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IMAGE SEGMENTATION APPLIED TO THE INVESTIGATION OF CRAQUELURE DOMAINS IN PAINTINGS

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Abstract
Old paintings are generally characterized by the presence of cracks patterns, formed during the drying process. This network of cracks, known as craquelure, represents a key feature for the authentication of artworks and the discovery of forgery. In this work, an image segmentation approach is used for a quantitative study of cracks patterns in paintings. We will show how the size distribution and orientation of the craquelure domains can be evaluated using this technique.

***Keywords**: Image processing, Image Segmentation, Craquelure, Cracks network.*

1. Introduction

In the past decades, there has been increased interest in the preservation and conservation of art objects. Several problems need to be faced by art experts, most notably authentication, discovery of forgery and detection of structural damage. The topic is not trivial, especially if the consequences related to wrong attributions are considered. A remarkable example is the art fraud scandal that involved the Knoedler Gallery in New York. Between 1994 and 2011, the Gallery sold forged paintings, including Mark Rothko's and Jackson Pollock's, which resulted in a turnover of approximately US$80 million (Rashbaum *et al.*, 2013). The following lawsuits probably were among the reasons for the Gallery closure on 28 November 2011, after 165 years of activity (Cohen, 2011). More recently (July 2018), two experts claimed that a painting allegedly by Parmigianino, and sold through Sotheby's in 2012, was fake (Noce, 2018). Considering that the painting had already been exhibited in Parma, Vienna and New York, it is evident that the detection of a forgery is not trivial.

A painting has a complex nature, as it consists of a multi-layer assembly of pictorial and varnish layers placed on a deformable support, canvas or panel. The support layer, e.g., paper, fabric (canvas), metal, etc., represents the base of the painting and should protect it from mechanical damage. The ground layer, often made of gypsum, is then deposited on the support layer, and serves as an intermediate between the support and the paint layers. The paint is, in turn, a mixture of pigments, responsible for colour, and binders, that help to form a three-dimensional network, where the pigment particles are entangled and bound. Finally, the varnish layer is sometimes used to protect the outer layers or enhance their visual perception. After application, the paint is subjected to drying and ageing processes, during which each layer, possessing different mechanical properties, reacts differently to the applied stresses. In the pictorial layer, stresses produce mechanical damages resulting in the formation of crack patterns.

The collection of detailed information about such a complex system, with the aim to allow accurate detection of damage and artist identification, is not straightforward. In the present work, the cracks patterns which are generally formed in old paintings will be studied. This network of cracks, known as craquelure, will be shown to be a broad indicator of authorship, and will be here analysed by an image segmentation approach to help and support art analysts.

Segmentation is an image processing method used for partitioning an image into multiple sets of pixels, defined as its "super-pixels." Different domains, and boundaries among them, can be then identified through application of this technique. This approach has been successfully applied to the analysis of Scanning Electron Microscopy (SEM) images of freeze-dried products (Arsiccio *et al.*, 2019). The dimension of the pores within the dried cake was estimated through the areas of the super-pixels of the segmented images. Here, the same technique will be extended to the field of art pieces, with the aim to determine the size distribution of craquelure domains in paintings, and the cracks orientation.

2. Background and context

The problems related to the analysis of art objects have traditionally been approached exploiting the personal expertise of art analysts. As evident from the previous discussion, it is apparent that this approach is not enough anymore, and several scientific methods have been proposed to help people working in this field (Craddock, 2009). Ultraviolet (UV) fluorescence has been used for artwork dating, as a correlation exists between the colour of the fluorescence and the age of the varnish coating (De la Rie, 1982). Infrared imaging methods, both in the near infrared (NIR) and in the short-wave infrared (SWIR) could also be used to reveal the presence of preparatory sketches or to assist the conservator (Faries, 2007). X-radiation methods can be used to detect structural features, such as inclusions and reinforcements in statues, or alterations, defects and degradations in paintings (Lui *et al.,* 2011). Acoustic imaging may also be applied to look for detachments and voids in frescoes and panel paintings (Siddiolo *et al.,* 2007), and subsurface defects may be detected using laser Doppler vibrometry (Castellini *et al.*, 2000). Finally, thermographic analysis could be used for defectoscopy and structure studies and may also reveal the presence of alterations and pentimenti (Gavrilov *et al.*, 2014).

