COMPUTER-ASSISTED PIGMENT IDENTIFICATION IN ARTWORKS

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ABSTRACT
False-color infrared represents a well known method for non-invasive pigment identification in artworks. This is particularly useful in the field of conservation of cultural heritage as it provides useful information about painting materials, techniques, retouches. However, the interpretation of a false-color image is still carried out just by "naked eye" evaluation, thus suffering from the doubts of a subjective exam. To this aim, we designed a computer-assisted system to support pigment identification in an artwork. Our system includes automated procedures for selecting investigation areas and for matching unknown pigments on the considered artwork with known standards in a database. Finally, information is made available for discussion among remotely located investigators through a shared virtual environment (i.e., a groupware).

KEY WORDS
Imaging techniques, false-color infrared, photomosaic, groupware.

1. Introduction

The field of conservation of cultural heritage makes use of different imaging techniques for scientific analysis of paintings, such as infrared (IR) reflection, false-color IR, colorimetry, fluorescence and ultraviolet (UV) reflection. Nowadays all these techniques have been improved and integrated into a fully digital multi-spectral portable system device with advanced documentation and processing capabilities [1, 2]. Obtained digital images have a very high quality thanks to their mega-pixel resolution. Among these techniques, IR reflectography is a non-destructive optical technique suitable for the analysis of painted surfaces such as panel and canvas paintings. The general principle of a digital multi-spectral system is based on the interaction between the painting constituents (pigments, binding media, varnishes) and the visible, UV, and IR radiations which enhance physical and chemical material properties.

The technique allows the recording of IR images called reflectograms, which reveals the drawing made by the author on the ground layer (the underdrawing) thanks to the transparency of the paint layers to the radiation in the near IR (wavelengths from 1 to 2 microns).

It is hence possible to reveal and study the composition and the state of conservation, study applied artistic technique, distinguish and locate past restoration intervention and analyze color and pigments. This can be done by using the false-color IR technique: a computer-based technique which combines color images and reflectograms to create a "pseudo-color" image where each pigment is represented by a specific false-color that depends on its type of interaction with the IR light [13].

Unfortunately, the interpretation of the false-color IR image is currently carried out just by direct examination of an investigator that visually identify all the area of interest in the painting and compare them with the outcomes of standard pigments of known composition (*standards*). Even if this is the procedure generally used, results could be uncertain due to the limits of a human being, or even contradictory as the interpretation depends greatly on the individual experience of the operator. For instance, an operator could miss some little area in the painting that deserved to be investigated, or false-color results for two pigments could be similar to a "naked eye" thus leading to an ambiguous association of the correct pigment to the area under examination.

In an attempt to overcome the above mentioned drawbacks, information technology could be put to good use both to identify artworks' area of interests for investigators and to augment the accuracy of pigments' analysis. Moreover, Internet communications could be exploited to generate a *groupware*, i.e., a computer-based system that provides a shared environment to a group of operators engaged in the task of analyzing a painting, even if located far away from each other [5].

To this aim, we designed a new integrated system to provide artworks' investigators with objective interpretation of false-color data. Specifically, our system can be subdivided into two main components: i) support to the digital acquisition of the false-color IR image from a painted surface and ii) integration of a standards' database with a groupware designed to facilitate investigators' discussion.

The rest of the paper is organized as follows. In Section 2 we review background information on imaging techniques for scientific analysis of paintings. Section 3 and Section 4 describe, respectively, the two main components of the system we designed to support the study of artworks. Finally, Section 5 concludes this paper.

2. Multi-spectral Scanner Imaging System: Background

The system employed in this research study is called Artist, a multi-spectral scanner imaging system produced by Art Innovation (the Netherlands). It is based on a digital camera which is capable to capture images in wavelengths within the UV, visible and IR regions. The camera includes a CCD sensor (CCD progressive scan image sensor) and produces high-resolution images with a response that covers the spectral range from 320 to 1100 nm. The camera is connected to the computer through a IEEE 1394 FireWire interface and digital images can be visualized on the screen in real time, allowing immediate evaluation of results. Painted surface can be illuminated with both two 30 W halogen lamps and an UV lamp with the main emission at 365 nm. Every radiation band reflected from the painted surface is selected by optical filters embedded in the body of the camera.

