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On the power spectral density applied to the analysis of old canvases

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ABSTRACT

A routine task for art historians is painting diagnostics, such as dating or attribution. Signal processing of the X-ray image of a canvas painting provides useful information about its fabric. However, previous methods may fail when very old and deteriorated artworks or canvases of small size are studied. We present a new framework to analyze and further characterize the paintings from their radiographs. First, we start from a general analysis of lattices and provide new unifying results about the theoretical spectra of weaves. Then, we use these results to infer the main structure of the fabric, like the type of weave and the thread densities. We propose a practical estimation of these theoretical results from paintings with the averaged power spectral density (PSD), which provides a more robust tool. Furthermore, we found that the PSD provides a characterization of the whole cloth. We search and discuss some distinctive features we may find in this characterization. We apply these results to several masterpieces of the 17th and 18th centuries from the Museo Nacional del Prado to show that this approach yields accurate results in thread counting and is very useful for paintings comparison, even in situations where previous methods fail.

1. Introduction

Lately, there has been a wider interest on acquiring and processing artwork image data, thanks to the greater computing capabilities and digital storage. Advances in technology for image data acquisition and the wide range of imaging modalities currently available have made that museums assemble vast digital libraries of images of their collections, not only for archiving but also for analyzing their pieces of art [1]. Moreover, an increasing number of scientists have approached this field to apply digital image processing and data analysis techniques. These techniques have proven useful for many crucial issues in artwork diagnostics, such as assessment of the conservation state, knowledge of the realization techniques, evaluation of the historical period and attribution of the painting, and the possibility of keeping trace of any modification of the artwork shape [2]. Therefore, interdisciplinary interaction between art historians and signal processing researchers is of greatest interest to elaborate image analysis tools that help to make reproducible automatic procedures and diagnostics on paintings [3–6].

Traditionally, one of the most common canvas analyses is based on X-ray images of paintings. The canvas fabric is initially coated with a priming substance, which generally contains lead. This ground layer varies in thickness according to the weave threads of the canvas, affecting the X-ray absorption. This makes the fabric pattern visible in radiographies of the painting [7]. Until a few years ago, art experts used X-rays to analyze the composition of the visible and hidden paint layers on the canvas, to assess the structural condition of paintings or for conservation purposes. More recently, however, researchers have realized that the threads pattern may carry also important art-historical information [8].

The first pattern measurement to be used was the thread densities [9,10]. They can be arranged in the form of a density map, i.e., a two-dimensional array in which every row and column indicates the position on the vertical and horizontal axes of the canvas where the thread counting has been performed. Each entry of the matrix, usually depicted as an image with an associated color map, corresponds to the local thread density at the corresponding position in the original X-ray image. The thread densities are not specific to each artwork, but characterize the roll from which the canvas was cut. Specifically, the weaving process itself results in the thread densities showing striped arrangements, in the direction of both warp (corresponding to the length of the roll placed on the loom) and weft (corresponding to the width of the roll) [11]. Thus, matching of the densities maps of two paintings makes it possible to identify aligned pieces of canvas from the same original roll, which is a strong indication that these two paintings were made in both the same workshop and period. Further researches include threads angles [12,13], since they provide information about

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the phenomenon known as cusping, i.e., the displacement of the threads from a rectilinear pattern caused by attaching the canvas to a stretcher with tacks before priming the surface. More recently, more complicated weave patterns, like twills, have also been studied [14].

Most of previous studies have used two-dimensional discrete Fourier transforms (2-D DFTs) to develop computer-assisted tools for analyzing canvas weaves [9–18]. To summarize, the locations of spectral peaks on the horizontal and vertical axes of the 2-D DFT correspond to the thread densities. In addition, thread tilting from alignment with the axes of the canvas leads to a corresponding rotation of the spectrum. This procedure is performed on a small piece of fabric and repeated until the whole canvas is analyzed, giving maps of local densities and angles for the entire painting. Other recent research has explored techniques that are more sophisticated, such as autocorrelation and pattern recognition algorithms [19], synchrosqueezed transforms [7] or machine learning models [8]. They try to develop maps of thread patterns that are more detailed. Once the paintings thread maps have been created, we need a method to relate them and help to match paintings. The customary way to do that makes use of two steps. The first one is a comparison of some weave feature, such as the mode or mean of the frequencies of the threads [20]. Provided a similarity is found, the second step is to compare some appropriate features, such as the averaged densities [13], average density deviations [14] or the histograms of the cross-correlations [18].

