Digital Analysis of Papers for the Authentication and Dating of Art

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The digital analysis of the paper structure can play a major role in the authentication, dating and attribution of art which is very important for art historians. In this paper, a digital analysis method is introduced for the extraction of structural features from machine-made papers. To generate digital images from these papers, we use a transmitted light scanning method; since it is a feasible and inexpensive method as compared to other methods such as e.g. x-ray imaging. In machine-made papers, two types of structure on the surface of a paper can be found: regular (periodic) and irregular (non-periodic). In this paper, we show that the power spectrum in Fourier domain is an adequate way to extract structural features and isolate regular and irregular structures. The structural features can be further used for authentication and dating of machine-made papers. Our method is a simple and inexpensive method with respect to costs and computational efficiency and it is invariant to direction in which the paper is scanned.

Digital Analysis, Machine-made Paper, Feature Extraction, Fourier Domain, Authentication and Dating of Art

1. INTRODUCTION

Although the basic process of making paper has not changed from 2000 years ago, the invention of the paper machine at the beginning of 19th century has improved the structure and the quality of the papers. Considering the history of paper manufacturing, we can classify the papers into two groups of hand-made and machine-made papers.

Hand-made papers were made in paper-mills using a rectangular sieve consisting of a frame and a bottom made of a wire mesh. From the thirteenth century on nearly all European paper-makers characterized their production by means of watermarks. These watermarks were made by wire figures, which were fixed on the wire mesh. The molds were dipped into tubs with liquid pulp. When lifting them out, the liquid drained out through the wire mesh and the fibers became interwoven to a sheet of paper. The pattern of the mesh with the watermark wire-figure attached on it was imprinted in the paper (see Karnaukhov et al. (2001), Rückert et al. (2009)). Laid lines and chain lines are two other important features in the wire pattern. Laid lines are reproductions of the wires in the sieve that should stop the paper pulp and let water through. These lines appear in paper as a high frequent and regular straight line pattern. Chain lines are nearly straight wires perpendicular to the laid lines in order to strengthen the sieve (see Staalduinen et al. (2006a)). Figure 1a shows watermark, laid lines and chain lines in a hand-made paper.

The invention of the paper machine at the beginning of the 19th century did increase mechanization of paper-making further and therefore did increase production capacity. The Frenchman Nicolas-Louis Robert is considered as the inventor of the first Fourdrinier wire paper machine. He constructed a prototype machine between 1796 and 1798. Based on the Roberts idea, Bryan Donkin in England succeeded to set in motion a paper machine in 1808 (see Rückert et al. (2009)). The paper machines used nowadays still have a similar construction, so that those machines are still often called Foudrinier machines. At the end of the 20th century, the technology behind the paper machine developed further, so that the production speed and the quality of the produced paper increased. A modern paper mill is divided into several sections, roughly corresponding to the processes involved in making hand-made paper. Pulp is refined and mixed in water with other additives to make a pulp slurry. The headbox of the paper-machine (Fourdrinier machine) distributes the slurry onto a continuously moving screen by which water drains from the slurry (by gravity or under vacuum). The wet paper sheet goes through presses and driers and is finally rolled into large rolls, often weighting several tons. Another type of paper-machine makes use of a cylinder mold that rotates while partially immersed in a tub of diluted pulp. The pulp is picked up by the wire and covers the mold as it rises out of the vat. A couch roller is pressed against the mold to smooth out the pulp, and picks the wet sheet off of the mold.

Digital paper analysis refers to the digital image processing methods applied on paper images with the aim of extracting structural features of the paper. It is important due of the broad range of its applications. Applications of digital paper analysis can be authentication and dating of art works such as etchings, aquarelles and drawings, as well as of manuscripts. There are many art works from which the painter or the date is not known. On the other hand, there are also many fake art works. Digital paper analysis can answer questions about the history of an art work and its validation by extracting the structural features of the paper and comparing it with the features from already known papers. Paper quality measurement is another application of digital paper analysis. The aspects for paper surface quality are the level of uniformity of fibre distribution across the paper surface. Using image processing methods, unwanted marks or fibre flocks on the paper surface can be identified and studied. This allows to find the source of these causes. Forensics identification can be also considered as an application of digital analysis of papers. In this application, papers as the physical substrate of documents are analyzed and studied. The paper identification helps to find the source and authority of documents.