The system is able to provide six imaging modes: visible reflection (400-700 nm), IR reflection (2 bands: IR1 700-950 nm and IR2 950-110 nm), UV reflection (320-400 nm), visible fluorescence (400-700 nm) and false-color IR mode. The CCD camera mounts two lenses: a wide angle lens 23 mm, F/1.4, and a zoom lens 18-108 mm, F/2.5, which allow a closer documentation of the painting's conditions.

2.1 False-color IR Imaging: Procedure

The false-color IR method is based on the combination of both RGB color and IR images. Only the red and green components of the color images are overlapped with the grey scale IR reflectogram. Usually the red RGB component is substituted with the IR, the green with the red, and the blue with the green (Fig. 1).

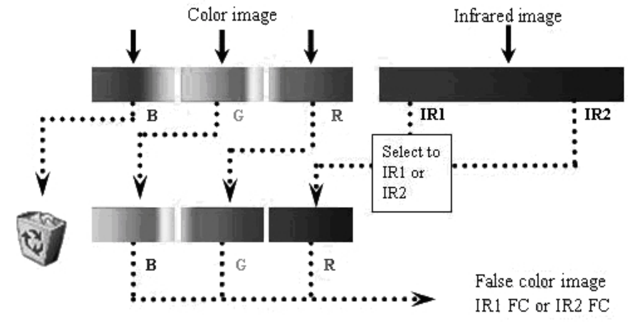

Figure 1. False Color IR Procedure.

Resulted images present pseudo-colors closely related with the chemical composition of the pigments, thus allowing the characterization of pigments whit similar hue under visible light. The different degree of IR radiation reflected by each pigment may also depend on the painting technique used by the artist. Indeed, paintings are generally complex systems characterized by paint layers with different thickness, color, and composition. Especially in the case of transparent pigments or thin layers, the ground preparations can give a significant contribution to the false-color image. In this particular case, complementary information obtained with other chemical analysis should be obtained in order to improve the interpretation of false-color data.

Reproducibility of false-color is a key factor. Imaging modes need to be calibrated with standards of known reflectance in order to compare images collected under different exposure conditions and employing different equipments [3]. The standard employed in this study is a 18% reflectance Grey card built by Kodak and characterized by certified reflectance percentage within the wavelength range covered by the sensibility of the utilized digital camera. The appropriate response of 18% Grey card can be checked, for each spectral region, through a reflectance histogram that is automatically provided by the system.

The first attempts to study the potentiality of false-color IR imaging made use of a photographic film color [4]. The development of specific electronic equipments lead to a great improvement of this diagnostic tool. Nowadays, the Artist system enables the automatic elaboration of false-color IR images; problems related with the different sizes of color and IR images are hence directly solved with the focus correction carried out during the acquisition phase.

2.2 The Case Study of the Famous Giotto's Crucifix

As an exemplar case for the application of false color IR imaging, we discuss here the study that we conducted to evaluate the state of conservation of Giotto's Crucifix (shown in Fig. 2) and to research the painting techniques utilized by Giotto. This artwork is exhibited at the Musei Civici agli Eremitani in Padua.

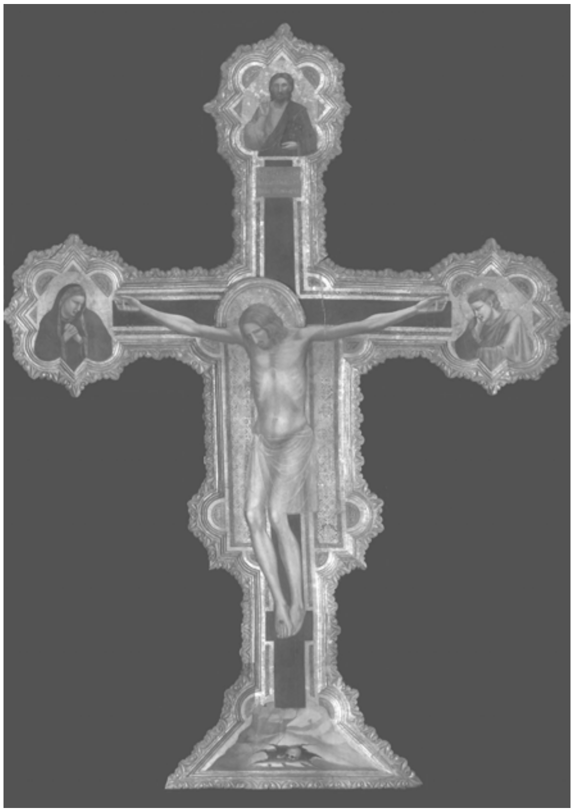

Figure 2. Color Image of Giotto's Crucifix.

