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OPPORTUNITIES AND ISSUES OF IMAGE PROCESSING FOR CULTURAL HERITAGE APPLICATIONS

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ABSTRACT

The application of image processing techniques for the analysis, the diagnosis and the restoration of artworks remains a very uncommon practise. Recently, however, there has been a greater interest in acquiring and processing image data of artworks: the efforts in this application field have been characterized by promising results, which proved the advantages that the use of digital image processing may have on several issues. In this paper the peculiarities and the state of the art of this application field will be described.

1. INTRODUCTION

The application of science and technology to the analysis of artworks dates back to several centuries ago. However, only in the last decades, analytical methods developed in the physical sciences have been applied to the analysis, conservation and dissemination of works of art. The interaction between the two worlds of science and humanities has never been easy, and this is also the case of image processing techniques for artwork analysis and restoration. As a matter of fact, the application of signal and image processing in this application field is still an uncommon practice. Lately, however, there has been a greater interest in the acquisition and processing of artwork image data for storage, transmission, representation and analysis purposes. This fact is due to two main factors: on one hand, new devices made it possible to acquire higher resolution images spending fewer time, new storage devices made it possible to store an increasing amount of information regarding an increasing number of images and computers became faster, making it possible to develop new powerful algorithms able to process this increasing amount of information; on the other hand an increasing number of scientists with a background in analytical techniques and interpretation of the data produced, has been approaching this field, stimulated by the projects funded by national and international governments (such as the Projects ACHOIR, CRISATEL, VASARI, NARCISSE, VISEUM, ARTISTE, VASARI, MARC [1], supported by the European Commission). Research efforts in this field have been supported by promising results, which proved that digital image processing may have an impact on several issues, such as material analysis (and therefore dating and provenance determination), discovery and interpretation of ancient technologies, artists' environment and mutual relationships, better knowledge of conservation materials and processes, and art dissemination and fruition.

There are several ways in which image processing techniques may give significant contributions in the art field. In this review four main application areas are identified: the achievement of digital reproductions, the pursuing of image diagnostics and analysis, the implementation of virtual restoration processes, and the problem of security in the fruition through multimedia applications [2, 3].

2. CULTURAL HERITAGE IMAGE ACQUISITION

Obtaining an exact (or as faithful as possible) reproduction of an artwork was one of the first developments in this area, with the connected activities of archiving, retrieval and dissemination, that greatly profit from the digital format. Most of museums, archives, and libraries are engaged in direct digital image capture of cultural heritage [4, 1].

Depending on the application and its requirements, the devices employed for image acquisition use passive or active detection schemes, and several kinds of sensors and radiation sources (lasers, LEDs, X-ray tubes, lamps). However, most of the current developments are concentrated on processing and analyzing the visible and near IR range images. Commercial RGB digital cameras are sometimes employed, where each sensor element has either a red, green or blue filter in front of it, and a simultaneous RGB image is acquired. More frequently custom devices for spectral imaging are developed. They are mainly based on two approaches, using in front of the detector either appropriate filters or a dispersive element. In systems using filters, interferential or tunable, a (small) number of monochromatic images are gathered, one for each transmission band chosen. For systems of this type, the sensor may be a single element, a row of sensors, or a two dimensional array [5]. With multispectral imaging it is possible e.g. to achieve higher color quality [6], orto achieve the spectral signature of each imaged element of the artwork. The number of filters in the solutions proposed in literature varies from 7 [1] to 32 [7]. As far as the spatial resolution is concerned, it may depend on the number of active elements on the detector, or on the sampling grid, if the system is realized with a single element sensor which is moved by translation slides and scans the acquisition area. In some cases a geometrical distortion is observed in the captured image, which needs to be corrected by postprocessing. Illumination uniformity is also generally necessary and a lack of it needs to be taken into account when processing the image, in order to get reliable color data. In many cases it is not possible to obtain, with the desired quality, an unique digital image of the artwork in a single acquisition. When several images representing sub-parts of the painting are acquired, it is possible to reconstruct an unique digital image representing the whole scene by means of image processing, as described later.