Our aim in this research is to develop a digital analysis method to study and extract structural features in machine-made papers for authentication and dating of papers. Several mechanisms in spatial and frequency domains have been proposed to extract these structural features of paper images. In this paper, we are looking for simple, feasible, and fast methods of generating and analyzing digital images. This paper is structured as follows. In Section 2, related research on digital paper analysis is studied. Section 3 explains different methods for generating digital images. In Section 4, we discuss an image processing methodology to detect a paper structure and study image features in Fourier domain. Section 5 explains how to extract the image features related to the paper structure. Section 6 studies feature comparison with proposing a method which is invariant to the orientation of the papers. Finally, conclusions are given in Section 7.

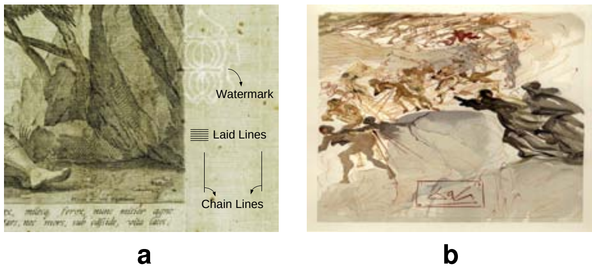

Figure 1: *Prints on a hand-made paper from 1594 (a), and on a machine-made paper from 1960th (b).*

2. RELATED RESEARCH

There are different applications of digital paper analysis in literature. Some works are done on authenticity determination and dating of art works, such as paintings and etchings. Watermarks, chain lines, and laid lines are the most important tool for dating and authentication of the hand-made papers. Several works have been done on detecting watermarks from original digital images, finding identical watermarks, and determining the identity of watermarks. Wenger et al. (2001) presented an integrated software system developed for storage, retrieval, manipulation, digital processing, and identification of watermarks in hand-made manuscripts. Staalduinen et al. (2006a) proposed a paper retrieval system based on specific paper features with respect to chain and laid lines. Otal et al. (2008) proposed an approach for watermark detection in X-ray images. They proposed a framework to detect watermarks by exploiting four line properties: line profile, line contrast, spatial connectivity and line length. Rauber et al. (1996) addressed retrieval and matching of watermarks based on textual and morphological criteria.

Besides authentication and dating of papers, digital paper analysis has been also used for paper quality measurements. I'Anson (1995) showed a method using Fast Fourier Transform (FFT) for detecting the presence of periodic marks in papers, enhancing their visibility and unambiguously identifying their source (see also Praast et al. (1986)). Hladnik et al. (2009) presented a method to investigate and quantify various print quality-related phenomena. In their work, they addressed identification of two types of patterns in a paper, periodic and non-periodic, as well as eliminating moire patterns using FFT. Reis and Bauer (2009) addressed an approach for evaluating and real time monitoring of paper formation using images acquired with a specific sensor. They applied wavelet texture analysis to raw images in order to compute a wavelet signature for each image on the basis of which their discrimination according to the formation quality level, is made.

Regarding analysis of machine-made papers for forensic applications, some methods are developed which are based on feature extraction in image transform domain. Miyata et al. (2002) proposed a non-destructive method for discriminating between different types of paper using Fourier transformation, and cross-correlation matching. Berger (2009) presented a method for the comparison of paper structure using light transmission images and frequency analysis. The method proposed by Berger (2009) computes the correlation of two images in different directions and also in both front and back sides images in order to find the similarity between them. For large databases where comparison should be done between large number of images, simpler and faster methods are required. In this work, we are looking for such mechanisms.

