Article

Multispectral Imaging, Image Enhancement, and Automated Writer Identification in Historical Manuscripts

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1. Introduction

This article deals with multispectral imaging (MSI) and image-processing techniques for the analysis of damaged historical manuscripts. Ancient manuscripts are often in a poor condition: the ink can be faded and there is often degradation caused by mold, water stains, and humidity as a result of bad preservation conditions. In order to decipher the latent texts, philologists are dependent on the support of experts from other disciplines. As part of the Sinaitic Glagolitic manuscripts project (http://www.caa.tuwien.ac.at/cvl/research/sinai/), our interdisciplinary team consisting of philologists and image-processing specialists is examining damaged parchment manuscripts and developing computational means for the digitization, image enhancement, and automated document analysis of historical manuscripts in order to facilitate philological research.

The manuscripts studied originate from Mt. Sinai, Egypt, and were written between the 10th and 12th centuries in Glagolitic, the oldest Slavonic script. They show the typical characteristics of ancient manuscripts as listed above. Several of the manuscripts also contain palimpsests, i.e., underwritten text that has been washed or scraped off so the page can serve as new writing material — and then be overwritten with new text. The readability of these palimpsests is of extraordinary value for philologists, since they are older than the visible text on the top and may contain historical information that would be lost otherwise.

MSI is used in order to enhance the legibility of such manuscripts. By applying post-processing techniques on multispectral images, the contrast and legibility of degraded manuscripts can be increased. One potential post-processing technique is Fisher's linear discriminant analysis (LDA), which belongs to the group of supervised dimension reduction methods. The results of this approach are described in the following.

Our project also explores image-processing methods employed in the field of document analysis. One of the methods developed comprises automated writer identification. We propose an approach that uses SIFT features (scale-invariant feature transform) and Gaussian mixture models (GMM). This was the first time that automated writer identification was applied on Glagolitic manuscripts. In experiments, the method achieved a writer identification rate of 98.9% on a dataset containing 363 Glagolitic folios.

This article is structured as follows: In section II, the general concept of MSI is presented as well as a detailed description of the MSI acquisition system used. Section III contains an introduction to post-processing techniques with a focus on LDA. Section IV outlines the proposed method for writer identification. The final section provides a conclusion and an outlook.

2. Multispectral imaging of ancient manuscripts

A. Concept of multispectral imaging

MSI is an imaging technique that produces images in selected narrow spectral ranges. A multispectral image can be described as the same image of one scene in different spectral ranges, i.e., at different wavelengths of the electromagnetic spectrum. The wavelengths can either be isolated by filters or using instruments that are sensitive to specific wavelengths, including light from frequencies above and beyond the visible light range such as infrared (IR) and ultraviolet (UV). MSI can reveal information in a document that cannot be seen by the human eye, since the latter is sensitive only to radiation from about 380 nm to 700 nm. Another asset of MSI is that it is a non-invasive technique and can therefore be used on any manuscript, even if it is in a fragile condition.

MSI was originally developed for remote sensing applications. In the early 1990s, the technique started to be applied in the fields of art conservation and art history.

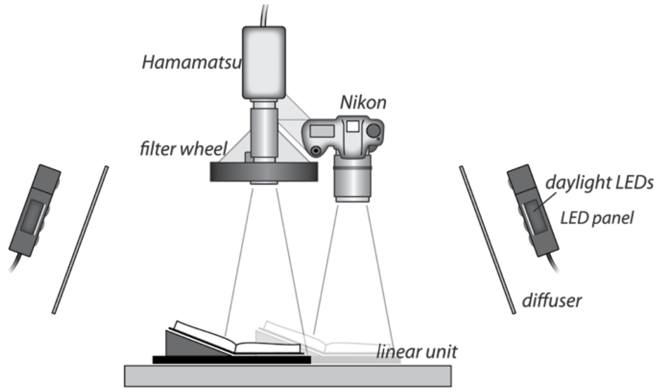

Fig. 1: Illustration of the MSI acquisition setup.

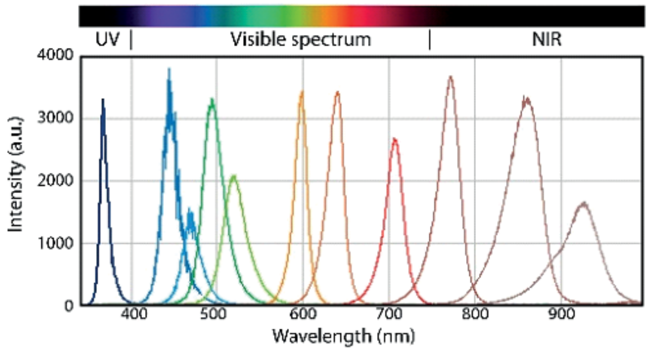

Fig. 2: Wavelengths of the LEDs used in the MSI system.