Recently, museums have started to assemble digital libraries of images of their collections, thanks to the progress in data acquisition technology. This could foster the application of image processing tools to support art experts in the tasks of artist identification and deterioration assessment. For instance, the Van Gogh and Kröller-Müller Museums in The Netherlands prepared a data set of 101 high-resolution grey-scale scans of paintings in their collections, mostly by van Gogh, and made it available to group of image processing researchers from different universities. The application of wavelet decompositions to this data set led to encouraging, but not perfect results (Johnson *et al.*, 2008). The use of image analysis applied to art objects is therefore promising, but further development is needed. Here, the application of image processing to the craquelure domains in paintings will be considered.

The term craquelure denotes the structure of cracks that is formed on the surface of a painting, because of drying, aging, impact or intentional patterning. As previously discussed, the chemical composition of the layers in a painting is different, and each layer exhibits specific mechanical properties. This contributes to the development of stresses in the pictorial layer. For instance, the pictorial layer tends to shrink as volatile solvents evaporate during drying. Non-uniform shrinkage, caused by differential adhesion to the sublayer by different paint species, leads to large tensile stresses in the top paint layer (Giorgiutti-Dauphiné and Pauchard, 2016). Craquelure formed during this drying process appears within days of painting, is usually isotropic and is characterized by shallow cracks in the topmost layers of paint. Compared to their drying counterparts, aging cracks are sharper, deeper, and are developed over the lifetime of the painting (Giorgiutti-Dauphiné and Pauchard, 2016). The pictorial layer becomes more brittle as it ages, and direct impacts, restoration processes, oxidation reactions or support deformation contribute to aging craquelure.

While craquelure is undesirable from the aesthetic point of view, it anyway reveals important properties of the pictorial matter or some information about the methods used by the artist. In 1997, Bucklow (Bucklow, 1997a) proposed a classification based on seven key features to describe craquelure morphology: local and global direction of cracks (isotropic or anisotropic pattern), cracks shape (curved or straight), cracks spacing, cracks thickness, organization of the crack network, connections between cracks and the relationship between cracks directions and the weave or grain direction of the support. This classification can be used to relate a specific crack pattern to various historic time periods, locations and painting styles, thus supporting the task of attribution. This is extremely important if we consider that induced craquelure is often used by forgers of Old Master paintings. Art forger Tony Tetro developed a technique based on the use of formaldehyde and a special baking process to induce formation of cracks in fake paintings (Hays, 2000). However, craquelure is unique, and challenging to reproduce artificially. This suggests that an accurate quantification of the cracks pattern on a painting surface may help with the task of discovery of forgery, as well.

In 2016 drying dispersions of colloidal particles in volatile solvents on non-porous substrates were used as model systems to study crack formation (Giorgiutti-Dauphiné and Pauchard, 2016). In 2018 (Flores, 2018), the evolution of crack entropy in old paintings was studied. The software package ImageJ was used to evaluate local directionalities by a gradient orientation method. However, according to the authors experience, the package ImageJ does not allow a completely reliable identification of different domains, because the edge detection approach implemented in the software gives satisfactory results only when boundaries between different regions can be clearly identified. Previous results have confirmed this in several cases (see for example Arsiccio *et al.,* 2019), and something similar occurs in the case of paintings craquelure, as well. The image segmentation method here discussed is therefore proposed as an improvement of already existing tools, with the aim to allow a more reliable analysis of cracks patterns in old paintings. We will show that using this technique it is possible to quantify both the size distribution and orientation of craquelure domains.

3. Methods and results

In (Arsiccio *et al.,* 2019), a procedure was proposed for the measurement and prediction of the pore size distribution of freeze-dried solutions in vials. Images obtained by scanning electron microscopy (SEM) were binarized and then segmented into domains to determine the pore size distribution. Here, the same approach will be applied to detect craquelure domains in paintings. The sample under investigation is *Girl with a pearl earring*, an oil on canvas painted by Johannes Vermeer around 1665, and stored in the Mauritshuis Museum (The Hague, Netherlands). This painting exhibits a complex pattern of cracks, that already attracted the attention of researchers in a previous work (Flores, 2018).