3. DIGITAL IMAGE GENERATION

For digital paper analysis, first we need to generate digital images and then to extract image features by applying digital image processing methods. Digital images of paper can be created by different methods to make the paper structure visible.

3.1. X-ray imaging

Three different X-ray technologies for paper structure imaging exist. These technologies are: beta radiography, electron radiography and soft-X-ray radiography (see Rückert et al. (2009)). The X-ray image generation technique consists of two steps. First the X-ray apparatus itself radiates low energy X-ray through the paper to a phosphor plate. The next step is reading out this phosphor plate by a laser reader. The generated images are directly available in digital format and do not require any post-processing. X-ray imaging provides in general good quality images, but it is quite a complex and expensive method (see Staalduinen et al. (2006b)).

3.2. Backlight imaging

In backlight imaging, a paper is put on a backlight foil and with a digital camera a digital backlight image is obtained. This image shows partially the paper structure as well as the print or drawing itself. Then a picture of the original print is made. By subtracting both images and by application of appropriate image enhancement techniques, a new image can be obtained which mainly shows the paper structure. Backlight imaging is an easy and cheap method, but the quality depends strongly on the content of the print or picture itself(see Staalduinen et al. (2006b)).

3.3. Transmitted light scanning

In a transmitted light scanner, light is transmitted through the paper, the light is catched and bordered to an image. For that purpose, it has a built-in light source, in general LED lights. The light source is usually connected to a ballast or other voltage regulator to ensure consistency of light over the scan pass. The sensor in the scanner is the device that reads the light reflected from, in this case, the paper. Most scanners use a charge coupled device (CCD) sensor array, which contains light-sensitive diodes that convert analog light waves into a digital signal. Both the light and sensor are mounted on carriers that move synchronously, at a constant rate, under and above the paper. Once the paper has been placed on the glass, the carriage moves to a calibration strip inside the scanner case. The sensor takes a series of measurements to calibrate color balance, contrast and brightness. Once calibrated, it moves to the start of the area of the paper to be scanned and scans the selected area by taking a series of slices of the image. Circuitry in the scanner then assembles these slices sequentially to create the whole image of the paper for transferring to a computer. The advantage of this method is that the scanners are inexpensive, readily available, and provide spatial alignments.

Among the three mentioned methods of generating digital images, we select transmitted light image since it is more feasible and efficient than the other two methods. It is not as expensive as X-ray and it is therefore feasible in any library or museum. Moreover, transmitted light images provide better quality images than backlight images.

After generating digital image by a transmitted light scanner, we need to select a suitable image processing mechanism in order to extract structural features of the paper. The prints on a paper is an issue that has to taken into account. They should be eliminated from the digital image since they can reduce the accuracy of extracted features. Processing an image with no prints can be obtained by selecting a part of the paper where there is no print. For instance, Figure 1b shows a print on a machine-made paper. The margins of the paper which has no print can be used for digital analysis. Another method is eliminating prints using a subtraction method. In this work, we consider pieces of papers with no or few prints on them.

4. IMAGE PROCESSING METHODOLOGY

In this section, an image processing method to extract the structural features of a paper is introduced. The structure of papers varies from hand-made to machine-made papers. For authentication and dating of artworks on hand-made papers, art historians prefer chain lines, laid lines, and if present watermarks, as the features since they

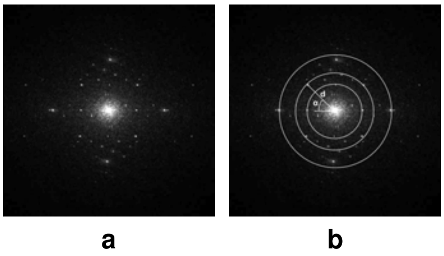

Figure 2: Power spectrum of a sample paper image (a), relation between wavelengths of the peaks and their distances from the center (b).

offer the best degree of certainty. The first two are not present in machine-made papers. Our aim in this research is digital analysis of machine-made papers. Therefore, we focus on the structure of these papers. Due to different stages in paper-making process, two types of structures can be found in the machine-made papers:

