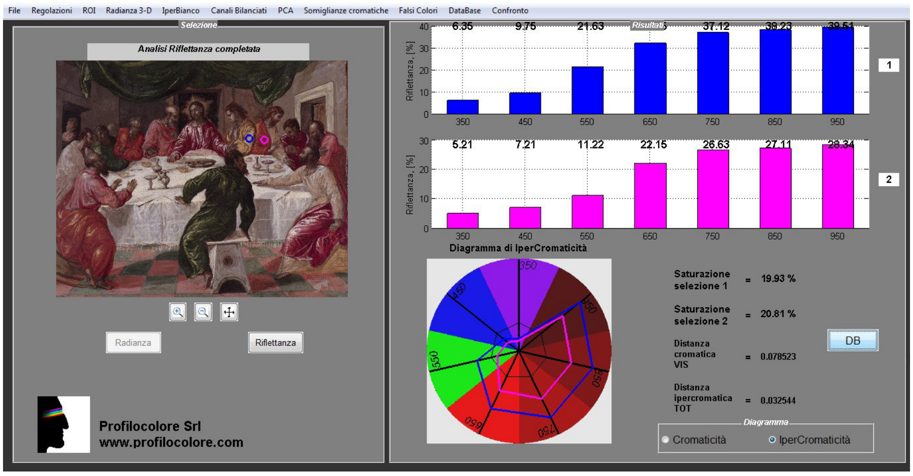

Figure 12. A yellow and a red compared in hypercolorimetry.

7.2 Search and comparison with database

Querying the database with search of pigments and drafts with similar reflectance returns Terra di Sienna as the most plausible for yellow shirt, and Cinabro + black for red draping. The notches of color to the right of the graphs show the visual perception that give their reflectances.

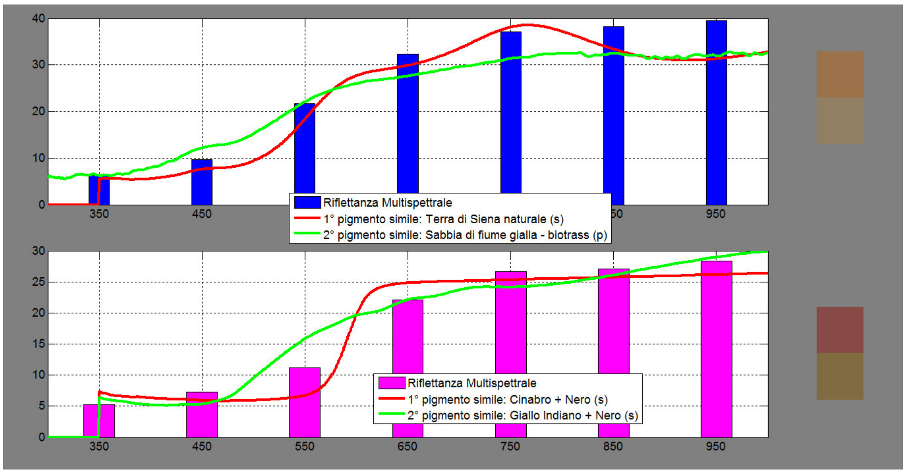

Figure 13. Database responses to the reflectances of a pair of spots

7.3 Similar colors comparision

Here two areas of similar color in the visible are chosen, to compare their hypercolorimetric responses. In spite of their similar aspect, moving to bands outside the visible the differences become quite big as per the radar diagram. The infrared components make the two pigments very different.

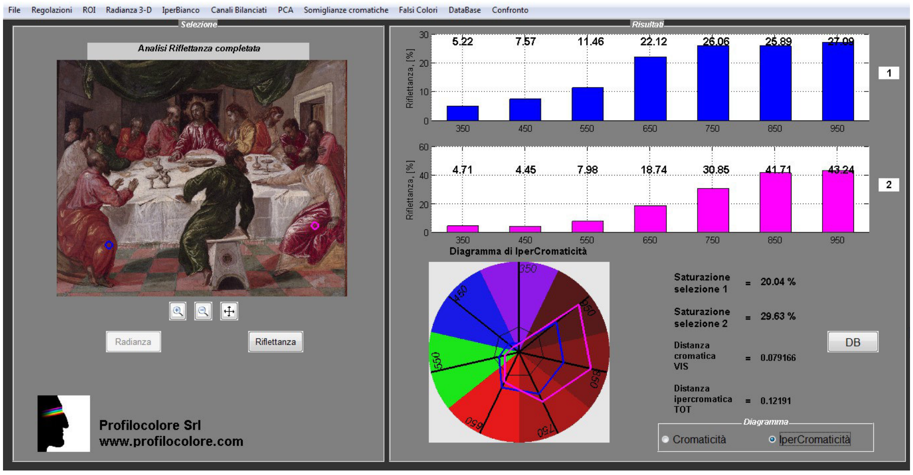

Figure 14. Simila color comparision. Infrared components show the difference.