Figure 3. Visible Fluorescence Image of Giotto's Crucifix; Detail of Saint John. Numerous Retouches (Black Areas) Are Visible on Saint John's Head and Dress.

A closer evaluation of the IR reflection, false-color IR, fluorescence and UV reflection images revealed and mapped several past restoration interventions. A great number of retouches became visible as well as damaged and degraded areas, which were concentrated mainly on the face of the Virgin and Saint John's dress (Fig. 3).

Reflectograms allowed an accurate study of the underdrawings, which revealed the traditional Giotto's painting technique. The use, as preparatory drawing material, of a light black pigment applied by brush with large outlines has been revealed, as well as the great attention paid by the author in drawing the Christ's anatomic details. False-color analysis of the crucifix provided a first indication of the pigments utilized by Giotto. The main color employed is the rare and expensive lapis lazuli blue pigment. This characterization was possible thanks to the red color showed by the pigment when observed in false-color mode which is linked to its high transparency to the IR radiation (Fig. 4). False-color IR images allowed also the identification of superimpositions of red lake glazes over cinnabar used by Giotto for the red painted areas.

3. False-color IR Image Acquisition of the Artwork

As anticipated in Section 1, our system can be subdivided into two main components. The first one is represented by all the hardware and software instruments employed for the digital acquisition of false-color IR image. Therefore, it also includes the camera and filters utilized to take digital images, both in color and in infrared (*VIS* and *IR* in Fig. 5, respectively), of the considered painting (step *A*). Since the short distance between the painting and the camera when this operation takes place, each of the digital images covers only a limited section of the painting. Several single images have hence to be taken to have the whole artwork in a digital form.

All of these single images have then to be merged to generate complete digital copies, both for VIS and IR modes, of the whole original painting (step *B*). This task can be done automatically by the means of existing software and algorithms that exploit the overlapping area of each picture to match them as pieces in a puzzle game [9-12].

Figure 4. IR Reflectance Image of Giotto's Crucifix; Detail of Virgin's Dress Made With a Pigment (Lapis Lazuli) that Results Transparent Under IR Radiation.

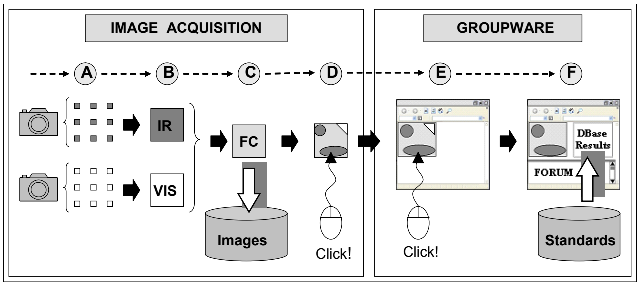

Figure 5. Work Steps in our System.

Having the two digital copies, VIS and IR images, another software tool is then responsible to combine the two images in a single one through the false-color technique (step *C*). The false-color IR image (FC) is the subject of the investigators' analysis.

Needless to say, all of these images represent a patrimony for the scientific community that has to be preserved. They are hence stored in good order in a database (called *Images* in Fig. 5).

3.1 Providing a Human Eye to a Computer: the Reversed Photomosaic Algorithm

Last but not least element of the first main component, another piece of software is responsible for allowing the operator to select a certain area within the false-color IR image and automatically highlight all the areas that would have the same appearance under a naked eye (step *D*).

This procedure represents one of the contributes of our work to the analysis of an artwork since, up to date, it has always been done through the direct work of the operator.

However, automatically highlighting detached areas that are characterized by a human sense property is not a trivial task. Indeed, we want the computer to fake to be able to see an image as a human eye (and brain) would do, and not just as a collection of tiny, single pixels. To this aim a possible solution can come from a technique named *photomosaic* (or *photographic mosaic*) [6-8].