- **Regular structure**: At the various steps of the paper manufacturing process, when the paper is formed, pressed, and dried; the paper comes into direct contact with parts of machine, like the screen, the felt, etc. Depending on the paper grade and exerted pressure, the surface structure of the fabric material can leave a periodic, regular marking in the paper surface. Regular structure can be used as features for paper identification as well as for quality measurements for fabrics.
- **Irregular structure**: In addition to regular structure, a paper sheet also has a non-uniform, irregular structure of fibres and other paper ingredients resulting in its cloudy visual appearance, known as (uneven) formation or cloudiness. The irregular structure is due to the quasi-random process of cellulose fibre distribution taking place during the paper forming stage (see Hladnik et al. (2009)). Irregular structure can be used especially for paper quality measurements.

The issue is to separate the regular and irregular structures. We consider irregular structure as noise because they are random. They can not be used for identification of a paper. Here, we focus on detecting regular structure. Evaluating the power spectrum in Fourier domain is an excellent way to detect periodic structure as will be shown in this paper. In the following section, feature extraction in the Fourier transform domain is studied.

4.1. Image Features in Fourier Domain

The power spectrum is a representation of the magnitude of the various frequency components of a 2D image that has been transformed from the spatial domain into the frequency domain. Different frequencies in the power spectrum are located at different distances and directions from the origin (the origin is customarily located in the center of the power spectrum). Higher frequency components of the image are located at greater distances from the origin.

Figure 2a shows the power spectrum of a sample paper image with size of 1200*1200 pixels and with resolution 600 dpi (dots per inch). The power at each location in the power spectrum is an indication of the frequency and orientation of a particular feature in the image. Different directions from the origin represent different orientations of features in the image. The issue is to extract frequency components related to these structural features. It is assumed that the wavelengths and orientation of the points with high amplitude (peaks) in the image power spectrum corresponds to the periodicity and direction of the wires in a paper. The location of a peak in the power spectrum indicates its wavelength and the direction of its repetition axis. The distance between a peak and the center of power spectrum is inversely proportional to its wavelength. Assume an image with the size of $N * N$ pixels and a resolution of R dpi. If the distance between a peak and the center of power spectrum is d pixels, then the wavelength of the peak in millimeter is calculated by λ:

$$\lambda = 25.4/R * N/d \quad (1)$$

In Equation 1, the value 25.4 is used to convert the wavelength from Inch to millimeter. The minimum wavelength is obtained when the distance d has its maximum value and the maximum wavelength is obtained when the distance d has its minimum value. As Figure 2b shows, the peaks located on the circles have the same distance to the center and therefore, they have the same wavelength. The peaks on outer circles have larger distance from the center of power spectrum and therefore, they have smaller wavelengths. In the same way, the peaks on inner circles have higher wavelengths. Ignoring the center of power spectrum, the maximum wavelength holds for $d = 1$ and the minimum wavelength is obtained when $d = N/\sqrt{2}$. Therefore:

$$\sqrt{2} * 25.4/R \leq \lambda \leq 25.4 * N/R \quad (2)$$

For instance, if we consider an image with the resolution $R = 600dpi$ and size $1200 * 1200$ pixels, then the minimum wavelength is $0.059mm$ while the maximum wavelength is $50.8mm$.

The angle of a peak shows its orientation. If we consider (x_c, y_c) and (x_p, y_p) as the coordinates of the center of the power spectrum and a peak p, respectively, then the angle of the peak p is