7.4 Spectral similarity

The availability of the spectral reflectance of the whole examined artwork, pixel by pixel, allows us to make comparisons between all the points of the image. In particular, it is often useful to ask the system a false-color map of spectral similarity of all pixels with respect to a fixed point. In this case it was taken the green strip at the bottom of the dress in the foreground. The system finds reflectances with different grade of similarities not only in almost all the rest of the green robe, but also in the green drapery above the scene and in another cloth of one of the Apostles on the left. Interestingly, there is also similarities in some dark areas (under the seat in the foreground, in the openings of the windows and the door ajar). It is likely that in this case, the author mixed more pigments, included the green, to achieve a dark enough color to fill the black shade.

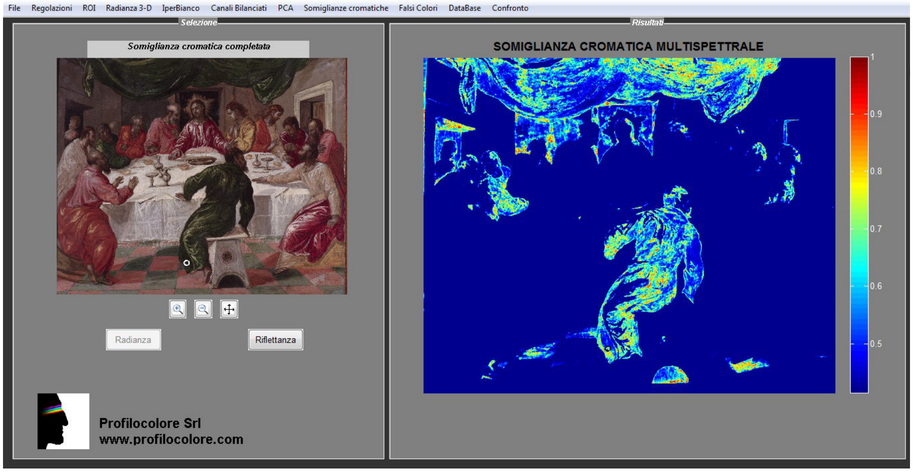

Figure 15. Spectral similarities to dark green of the foreground cloth.

Just to better explore this hypothesis we select a point in the dark behind Jesus head and search areas with similar spectral reflectance. Now all the darkest areas resonates included the darker greens.

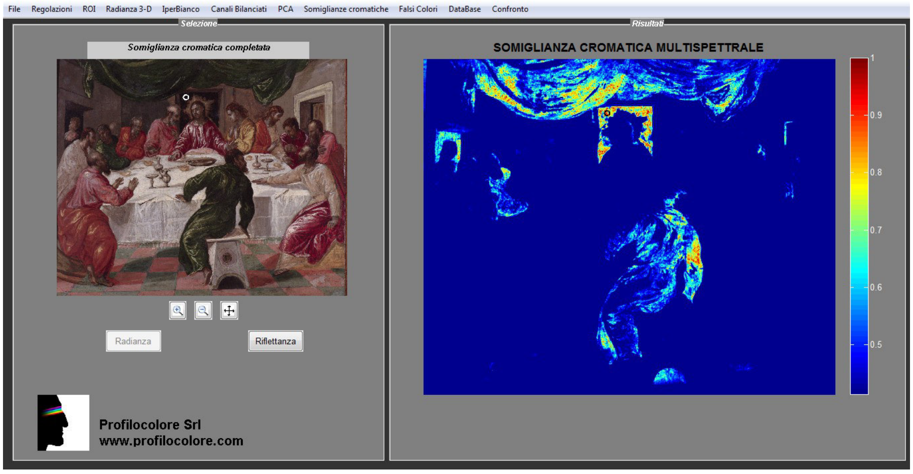

Figure 16. Looking for pigments used in the darkest areas. It happens that there is a partial overlap with the dark green.

8. GIOVANNI BATTISTA CIMA CALLED CIMA DA CONEGLIANO - MADONNA CON IL BAMBINO

Figure 17. 8. Giovanni Battista Cima called Cima Da Conegliano - Madonna con il bambino. Pinacoteca Nazionale di Bologna.