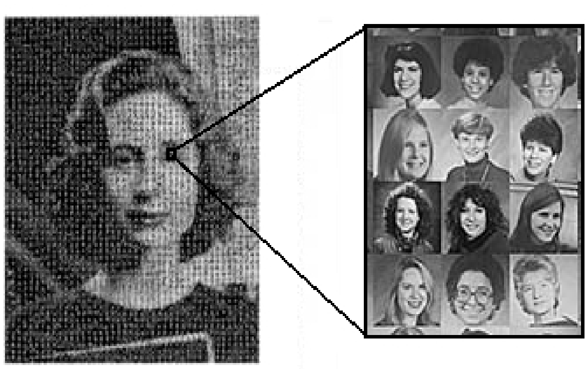

Figure 6. A Photomosaic Picture (Left) Composed by Hundreds of Small Tile Images (Right); Original Image From [7].

An image obtained through photomosaic is made up of many smaller, even completely different, tile images. Taking a close look, one can see all the small tile images; however, when seen together at a distance, they suggest an entirely different image (Fig. 6). This is due to how humans perceive images and to the well known property by which we *look* with our eyes but we *see* with our brain. Photomosaic exploits this principle and transform an input image into a grid of thumbnail images preserving the overall appearance. More in detail, a photomosaic algorithm is endowed with a database of images. The algorithm delves into this database to determine which thumbnail images best approximate the various blocks of pixels composing the main image. This can be done by simply matching the average RGB color of the candidate tile image with the considered block of pixel in the original one. However, also other features such as luminosity and contrast can be considered.

Taking inspiration from the photomosaic technique, we propose to use an algorithm that we name *reversed photomosaic* to provide some sort of "human sight" to the computer. The aim is that of automating a procedure that is currently performed directly by the investigator of the artwork. In essence, our algorithm helps the investigator when she/he has selected a certain area and wants the computer to automatically identify all the areas in the main image that she/he would perceive as similar. Needless to say, this automated procedure could substitute or just integrate the investigator's work.

We explain our reversed photomosaic algorithm with the help of the pseudocode in Fig. 7. First, the image is acquired with techniques discussed in Section 2 (line 1). Then, the operator is asked to choose the granularity of the area-selecting function or, in other words, the size of pixel blocks that will be managed by the algorithm (line 2). The image can hence be completely subdivided in blocks of pixels having the size requested by the operator (line 3). Visual characteristics that features each of the blocks (e.g., RGB, luminosity, contrast) are calculated and stored with the corresponding block (tile image) in a database (line 4). This procedure differs from the original photomosaic algorithm as the latter utilizes other images (reduced in size) to build this database whereas, with our algorithm, the database is entirely composed by chunks of the original image. When the operator selects one point of the main image (line 5), the algorithm considers the block including that point and extracts from the database all the other blocks that present the same visual characteristics (line 6). Since, to this aim, we use the same piece of algorithm, these blocks are the same that would be chosen by the original photomosaic technique given the input image we are considering and the database we just built. Last step in the reversed photomosaic algorithm, areas of the original image that are composed by contiguous blocks that have just been selected by the algorithm are finally highlighted on the screen (line 7).

```
Image := image_acquisition();
Size := input_block_size();
Set_blocks := subdivide(Image, Size);
DB := create_blocks_DB(Set_blocks);
Point := area_selection();
Set_select := photomosaic(Point, DB);
visualize(Set_select);
```

Figure 7. The Reversed Photomosaic Algorithm.

The operator can then select other areas for her/his studies and generate a new image that highlights all the areas found by the various run of the reversed photomosaic algorithm. Within this final image, the highlighted areas will be object of study. In our specific case, this image is hence the false-color IR image with some areas highlighted as requested by the operator and performed by the reversed photomosaic algorithm. The operator can select (with a click on the mouse) different points within this image. Each of these selections activates the reversed photomosaic algorithm that generates a new group of emphasized areas. To discriminate among different groups within the same image, each group of areas will be highlighted with a different color.

For the sake of clarity, from here on, we call the final image obtained through this process the *study image*.

4. Analyzing the Study Image within the Groupware

In the scenario depicted till now, the study image has seen only by the operator that handled its generation. However, a more comprehensive analysis on the study image could be performed enlarging the group of investigators and adding some information technology aid to support their work. As depicted in Fig. 5, we have designed our system to include a second main component, i.e., a groupware making use of a web site, to generate a cooperative work environment to foster the interaction and discussion among investigators. Furthermore, it also includes a module designed to help investigators in their evaluation by providing suggestions.

Focusing on the cooperative work environment, as soon as the operator is done with the selection of areas to highlight, the resulting study image is converted into an image map published on a web page remotely accessible by interested investigators (step *E* in Fig. 5). Each of the emphasized areas of the study image is now clickable in order to access another web page related to that area. All the areas belonging to the same group are linked to the same web page.