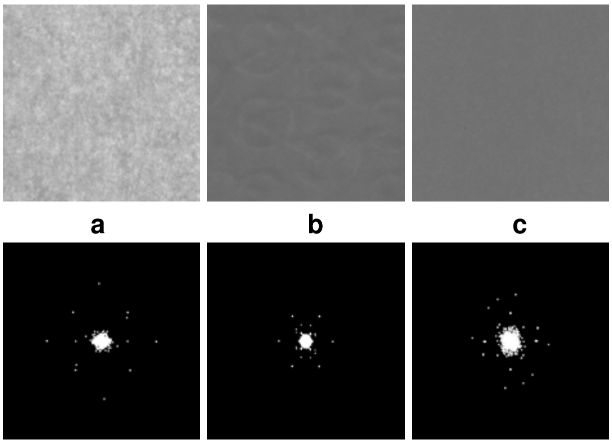

__Figure 3:__ Three sample papers from three sets of 8 similar papers (a,b,c), identical peaks in each set (d,e,f).

calculated as:

$$\alpha = \arctan((xc - xp)/(yc - yp)) \quad (3)$$

We consider the wavelengths and angles of the peaks as the two features for paper identifications. The angle of a peak is related to the direction of periodic structure and the wavelength shows periodicity of the periodic structure. To extract optimal features, we need to explore which peaks are the most relevant to the regular (periodic) structure. In other words, we should find the wavelengths which are related to such structure. In the following section, the wavelength range in which the regular structure is located, is studied.

4.2. Wavelength range related to regular structure

As mentioned in the previous section, the location of peaks in the power spectrum represents the periodicity and direction of the regular structure. The regular structure is supposed to be identical for similar papers. Similar papers are considered to be from the same factory, the same machine and the same time period. Assuming that the peaks related to the regular structure are located at identical positions (with identical wavelengths) in the power spectrum of similar images, we have performed some experiments to explore the wavelength range related to regular structure. In these experiments, the identical peaks between similar papers and between non-similar papers are extracted.

For our experiments, we selected 24 papers; three sets, each containing 8 similar papers. Figures 3a, 3b, and 3c show three paper samples from each set. The papers in the first set (Figure 3a) are from 2009; the second set (Figure 3b) are from 1959; and the the third set (Figure 3c) are from 2000. The

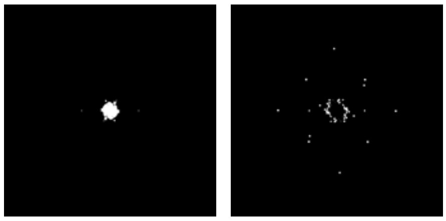

__Figure 4:__ Identical peaks in non-similar papers (a), unique identical peaks in a set of 8 similar papers (b).

papers are scanned with a resolution of 600 dpi. The resolution 600 dpi is selected since it is feasible with a normal scanner. The images with size of 1200*1200 pixels are considered for digital analysis. We attempt to select the images with smallest possible size since the smaller the size of the image, the more easier is to find a piece of paper without print. Thus the maximum and minimum wavelengths are $50.8mm$ and $0.059mm$ respectively.

The power spectrum of each image is computed and from each power spectrum, 700 top peaks are extracted. A dilation filter with the size $5 * 5$ is applied in order to enlarge the peaks. After extracting the peaks, the identical peaks in the similar papers in the three sets are computed. Figures 3d, 3e, and 3f depict binary images that show the identical peaks between 8 similar papers in each set. By comparing the three figures, we can observe that peaks with higher wavelengths (peaks close to the center of power spectrum) are common in the three non-similar sets. By applying the AND operation between the binary images in Figures 3d, 3e, and 3f, we obtain the similar peaks in non-similar papers. Figure 4a shows this similarity. Subtracting any of the images in Figures 3d, 3e, or 3f, from the image in Figure 4a shows the unique identical peaks of similar papers in the corresponding set. For instance, Figure 4b shows the unique identical peaks in the first set. By calculating the wavelengths of the peaks, we observe that the most unique identical peaks in similar papers have wavelengths smaller than $0.8mm$. These peaks can identify the unique features of the paper. The most identical peaks in non-similar papers have wavelengths larger than $0.8mm$. These peaks may specify the image features that are common between non-similar papers.