3. ART DIAGNOSTICS BY IMAGING

Another promising set of applications is the possibility to infer spectral data about a painting without coming into physical contact with it. Non-invasivity of diagnostic techniques, in fact, is a highly desirable feature in a field where owners are not entrusting too invasive attentions, and however most of the current techniques imply microsampling of the painting for subsequent physical-chemical analysis. Non-invasive diagnostics is achieved by exploiting the fact that the materials comprising the various layers of a painting reflect, absorb and emit electromagnetic radiation in ways that depend on their molecular composition and shape. If the radiation arriving at the sensor is measured with sufficient accuracy, the resulting spectral signature can be revealed. With multispectral imaging techniques, the entire surface of a painting is measured with good accuracy. The radiating sources may not be limited to the visible range, but cover the spectrum from UV to IR wavelengths. Similarly to the medical field, various sensing techniques (such as e.g. spectroscopy, UV induced visible fluorescence analysis, reflectography, X-rays scanning etc.) based on different physical principles, capture different and often complementary information. Many crucial issues in artwork diagnostics, such as the assessment of the conservation state, the knowledge of the realization techniques, the evaluation of the historical period and the attribution of the painting, the possibility of keeping trace of any modification of the artwork shape etc., depend on different modalities that need to be joined together to draw reliable conclusions. The comparison of datasets is usually an interactive process done by the art historian (or conservator) studying the opera. Therefore, professionals in the field are greatly interested in having the possibility to automatically and meaningfully combine different diagnostics modalities [8].

At this aim, an useful tool is the registration procedure. Registration is the determination of a geometrical transformation that aligns points in one picture with corresponding points in another picture. It is an effective procedure in all the cases in which the analysis of the painting can be performed by gaining the information coming from different images taken at different time (e.g. historical pictures versus current pictures) [9], or from different points of view or by means of different sensors thus acquiring the images in different spectral bands (e.g. IR-reflectograms, X-radiographies) [10]. In [9] Zitová *et al.* present a registration method in the framework of a restoration process of a medieval mosaic. Two pictures of the mosaic are available: an historical black and white photograph taken in 1879, and a current one taken by a digital camera. The availability of these pictures gave to the restorers the possibility to compare the conservation of the mosaic at the end of 19th century and at present. However, to make the comparison, it was required to apply a registration process, since the images were taken from different locations and with a different spatial resolution. Cappellini *et al.* [10] propose an automatic algorithm, based on the computation of the maximum of the mutual information, with the aim to achieve a multispectral calibrated UV fluorescence image of the painting surface. In order to achieve it, 14 multispectral images of the same area of a painting, 7 relative to the UV induced visible fluorescence, and 7 relative to the reflectance in the visible range, were acquired with a monochrome CCD camera equipped with a filter wheel, and resulted slightly misaligned with respect to each other, due to a different optical path and some randomness in the positioning of the filter in front of the camera objective. To combine correctly the different information provided by the multispectral images a registration algorithm was needed.

Another application of image processing in this field, consists in the analysis of paintings. Usually art theorists classify a painting based on a set of attributes called painting style, that give an artwork its character and allow it to be attributed to a particular artist, school or period. Some papers have recently proposed algorithms for the digital analysis of painting images providing to art theorists some specific quantifiable features in the paintings that could be useful for their classification, like brush strokes [11], or a set of global features of paintings [12], or the color relief of skin patches in painting [13]. Another application for the analysis of paintings is the extraction of borders or edges of the painting, in order to get a better knowledge of the art-work itself. The revealed features are not only painting's elements (i.e. contours of subjects present in the painting), but also characteristics of the layer, for example bonds of a wood panels, micro-cracks occurred on the varnish, engravings, etc.. Edge extraction can be useful for monitoring a restoration work, for highlighting some particular features of the painting (e.g. position and size of lacunas), for studying the geometrical structure of the painting, etc.. Nowadays, the approach of the restorers is to manually draw the borders by means of transparent sheets leaned over the painting itself or by means of some general purpose software: in any case, the task is really time consuming. In [14] it has been proposed a semi-automatic image processing tool for extracting edges in art-works.

In many cases, the painting to be analyzed is so big that it is not possible to obtain, in a single acquisition, an unique digital image with the desired quality. On the contrary, several images representing sub-parts of the painting are obtained. In this case, it is possible to reconstruct an unique digital image representing the whole scene by means of mosaicing algorithms, that join a certain number of overlapping sub-images of the to-be-reproduced scene [15]. Generally, mosaicing involves a pair of sub-images at a time, which are joined together. This operation is repeated for all the sub-images, using the one obtained in the previous step as a reference and joining another one to it: in this way the whole representation of the painting will be generated in an incremental way using a new sub-image a time. The main problem to solve is that the sub-images, even if taken in the same acquisition session, can show color variations and small geometric distortions from each other, due to lighting and position modifications. So, it is easy to understand that joining several sub-images together involves a certain number of difficult tasks: a mosaicing procedure starts from the hypothesis that, given two images to be joined (called reference image and non-reference one), the overlapping part of the non-reference image is a transformed version of the same part of the reference image; after having estimated this transformation, it is possible to apply its inverse to the whole sub-image, to reduce the geometric distortion between the two images. The different possible approaches differ according to the transformations used to model the geometric distortions and to the strategy implemented for estimating it. Mosaicing is also very useful when there arises the need of obtaining a flatten version of a painting or a fresco applied to a curved surface: the processing allows to obtain a view of the artwork as if it was painted into a flat surface and not into a curved one. In order to flatten the painting, it is required to estimate the parameters of an equation describing the curved surface and the transformation that relates points in the camera coordinate system with the points in the object coordinate system; then, thanks to an iterative process, the acquired image can be back projected on the surface and subsequently flattened [16, 17].