As previously mentioned, image segmentation consists in partitioning an image into multiple sets of pixels, defined as super-pixels, in order to simplify the representation and make the image ready for the following desired analyses. During segmentation, a label is assigned to every pixel in the image, so that pixels having the same label share certain characteristics. Consequently, the result of segmentation is the identification of a set of "segments", or "super-pixels", covering the whole image.

In general, starting from an RGB image having $N_x \times N_y$ pixels and represented by the three-channel brightness function $b_c : I \to B$, where $I = [1, N_x] \times [1, N_y] \subset \mathrm{N}^2$ and $B = [0,255]^3 \subset \mathrm{N}^3$, a grey-tone map can be obtained as,

$$\boldsymbol{\beta}(i, j) = \frac{1}{3} \sum_{c=1}^{3} b_c(i, j) \tag{1}$$

where the index *c* corresponds to the three RGB channels. The integer indices *i* and *j* cover the whole *x* and *y* extension of the image frame.

Afterwards, a method for the thresholding of the brightness map must be defined. The thresholding is carried out using a clip-level (the threshold value τ), according to which a grey-scale image is turned into a binary image **T***(i,j)*,

$$\begin{aligned} \boldsymbol{\beta}(i, j) \le \tau \to \mathbf{T}(i, j) = 0 \text{ black} \\ \boldsymbol{\beta}(i, j) > \tau \to \mathbf{T}(i, j) = 255 \text{ white} \end{aligned} \tag{2}$$

In the present work, a visual choice of thresholding has been made, but automation of the process would be possible.

The binary image that is eventually obtained contains a matrix of pixels, defining black and white domains. Starting from the left/upper corner of this matrix, and moving along the rows and columns of the matrix, it is therefore possible to characterize each black pixel by a sequential integer number *k*.

Some of these labels k will then identify the domains, or super-pixels, to which the pixels belong (see Figure 1).

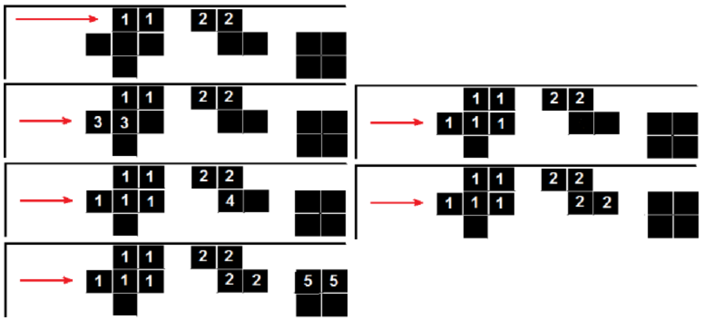

Fig. 1. The white pixels share the same label, k=0. Each black pixel has a label k≠0, with an increasing value as we move from left to right on the rows. However, the final value is fixed according to the labels of the black pixels above and on the left of the considered pixel. From (Arsiccio et al., 2019). Reprinted by permission of the publisher (Taylor & Francis Ltd, http://www.tandfonline.com).

The labels of the nearest black pixels above (subscript A) and on the left (subscript L) determine the label k of the black pixel being considered, based on the equation $k = \min(k_A, k_L)$. Finally, the pixels with the largest labels in a given domain change their labels to the smallest value in the same domain (see Figure 1). A Fortran 77 code was used in this work to perform these operations, according to the following algorithm,

$$\begin{aligned} &\mathbf{T}(i,j) = 255 \rightarrow \mathbf{K}(i,j) = 0 \\ &\mathbf{T}(i,j) = 0 \rightarrow \mathbf{K}(i,j) = k, k \neq 0, k \subset N \end{aligned} \quad (3)$$

A new representation can be eventually proposed, where a different colour tone is associated to each label and, therefore, to each super-pixel.

This new representation is suitable for performing some calculations. For instance, the number of pixels in each super-pixel can be computed, making it possible to compute the size distribution of the different domains.