5. FEATURE EXTRACTION

We consider wavelength and orientation of peaks in the power spectrum as the features to determine the regular structure in a paper. The wavelength of peaks indicate the periodicity of regular wire structure and the orientation of peaks determine the

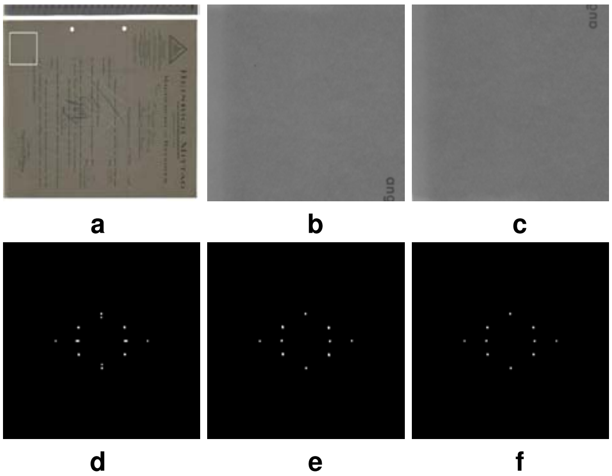

Figure 5: *A sample paper (a), front side and back side of a piece of the paper (b,c), 50 top peaks with the wavelengths smaller than $0.8mm$ extracted from the power spectrum of front and back side images (d,e), feature peaks (f).*

direction of the wires. For instance, the horizontal peaks are indicators of vertical patterns. However, not all peaks extracted from the power spectrum are relevant to the regular structure and some may be related to irregular formation on the surface of a paper or noise. Therefore, to have more reliable features, we extract the peaks from the images provided by scanning both sides of a paper. The extracted peaks related to the paper structure are supposed to be identical for the front and back side images. Therefore, we select the identical peaks from both images. We call these peaks as the *'feature peaks'* that can be used for a paper identification.

Figure 5a shows a paper with the size of 5493*7200 pixels dating from 1939. To extract features of this paper, we select a small piece of this paper with no print (e.g. the one shown with a white rectangle in Figure 5a). Figures 5b and 5c show the front and back sides of the piece of the paper with the size of 1200*1200 pixels. We extract the 50 top peaks with the wavelengths smaller than $0.8mm$ from the images of front and back sides. A dilation filter with the size $5 * 5$ is applied to enlarge the peaks. Figures 5d and 5e show these peaks. After extracting the peaks from both images, the so-called feature peaks are obtained by computing the common peaks extracted from the two images. Figure 5f depicts the feature peaks of this paper.

To study the feature peaks in similar and non-similar papers, we choose two similar papers (shown in Figure 6a_1 and 6a_2) and a different paper which is not similar to the first two (shown in Figures 6a_3). Two images of each paper are provided by scanning both sides of the paper in the resolution 600dpi and the size of 1200*1200 pixels. The power spectrum of each image is computed and 50 top peaks with the wavelengths smaller than $0.8mm$ are extracted from each image. In Figure 6, the binary images with the label b and c show the extracted peaks from the power spectrums of front and back sides of each paper respectively. The identical peaks are computed between the peaks extracted from images of front and back sides of the paper. These peaks present the feature peaks. Images with the label d in Figure 6 depict the feature peaks for each paper.

We expect the feature peaks to be identical in the similar papers. Figures 7a show the identical peaks of the two similar papers presented in Figures 6a_1 and 6a_2. The identical peaks are obtained by applying the AND operation on the binary images of feature peaks. It should be noticed that we assume that the front side and back side of all papers are scanned in the same orientation. Therefore, the orientation (angles) of the peaks is identical in the similar papers. We also compute the similarity between two non-similar papers in Figures 6a_1 and 6a_3 . This similarity is shown in Figure 7b. As it can be observed from the Figure 7b, the identical peaks between two non-similar papers are only two horizontal peaks. These peaks can represent the structure which is common in the two papers.