The imaging technique has also proven to be an effective method for the analysis and preservation of ancient manuscripts, as shown in the famous Archimedes palimpsest project.

The results of that project demonstrate that imaging in the UV spectral range in particular succeeds in providing additional data.

Several research studies have been carried out in the field of MSI for the enhancement of readability in ancient documents, of which just a few are mentioned in the following: Easton, Knox, and Christens-Barry introduce an MSI acquisition system that makes use of narrow-band LEDs. Bianco et al. describe an MSI apparatus that uses a filter wheel consisting of eight different optical filters and a monochromatic camera. Lettner et al. introduce a similar MSI system with an extra single-lens reflex camera. Finally, Rapantzikos and Balas make use of a system with optical filters for imaging in 34 narrow spectral bands.

B. MSI acquisition system

Since the manuscripts investigated are stored in different places and often even in different countries, our aim was to develop an apparatus that was robust, easily portable, and allowed fast setup and imaging. We constructed a portable MSI system consisting of two multispectral LED panels and two different cameras (illustrated by fig. 1). The setup takes approximately one hour. The two cameras are a Hamamatsu C9300-124 and a Nikon D4. The Hamamatsu camera is a near-infrared (NIR) grayscale camera with a cooled CCD chip and provides a resolution of 4000 x 2672 pixels. It possesses a spectral sensitivity ranging from UV to NIR (330 nm – 1000 nm). The Nikon camera is a traditional RGB camera with a resolution of 4928 x 3280 pixels and is utilized for UV fluorescence and visible light images.

The objects being investigated are placed on a board which is attached to a linear unit. The linear unit permits automatic shifting between the two camera positions. Thus, once positioned, there is no additional interaction with the manuscript apart from turning the folios.

Concerning the lighting system, we have made certain improvements in recent years. In the beginning we used optical filters built in a filter wheel which was placed in front of the Hamamatsu camera. Since the different filters within a filter wheel are not aligned exactly parallel, a shift occurs between single images. The filter influence is described by Brauers, Schulte, and Aach.[1] The shift has to be corrected for the statistical combination of different spectral bands. An additional drawback was the illumination system, where the illumination had to be switched manually between UV and white light illumination. In order to avoid these drawbacks, we constructed an image acquisition system where the multispectral images are gained by the lighting. For this purpose, two Eureka!Light™ (Archimedes project) LED panels were acquired, providing 11 different wavelengths (see fig. 2). Four white LED panels are attached to the left and right of the Eureka!Light™ panels. Additionally, two diffusers are situated between the lighting and the object in order to distribute the illumination uniformly.

Using LED panels with different wavelengths means that a filter wheel is redundant. This has the welcome side effect that optical distortions caused by filters can be avoided. Two filters are still required, however: the SP400 (400 nm short-pass filter) for UV fluorescence imaging and the LP400 (400 nm long-pass filter) for UV reflectography. An example of the results of multispectral imaging is shown in fig. 3.

[1] Brauers, Schulte, and Aach 2008.

Fig. 3: Vienna Folia. White light image (left) and UV fluorescence image (right).

3. Post-processing methods: dimension reduction techniques focusing on LDA

As described in the preceding chapter, the contrast and readability of historical texts can be enhanced with the aid of MSI. However, some sections of the manuscripts still remain illegible. At this point, post-processing methods such as dimension reduction techniques may assist in reconstructing these sections. Dimension reduction techniques reduce the dimensionality of the multispectral scan with the objective of extracting the relevant information, i.e. the text. Regarding manuscripts with one text, this means that the output from the MSI scans is at best a single image showing the writing. For palimpsests containing two layers of text, the reduction of dimensionality results in two images, one showing the overwriting and the other containing the underwriting.

Basically, dimension reduction techniques can be grouped into supervised methods (such as LDA) and unsupervised methods (such as PCA and ICA). For the former, class information is necessary to select different features, whereas this is irrelevant for the latter, since the relevant information in the MS scans is extracted by the approaches.