4. VIRTUAL RESTORATION OF ARTWORKS

The third important cluster of applications of image processing techniques to painting images is virtual restoration. Different methods have been studied, with various goals. The present visual appearance of a painting may be altered due to ageing or unfortunate events. It is certainly questionable whether a real conservation treatment should aim at bringing the artwork back in time at the moment in which the artist completed it. However, on a virtual representation of the artwork, many more options are possible.

The crack removal is, e.g. a rather straightforward application, which proved to improve the readability of the image to a significant extent. Virtual cleaning is another controversial issue. The varnish which is usually laid over painting is easily altered by time, and the legibility of the painting greatly suffers from it. Varnish removal is a challenging task for a conservator, and it is often debated how and even whether to proceed. Virtual cleaning intends to help in taking such a decision, showing images of several hypothetical procedures. Such a process has been fiercely opposed by some conservators because it is supposedly suggesting a target which is not always achievable, and therefore may be perceived to lay the blame on the restorer for not having been able to successfully clean the painting. Another increasingly pursued task is the virtual composition of fragments of a painting, which achieves obvious advantages and impressive results, virtually join parts of paintings which are now hosted in different museums or are lost but reproduced in some old postcard.

As tools for artwork restoration, image-processing techniques serve two purposes [18]. They can be used as a guide to the actual restoration of the artwork (computer-guided restoration). Otherwise, they can produce a digitally restored version of the work, valuable by itself, although the restoration is only virtual and cannot be reproduced on the real piece of work (virtual restoration).

The tools for virtually cleaning dirty paintings belong to the first class of methods. Several phenomena can degrade the colors of paintings, deteriorating their appearance. Cleaning is usually performed by conservation experts with a trial and error approach: different chemical cleaning substances are applied in small regions of the painting to select the most appropriate for cleaning the entire painting. A digital color restoration technique, by relying on the cleaned small patches of the painting, can provide an estimate of the final result when the same cleaning methodology is applied to the whole piece of work. Restorers could then use this tool to choose which cleaning procedure is likely to give the best result. A digital color cleaning algorithm can work in two different ways. A first class of methods [19, 20, 16] is based on the assumption to have a digital copy of the painting before the cleaning process, and one of the same painting after that some regions have been cleaned chemically; otherwise, let us suppose to have only the digital image of the painting after the cleaning of the small patches, with the hypothesis that the colors used by the painter, present in the cleaned patches, are present also in other parts of the painting. If $\mathbf{I}$ represents the digital image of the dirty painting, and $\mathbf{I_c}$ the digital image of the same painting after the cleaning process of some patches, it is the aim of the algorithm to find the mathematical color transformation $\mathscr{T}$ that maps the dirty colors into the cleaned ones, such that in the cleaned area $\mathbf{I}' = \mathscr{T}[\mathbf{I}]$ is as close as possible to $\mathbf{I_c}$. Subsequently, the same transformation can be applied to the entire image, obtaining a virtually cleaned image. The proposed methods in literature differ with regard to the chosen color coordinates and to the particular model used for the color transformation $\mathscr{T}$. A second class of methods [21, 22] do not rely on the comparison between cleaned and dirty regions of the painting, but develop a model trying to estimate the degradation process occurred in time, and according to this model they reconstruct the original visual aspect of uncleaned artworks.

Into the class of methods for virtual artwork restoration, we can include the algorithms for removing cracks from paintings and frescos. Cracks are often caused by a rapid loss of water in the painting's varnish: when the painting itself is located in a dry environment, a non-uniform contraction of the varnish covering can cause the birth of cracks. With image processing tools it is possible to entirely remove cracks by means of interpolation techniques. An algorithm for crack removal is usually a two-step procedure: first, the cracks have to be detected; next, the selected cracks are filled in. The crack selection step can be semi-automatic, or automatic. In the first case, the aid of the user is requested to let him choose a starting point of the crack, from which it is possible to start an iterative process able to identify the whole crack by assuming the hypothesis that a crack is darker than the background and it is characterized by a rather elongated structure [19, 18]. In automatic crack selection, cracks are identified by means of a proper filter, like Gabor filters [23], or a morphological filter called top-hat transform [24, 16, 25]. However, with this approach not only cracks, but even brush strokes and other texture characteristic could be detected. This problem can be solved by discriminating brush strokes and cracks on the basis of shape, hue or saturation values [24, 16], or thickness and favored orientation [26, 27]. Let us note that crack analysis can also be used as a feature for the analysis of an artwork, e.g. it can be useful for the evaluation of the material used, or its authenticity [23].