The similarity between any two papers can be computed by comparing the feature peaks of the papers. In the other words, the similarity is measured by the number of peaks with identical wavelengths and angles in the two feature peaks images. To compute the similarity between two images of feature peaks, only an AND operation between binary images is not always sufficient. As two similar papers can be scanned in different orientations, the identical peaks extracted from two images may not have similar angles. In the next section, we study how to compare feature peaks.

6. FEATURE COMPARISON

In the previous section, we discussed how to extract the feature peaks from a paper image. The top peaks from the power spectrum of front and back sides images are extracted and then by applying an AND operation on the binary images of peaks, the feature peaks are obtained. The feature peaks are presented in a binary image that show the wavelengths and orientation (angles) of the peaks. The angles of the peaks are dependent on the orientation in which the paper is scanned but the wavelengths are invariant to the orientation. For example, we select a sample paper and its rotated version over 40 degrees (shown in Figures 8a and 8b respectively). An image with a resolution of 600

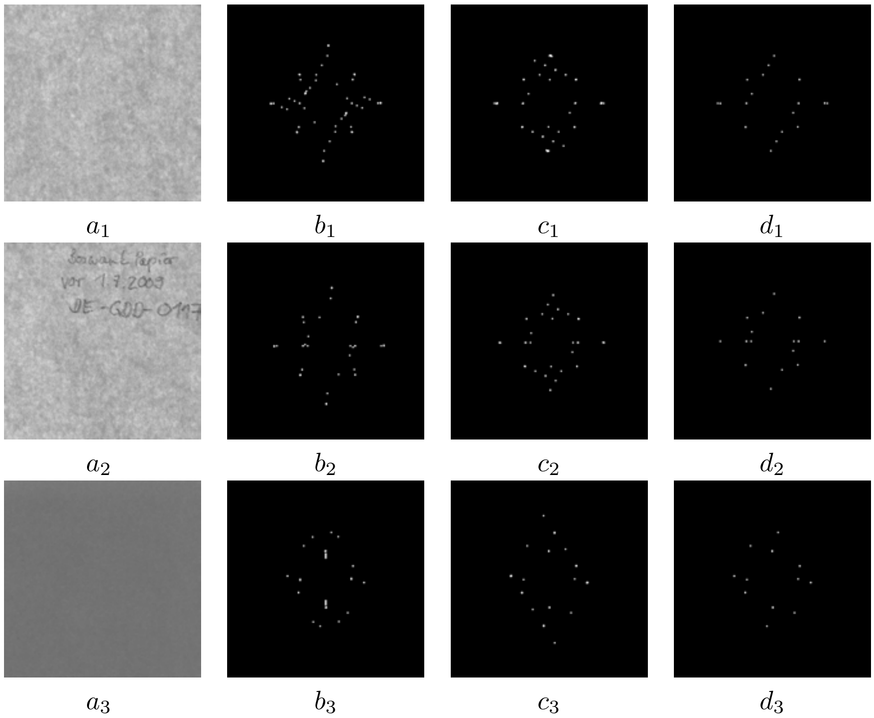

Figure 6: *Two similar papers (a_1,a_2); a different paper (a_3); the peaks extracted from front side images (b_1,b_2,b_3); the peaks extracted from back side images (c_1,c_2,c_3); feature peaks (d_1,d_2,d_3).*

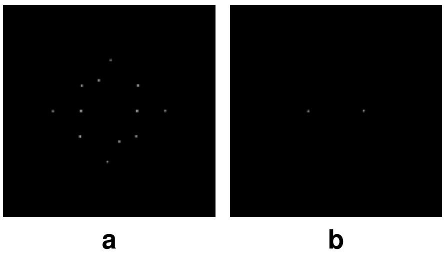

Figure 7: *Identical feature peaks between similar papers in Figures 6a_1 and 6a_2 (a), identical feature peaks between two non-similar papers in Figures 6a_1 and 6a_3 (b).*

dpi and the size of 1200*1200 pixels is generated from each paper. Then, we extract the peaks from the power spectrums of the two images with the wavelengths smaller than $0.8mm$ (see Figures 8c and 8d). From the figures, it is observed that the peaks in two images have the same wavelengths but different angles. The difference between angles of the corresponding peaks in the two images is equal to the rotation angle of the paper.