Previous studies[2] have proven that the application of unsupervised dimension reduction techniques such as principal component analysis (PCA) and independent component analysis (ICA) can enhance the contrast of degraded writings. Recently, we proposed a new enhancement technique based on a supervised dimension reduction approach, namely Fisher's linear discriminant analysis (LDA).[3] To the best of our knowledge, this was the first time that the LDA approach had been applied to historical documents. In a qualitative analysis (where the images were assessed by philologists familiar with the script of the relevant manuscripts), it was shown that the LDA-based approach produces partially better results than the unsupervised methods.

As a supervised dimension reduction tool – in other words, a method demanding additional information apart from the MSI data – the LDA-based method requires prior labeling of a subset of the multispectral data. The labeling is performed in a semi-automated label-generation step in which a subset of the multispectral data is labeled as belonging to the text or the background. The method was tested on two Glagolitic manuscripts, namely 'Missale Sinaiticum' and 'Glagolitic Fragments'. Since the text in the first manuscript is only partially visible in the multispectral images, the labeling is applied on PCA images where an enhancement in readability is achieved. Due to the bad condition of the writings, however, labeling by applying a binarization algorithm would still not be effective. Additionally, in the case of 'Missale Sinaiticum', it is not predefined in which wavelength the text is best visible, and hence it is not known a priori to which image of the multispectral scan the binarization algorithm should be applied.

Instead we noticed that the text line scheme is more recognizable in the PCA images than the single characters. Therefore, the samples are labeled as belonging either to text line or intermediate regions. In order to identify these regions, a text line detection algorithm similar to the one proposed in

[2] For example Easton, Christens-Barry, and Knox 2011; Salerno, Toazzini, and Bedini, 2007; Hyvärinen and Oja 2000.

[3] Hollaus, Gau, and Sablatnig 2013.

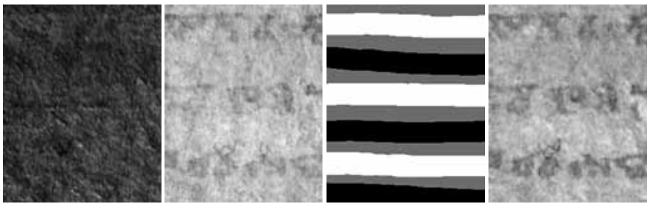

Fig. 4 (from left to right): UV reflectography image, PCA input image, text line detection result obtained on the PCA image, LDA output image.

Bar-Yosef et al.[4] is applied on the PCA image. The output of the method comprises lines passing through text lines and lines passing through intermediate regions between text lines. These lines are then dilated with a disk-structuring element in order to increase the number of samples. The labeled pixels are then utilized for training an LDA classifier. The hyperplane found by the classifier is subsequently used for the dimension reduction of the entire multispectral scan. The resulting image is in turn used in a further labeling step. A sample of the output from this stage is shown in fig. 4. The writing is most visible in the UV reflectography image in this case, but it should be noted that the writing is still barely visible. This can be attributed to a chemical reaction causing the ink to discolor from black to white.

The example shows that the text is usually more visible at this stage in comparison to the unprocessed multispectral images, and hence a binarization algorithm can be successfully applied. A binarization approach[5] is therefore used for a further labeling step. The binarization technique is specially designed for historical manuscripts and is mainly dependent on a single parameter that describes the average stroke width. The stroke width is identified manually and is similar within each folio of the manuscripts investigated, except for strokes which belong to initials. Unlike labeling based on text lines, this labeling step is used to label characters instead of text line regions. The output of the binarization approach is then used again in order to label a subset of the multispectral data and perform LDA-based dimension reduction.

Figs. 5 and 6 show images from a multispectral scan and the corresponding results of enhancement. The writing is most visible in the UV fluorescence image compared to the other multispectral images. Nevertheless, the legibility of the writing is limited, since the text is affected by bleeding degradations and corrupted by background clutter. These degradations are best restored using the LDA-based approach.

Furthermore, the examination showed that the LDA-based technique yields better results if it is applied to a region with a similar contrast. If there are both very dark and very bright areas in the background, the text line detection algorithm will fail.[6]

4. Automated writer identification

Automated writer identification for ancient, degraded manuscripts is a desirable technique for paleographers to use. The aim of a paleographer's work is to date, localize, and verify historical documents and – in the best-case scenario – to identify the author of the work. A great number of manuscripts have been digitized in recent years in order to protect them from abrasion and make the documents available to researchers quickly and easily (and to anyone else with an interest in them, for that matter).