All these methods have proven successful when applied to artworks of Vincent van Gogh, Johannes Vermeer or Diego Velázquez. Nevertheless, they show a poor performance when applied to some other paintings, especially to deteriorated ones. In these ones, fabric is much more irregular and usually exhibits larger twisting due to frames or seams. Also, part of the original canvas may be missing or primer can be thick enough to not let some threads be distinguishable in the X-ray. Therefore, a mere thread count may not provide any consistent result. In addition, thread density maps are useful when matching two adjacent canvases but much less appropriate when they come from slices apart in their roll. In particular, if we are dealing with small canvases the probability that they are contiguous pieces of fabric is fewer.

In this paper, we propose a different approach. Rather than finding an extremely exhaustive thread map, we search for a pattern that characterizes the whole roll and even the production process. This pattern allows to deal with fabrics with more sophisticated configurations. Other research has addressed the issue of canvas characterization and comparison [21], by using texture recognition and machine learning.

To characterize the painting, we roughly follow the model proposed in [22], which uses Fourier analysis like the aforementioned papers but from a different point of view. Instead of locating the greatest spectral peak on the horizontal and vertical axes, a wider collection of maxima is found. In this paper we also do that, but the position of these maxima is selected according to a thorough theoretical study that we derive from lattices and apply to weave patterns. Our first contribution is a proof that a lattice and its reciprocal are merely a rotation of 90° one from the other and that their areas are inverses. With this result, we derive the whole theory of fundamental triangles in the space and frequency domains, which are of crucial importance for our proposed thread counting method.

In addition, instead of divide the canvas into small pieces and perform the analysis for each one independently, we average the maxima for the entire painting. Furthermore, we propose to calculate an estimation of the power spectral density (PSD) instead of simply perform a DFT, since it is more appropriate to deal with random signals [23]. More precisely, an averaged periodogram proves a suitable choice. We find that the position of the averaged maxima of the spectral density follows a pattern that is strictly related to the fabric structure. Accordingly, we extract a set of parameters who completely characterize the weave. This characterisation remains stable, provided that the manufacturing technique does not change. This novel method exhibits promising results in paintings by Goya, Velázquez or Rivera.

From the above discussion, the contribution of this paper is threefold. The first one is of theoretical kind. We prove that the Fourier transform of a 2-dimensional periodic structure, such a weave, has a triangular shaped repetitive pattern and we fully characterize it. Up to our knowledge, there is only some rough, not rigorous results about this issue in the literature [22]. The two other contributions of our paper are of practical nature. On the one hand, our PSD analysis will serve as a counting technique, providing reliable results even in situations where the standard DFT-based count fails. On the other hand, our method yields some features that help us to characterize the canvases so that an accurate comparison between them is possible, with better results than previous techniques. Actually, the curators at the Museo Nacional del Prado found these features useful and considered the PSD images of great interest for their studies.

2. Standard DFT method for thread counting

The simplest yet most widely used method for canvas analysis is thread counting. The vertical threads mounted in a loom are called the warp while the horizontal strands are known as the weft. However, the warp and the weft may be associated to either the vertical or the horizontal fibers in the canvas because the artist places the piece of weave on the stretcher in any position.

Thread count data is commonly employed as evidence for dating and attribution of paintings [10]. The horizontal and vertical thread count statistics provide information about the roll from which it was cut. If the statistics of two canvases disagree (even when allowing for rotation), then they most likely have a different origin, whereas if they agree to some tolerance level they could have been cut from the same roll. This helps the art historian to conclude whether two paintings are contemporary with each other [13].

Manual thread counting is a very tedious process. In addition, the strands do not run in precise straight lines and this makes a human measurement difficult. By using signal processing techniques, the hope is to develop algorithms that simplify and enhance manual measurements, allowing a more detailed analysis of paintings.

The standard method to perform an automatic counting lies on the hypothesis that the threads follow an approximately periodic pattern. This pattern may be supposed to follow a sinusoidal model [9,10] or other shapes like rectangles [14]. In any case, it is assumed that both horizontal and vertical strands have a fundamental frequency of repetition. For that reason, the core of the standard thread counting algorithm is a discrete Fourier transform (DFT).

More precisely, the X-ray image of the canvas is windowed into small swatches (squares of side about 1 cm) and its two-dimensional DFT is computed. To obtain spectral details, the Fourier transform size is much larger than the windowed section. Ignoring the lowest spectral components, which are due to the prevalent grey-colored tones in the painting, several dominant peaks appears in the DFT. However, thanks to the real nature of numbers representing the image, the spectrum is symmetrical. Then, only half of these peaks are distinct. In particular, for a plain-weave the dominant peak in the x-axis (vertical threads frequency) corresponds to the vertical threads counting while the main peak in the y-axis (horizontal threads frequency) belongs to the horizontal threads counting.