To find the similarity between the feature peaks of two images, one way is applying AND operation between two binary images in different orientations (angles) and to study in which angle the largest similarity between two images is obtained. This method is simple, but time consuming. Therefore, we propose a new and fast method to find the rotation angle. In our method, first we compute the wavelengths and angles of all feature peaks extracted from each of two images. Then, we calculate the difference between angles of the peaks which have similar wavelengths in the two images (an error distance of 5 pixels for similar wavelengths is considered). The angle differences are stored in a vector where each element of this vector shows the difference between angles of two peaks with similar wavelength. By depicting the histogram of this vector, we observe that the highest value in this histogram shows the rotation angle. This is the angle in which if one of the two images is rotated, the largest similarity and overlap between feature peaks of two images are observed. Figure 9 shows the histogram of angle differences for the two images shown in Figures 8c and 8d. As can be seen from the histogram, the highest value appears in 40 that is the angle over which the image is rotated.

7. CONCLUSIONS

In this paper, we proposed a digital analysis method for feature extraction from machine-made papers which can be used for authentication and dating of art. The digital images were produced by transmitted light scanning. Two types of structures are recognized in machine-made papers namely regular (periodic) and irregular (non-periodic) where the regular structure can be used for paper identification. We studied the image features in Fourier domain to present the regular structure of a

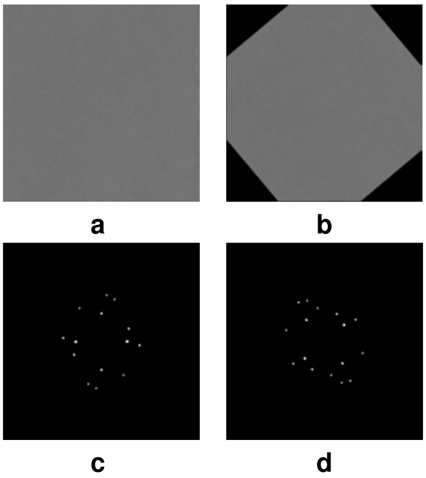

Figure 8: *A sample paper (a), the paper rotated over 40 degrees (b), the 50 top peaks extracted from the paper image and the rotated image (c,d).*

paper. From this, we concluded that the wavelengths and angles of the peaks (components with high amplitudes) are unique features which represent the periodicity and direction of periodic patterns in a paper. The notion of feature peaks was introduced, being the peaks that are common in both front and back side images. It was shown that these feature peaks are discriminative for distinguishing similar and non-similar papers. However, the wavelengths of the peaks are invariant to the orientation of the paper's image but the peaks angles are dependent on the orientation. To compare feature peaks of different papers which are scanned in different orientations, we proposed a simple and fast method to calculate the rotation angle between different papers. This method gives the rotation angle for which two papers have the largest similarity.

In future work, we will measure the similarity between two papers using the extracted features from this work. This measurement would give a number that shows to what extent there is similarity.

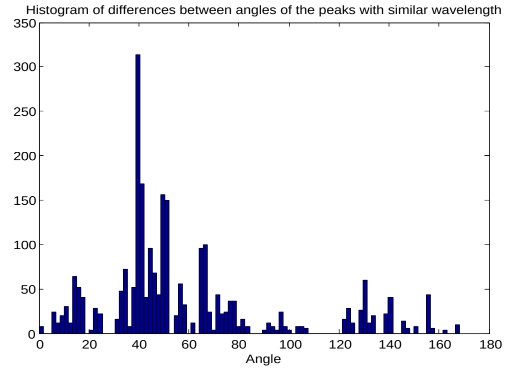

Figure 9: *Histogram of the differences between angles of the peaks with similar wavelengths extracted from two images shown in Figures 8c and 8d.*

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