In Figure 2, for instance, two areas A and B of the painting under investigation were chosen to provide some examples of the proposed approach. Region B required a pre-processing to enhance the contrast. This pre-processing was carried out using the Retinex tool of GIMP, the GNU image processing software. The Retinex tool makes it possible to increase the contrast, while keeping the details of the texture. The segmentation that we have described above makes it possible to label each domain of the craquelure with a different colour. For each domain, corresponding to a given colour, it is then possible to compute the size in pixels, that is, the number of pixels contained in the domain, and the centre of mass of the domain. In the lowest panel of Figure 2, the resulting size distribution is shown, as number of pixels per domain. The segmentation approach allowed the identification of substantially different cracks patterns for the two regions, as clearly emerges from the corresponding size distributions.

The proposed approach is quantitative. As further development, the centre of mass of each domain in the image frame could be identified. Knowing the coordinates x_{cm} and y_{cm} of this centre, it would be possible to measure its distance from the boundary of the domain, along any direction, as proposed by Sparavigna (2017). Therefore, the shape of each domain could be described in detail. However, a different method, based on edge detection, would also be possible. In this case, each edge between different craquelure domains could be detected and investigated.

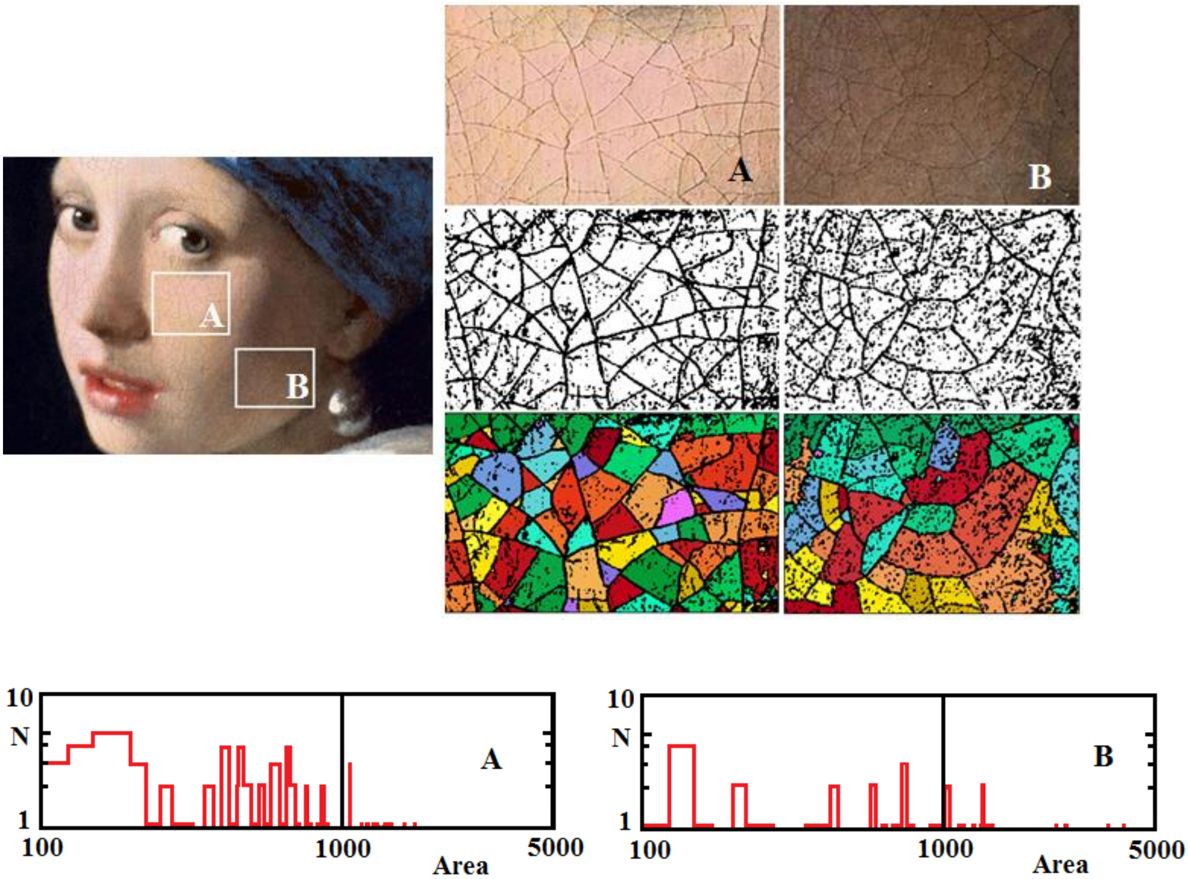

Fig. 2. Two areas A and B of Vermeer's painting "Girl with a pearl earring" (from https://it.wikipedia.org/wiki/Jan_Vermeer#/media/File:Girl_with_a_Pearl_Earring.jpg) have been selected. The corresponding images have been binarized (black and white) and segmented (coloured domains). Each domain has been labelled by a different colour and measured. In the lower part of the image, the resulting size distribution is shown, as number of pixels per domain.