8.1 Spectral reflectance

We focus here on the tissues of the robe of the Virgin, the red dress and blue mantle. The spectral reflectances in the two areas indicated by the blue and pink circles are shown in figure.

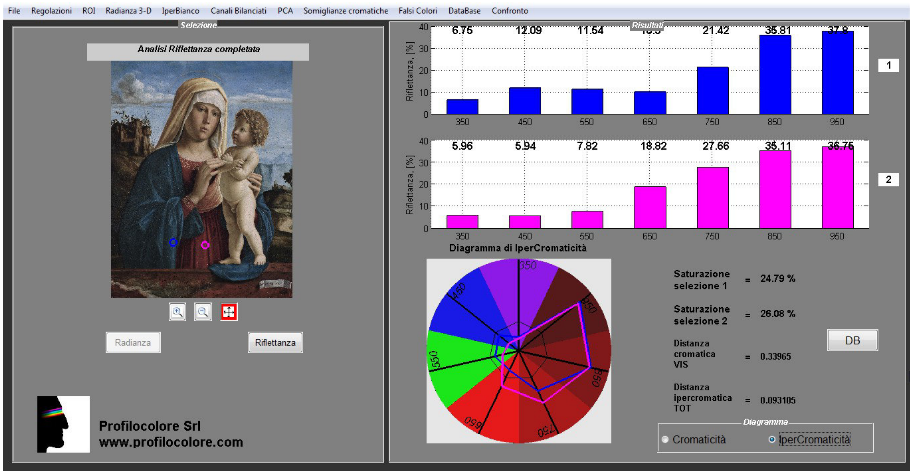

Figure 18. Red dress and blue mantle comparision.

As is to be expected, and as you can see from the hypercromaticity diagram, blue and green components are higher on the mantle, while the red component prevails over the dress. The UV components, IR2 and IR3 are equal while the component IR1 is higher in red.

The query of the database suggests that the pigments are closer to Indaco + Lapislazzulo for the cloak and Terra di Sienna bruciata for the dress. As a second choice are suggested respectively Smaltino and Cinabro+Nero.

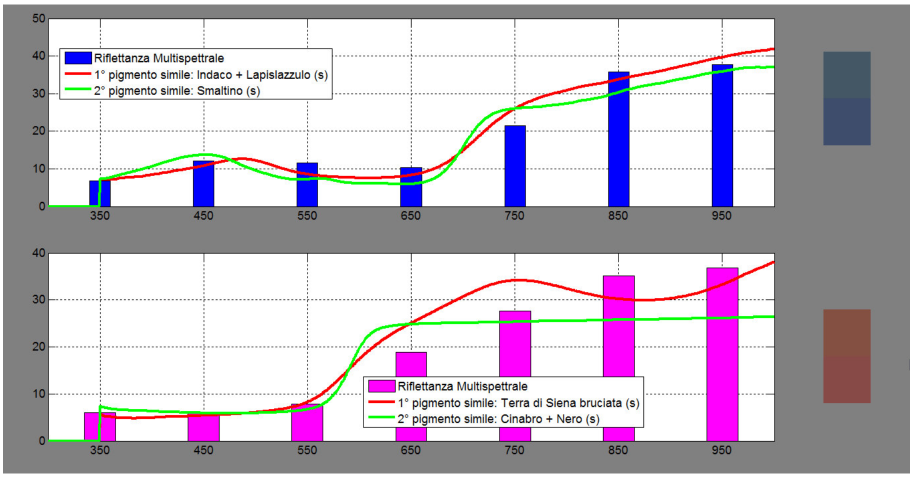

Figure 19. Database responses to the red and blue of the cloaths.

It is obvious that the similarities in the database in this case are rather ambiguous, and will therefore be necessary to proceed with other reasoning to reach the definition of pigments actually used.

8.2 Spectral similarity

In this case the spectral similarities reveal interesting details about the sequence followed by the author in producing the artwork.