Another technique belonging to the class of methods for virtual artwork restoration is lacuna filling. Lacunas are a very common damage which can occur to paintings and more often to frescos and wall paintings, when some parts of the fresco collapse and fall down; in this case the effect is the creation of areas, sometimes large, where the original image is lost. Actual restoration techniques tend to fill these areas with a uniform color or a set of colors, to give the impression of the continuity of the image. By means of image processing tools it is possible to accomplish the same task to the digital version of the art work. In particular, two virtual filling procedures have been proposed so far: the former simulates filling techniques actually performed in the restoration laboratories, in order to simulate and compare real restoration methods [28, 18]; the latter is based on a texture synthesization procedure to fill lacuna regions with the appropriate textures, in order to obtain a restored image where the boundary between original and synthesized paintings is seamless [29]. In particular, in [28, 18], the method (that is semi automatic) consists of two steps: the segmentation of the lacuna and its restoration, i.e. filling. During the first step, the user is asked to choose a pixel belonging to the lacuna, that has to be restored; then, an automatic procedure recovers all the lacuna using an ad-hoc segmentation algorithm developed for this particular application. During the second step, it is possible for the user to experiment several implemented filling techniques that simulate restoration techniques actually performed in the restoration laboratories; in fact, the main idea of the proposed algorithm is to provide to the user the possibility of virtually comparing different restoration solutions, in order to select the most suitable one for the specific art work. In particular, the restoration methods have been implemented by basically referring to two different restoration schools : the " *Scuola Romana*" of Cesare Brandi and the "*Scuola Fiorentina*" of Umberto Baldini [28]. In [29] Pei *et al.* propose a texture synthesis procedure to eliminate, from ancient paintings, undesirable patterns and fill such lacuna regions with the appropriate textures, so that boundaries between original and synthesized painting are seamless. After the selection of the to be restored region, the texture synthesization procedure includes four phases: neighborhood assignment, possible neighborhood collection, auxiliary and synthesization.

Another increasingly pursued task is the virtual composition of fragments of a painting, a problem similar to image mosaicing. In [30] a methodology has been proposed for the computer-aided reconstruction fragments of wall paintings. According to this methodology, each fragment is photographed, its picture is introduced to the computer, its contour is obtained, and, subsequently, all of the fragments contours are compared to reconstruct the whole wall paintings from a set of fragments.

5. CULTURAL HERITAGE CONTENT FRUITION

Thanks to the birth of virtual art gallery, museums are able to show their masterpieces in order to attract new visitors, and new artists are able to show their works in order to increase their fame. But at the same time these images are at the mercy of users who can make an illicit use of them: digital reproductions of art works belong to the legal owner, such as museums or artists, as the real art works. Consequently, it arises the need of a simple and effective way by means of which it is possible to guarantee the property of the image against illicit uses. One possibility to solve this problem, is by means of digital watermarking, that allows to insert in the image an invisible code identifying the image, without degrading its quality [31, 32]. So, each artist who would like to publish his works on the web could mark them, in order to prevent their illegal use; the information which could be inserted are of several types, such as the copyright owner, the creator of the work, the authorized consumers and so on. In the case that someone has make an illicit use of an image, and that image has been put at the attention of the museum curator, the watermark gives the possibility of a legal action against the "thief".

6. CONCLUSIONS

As outlined in the previous sections, this research area presents a large number of interesting challenges. Several issues are common to the general research area of digital color imaging. However, conservation issues are especially important for art objects. The acquisition process must not harm the artwork, and a damage could easily occur due to an incorrect handling or irradiation with high intensity light sources. In general it is not possible, or not desirable, to move art objects, although their position is sometimes not ideal for scientific investigation. Clearly it is also desirable to digitize the artwork once, and in a manner that facilitates a variety of applications. This imposes highly demanding requirements to the acquisition devices and methods. However, the true peculiarity of this field lies in the fact that each work of art is by its nature unique: dimensions, materials and techniques may change enormously for artworks produced in different periods and by different artists. Moreover each object is without an equal because of its specific history: exposition to different environmental conditions, accidents or restorations of past owners or conservators, and simply the passing of time, transform the original piece in an unmatched manner. To infer definitive data about original materials and conservation conditions is therefore hard.

Moreover, there is the need to bring together scientists with different backgrounds and belonging to different cultural areas. In many cases, the main obstacle to the application of image processing technologies to the art field is represented by a cultural distance between technical researchers and researchers belonging to the humanistic area. In spite of the above difficulties, there is a clear demand for new computational tools able to help know more about works of art, hence the application of image processing to the study of art works will be one of the most interesting signal processing research areas in the next years.

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