The edges orientation may afterwards be investigated. Supposing to use the horizontal axis as the axis of a polar frame, the angle that each edge forms with the reference axis can be measured. In order to automate the analysis, the edges of the domains need to be further enhanced and the domains with a size less than a fixed threshold must be removed. In the case of the craquelure shown in panel A of Figure 2, a 10-pixel threshold was chosen, and the results obtained are displayed in Figure 3. The panel on the left is the output of a filtering process, that was performed to enlarge the edges and reduce the number of white pixels. The applied filter is the GNU Image Manipulation Program (GIMP) Dilate. Afterwards, the crossing points were removed as shown in the right panel of the Figure.

To measure the orientation of the edges, the method proposed in Sparavigna (2019) for rod-like objects was used. The black and white image, as given in the right panel of Figure 3, was segmented and the elements I_{xx}, I_{yy} and I_{xy} of a matrix of inertia were evaluated for each segment,

$$I_{xx} = \sum_i (y_i - y_{cm})^2, I_{yy} = \sum_i (x_i - x_{cm})^2, I_{xy} = I_{yx} = -\sum_i (x_i - x_{cm})(y_i - y_{cm}) \quad (4)$$

where index i runs over the total number N of pixels in the domain, while x_i and y_i are the coordinates of the i-th pixel.

Two lengths $L_{xx} = \sqrt{I_{xx}/N}$, $L_{yy} = \sqrt{I_{yy}/N}$ were then associated to the diagonal elements of the matrix. Their ratio corresponds to the arctangent of an angle, between 0 and 90 degrees $\theta = \tan^{-1}(L_{yy}/L_{xx})$; the element outside the diagonal is related to the sign of this angle $\theta = \frac{I_{xy}}{|I_{xy}|}\tan^{-1}(L_{yy}/L_{xx})$, and hence to the orientation of the segmented rod-like object. Using this procedure, the distribution of the edge orientation for the image in the right panel of Figure 3 could be obtained, as shown in Figure 4.

Fig. 3. Panel A in Figure 2 as pre-processed for the analyses of the crack orientation. Edges are enhanced by means of the Dilate GIMP filter (left panel) and then separated by removing the crossing points (right panel).

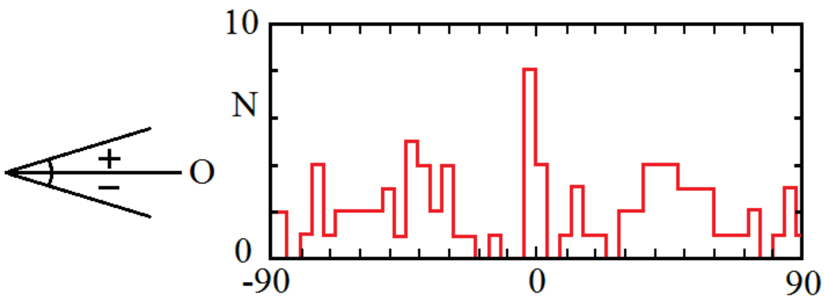

Fig. 4. Distribution of the edge orientation as function of the angle formed with the horizontal axis, for panel A in Figure 2.

Finally, a further example is considered in Figure 5, where *Portrait of a young woman*, painted by Petrus Christus around 1470, is shown. The region of the painting surrounding the nose of the woman is considered. Using the retinex filter, the craquelure structure can be enhanced, as evident in the lower panel on the right of the Figure. Applying the same approach as in Figure 3, that is, analysing each edge of the craquelure pattern, the distribution of the crack orientation can eventually be obtained (Figure 6).