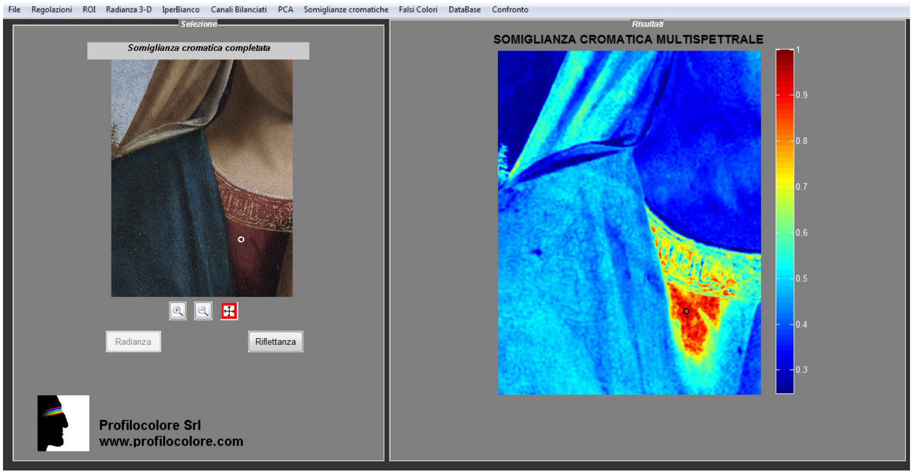

Figure 20. Spectral similarities reveal overlapping of pigments.

As it is quite clear, under the cloak remains a trace of the neckline of the dress. It is possible to see this only thanks to the upper spectral reflectance that is partially transparent (non in the visible), so get influenced by the spectral reflectance of the dress below. In this case it is not a classical underlying drawing, normally observable in the infrared bands, but just a slight spectral deviation that reveals the overlap.

9. 8. GUIDO RENI - LA STRAGE DEGLI INNOCENTI

Figure 21. 9. Guido Reni - La strage degli Innocenti. Pinacoteca Nazionale di Bologna.

9.1 Principle Components analysis (PCA)

Thanks to standardized Hypercolorimetry and therefore a balanced gain in the various bands which must are equal energy (i.e. a flat spectral radiance across the spectrum should appear with the same intensity in all bands), The principal components analysis becomes of particular interest. The PCA is a statical method to rotate the n-dimansional space and assign each axis a specific meaning in terms of separating the pixels of the image. Starting from the 7 components of the hypercolorimetry you can choose an appropriate subset to extract details from the otherwise latent and hidden image.

The following example is a remarkable one to show what could be hidden under first layers of pigments.

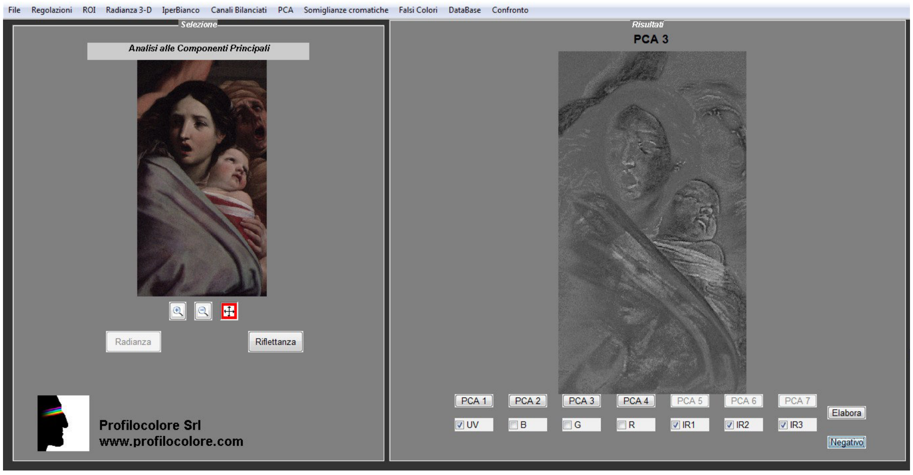

Figure 22. Under the mantle there is a first version of the painting where the woman was lower that in the final version.

10. CONCLUSIONS

In this paper, we proposed just a few examples of analysis where the Hypercolorimetric Multispectral Imaging approach was useful to highlight details and latent images, hard to find otherwise.

The homogeneity and consistency of image processing, and then the standardization, ensure the repeatability of the results and the possibility of comparison and analysis of reliefs between different researchers and between images obtained in different environments. This seems to the authors an important and hitherto lacking point in analysis of non-invasive diagnostic procedures.

Another important element introduced in the system is the database of pigments and drawings up, which provides an excellent reference in the identification of the material used to realize the work. But it is highly recommended to use this tool with absolute caution, since the reflectance of an absolute pigment, measured instrumentally, may greatly deviate from the overall reflectance present in a point of the artwork. This is firstly due to glazings which, by their intrinsic nature, were stretched to alter the appearance of the underlying pigment without covering it completely, and then because some pigments may have a certain transparency to infrared rays, and then the emerging reflectance may be the result of two reflectances differently mixed as a function of the wavelength.

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