A web page related to a certain area of the study image represents both a source of information about the pigment used by the author for that area and a virtual environment for cooperative work and shared discussion among investigators (step *F*). In particular, it includes suggestions provided by the system regarding possible pigments matching the considered area's false-color (*DBase Results*) and a forum for investigators to compare their opinions about that area (*FORUM*).

4.1 Providing the Computer Logic to a Human: the Standards' Database Support to Pigment Investigation

The groupware is equipped also with a database of standard pigments of known composition, which is used for automatic RGB comparisons between the various standards and the false-color of the artwork's investigated area. Possible pigments are presented to investigators along with a confidence degree and ordered by verisimilitude (Fig. 8).

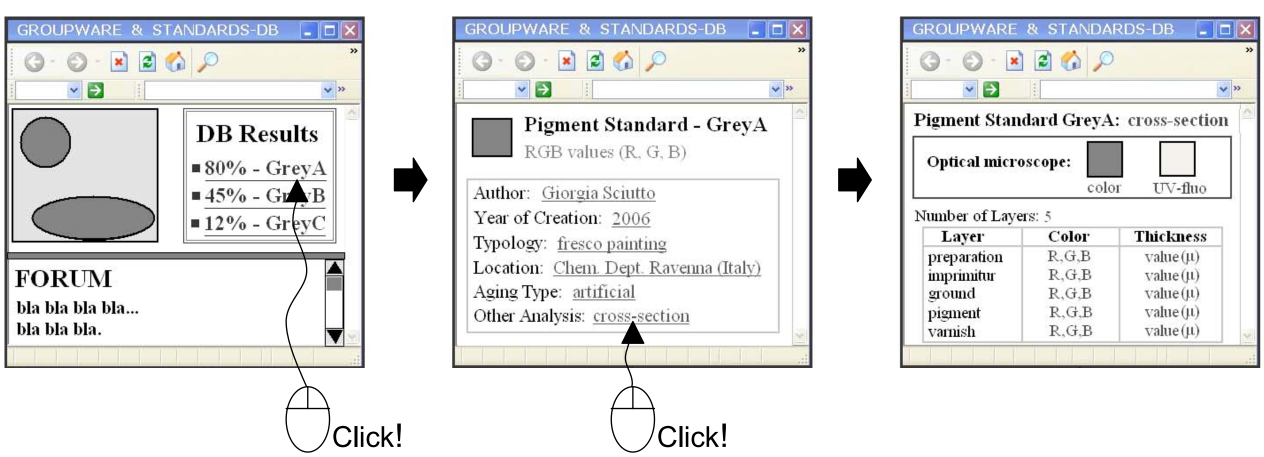

Figure 8. Example of Computer Support to the Investigator through the Combination of the Standards' Database with the Groupware.

Needless to say, the settings utilized to obtain the false-color IR images of the artwork and of the standards should have preferably been identical. However, hypotheses can be formulated even in the case where the two settings do not perfectly match. Clearly, these hypotheses will present a lower degree of confidence exposed on the groupware.

Complementary information that can be stored in the standards' database regards other analytical techniques (i.e., Fourier Transform IR micro Spectroscopy, X-Ray Fluorescence, Scanning Electron Microscopy and Gas Chromatography Mass Spectrometry) that can be used for the automatic interpretation of the study image. An investigator has to be able to retrieve such information, when available, with just one click, as shown by the example in Fig. 8.

5. Conclusion

The false-color IR technique offers the possibility to identify pigments by combining color and IR images. This is particularly useful in the field of conservation of artworks as it provides information about painting materials and techniques adopted by the artist, and possible retouches that have been added later. However, the interpretation of a false-color image is typically carried out just by visual examination directly performed with naked eyes by an operator.

In this paper, we propose a new integrated system for computer-assisted pigment identification for objective interpretation of false-colors. Our system supports the work of investigators at various stages. First, through a reversed photomosaic technique, it helps the operator in highlighting all the areas of the painting that deserve to be studied. Then, hypotheses on the pigment's composition are automatically formulated by comparing the unknown image with false-color data stored in a standards' database. The aim is that of overcoming, at least at the very first stage of the study of an artwork, the natural drawbacks of a subjective human examination. Finally, all this information is made available on a groupware to facilitate the discussion among investigators and produce a final comprehensive evaluation.

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