As we can see comparing Figures 4 and 6, the distribution of the edge orientation is different. This is expected according to the work by Bucklow (Bucklow, 1997b; Bucklow, 1999), where it was shown that the craquelure pattern changes with painting style, for instance French, Flemish, Dutch and Italian, therefore being an indicator of authorship.

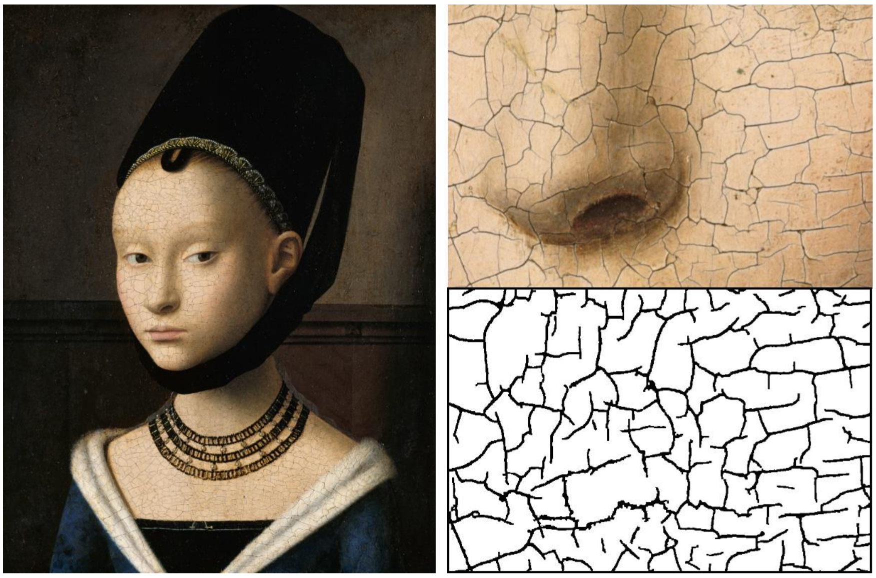

Fig. 5. The Portrait of a young woman, Petrus Christus, Gemäldegalerie, Berlin (from https://en.wikipedia.org/wiki/Portrait_of_a_Young_Girl_(Christus)#/media/File:Petrus_Christus_-_Portrait_of_a_Young_Woman_-_Google_Art_Project.jpg). The area under investigation is shown in the upper panel on the right, and the corresponding craquelure is displayed in the lower panel.

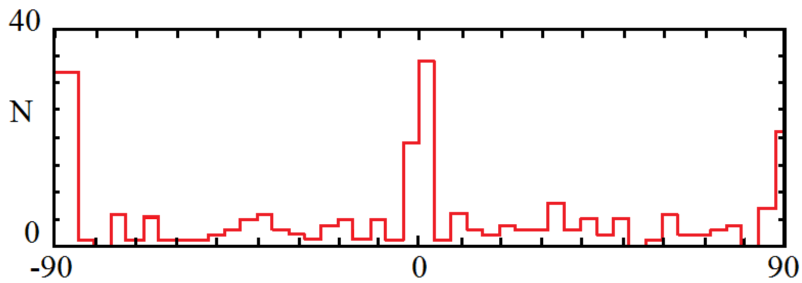

Fig. 6. Distribution of the edge orientation as function of the angle formed with the horizontal axis, for the craquelure in Figure 5.

4. Conclusions

The drying (together with ageing) process impacts on the visual characteristics of paintings, but the results of these physical processes and of the artist creativity may be used in the perspective of giving new tools for analysis, valorisation and protection of the Cultural Heritage.

An image analysis approach has been proposed in the present work for the analysis of the craquelure domains in paintings. Using *Girl with a pearl earring* by Vermeer as model system, we showed that the proposed technique allows quantification of the size distribution of the cracks pattern. At the same time, using the painting by Vermeer and the *Portrait of a young woman* by Petrus Christus, we showed that the distribution of the crack orientation can also be determined. The knowledge of the size distribution of the craquelure domains and of the edge orientation allows an exhaustive quantification of the cracks pattern.

This information is of great interest to art experts, as it could help with the task of artist attribution and identification of forged artworks. Further studies will be made to improve the method, with the aim to make it a reliable and sensitive approach for the analysis of art pieces.

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