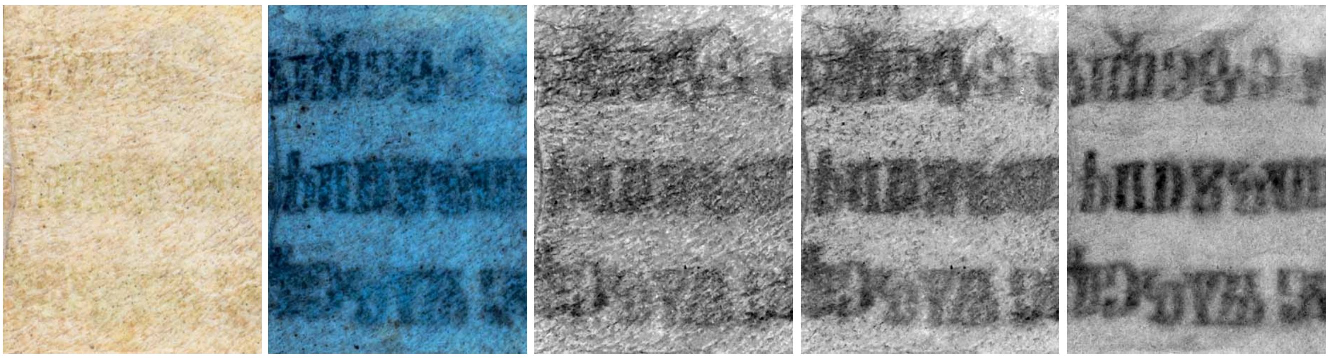

Fig. 5 (from left to right): white light image, UV fluorescence image, PCA result, ICA result, LDA result.

[4] Bar-Yosef et al. 2009. For a detailed description of the procedure applied, see Hollaus, Gau, and Sablatnig 2013.

[5] Su, Lu, and Tan 2010.

[6] This issue is discussed in more detail in Hollaus, Gau, and Sablatnig 2013.

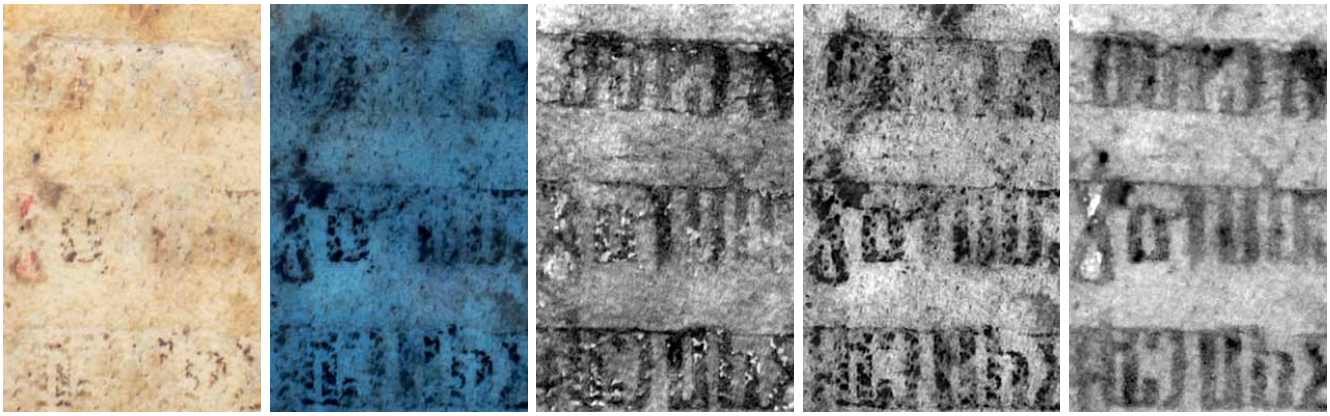

Fig. 6 (from left to right): white light image, UV fluorescence image, PCA result, ICA result, LDA result.

This trend is set to increase in the future. An automated method that can 'learn' to recognize and discriminate the typical writing styles of different authors within the vast jungle of data would therefore greatly facilitate the work of the paleographer. At present, paleographers almost exclusively use manual methods to solve this task. Thus, it was an essential objective of our project to create an effective model for writer identification.

Most of the writer identification models that can be found in literature are concerned with modern handwritings. Particularly over the past decade, however, several attempts have been made to design methods of automated writer identification for medieval manuscripts. Among the researchers, the following apply their methods on binarized images: Bensefia, Paquet, and Heutte[7] work with grapheme features and apply their method both on modern handwritings and on handwritings from the 19th century. The same approach is used for modern handwritings, whereby the results gained for modern writings are significantly superior to the results obtained for ancient writings.

Bulacu and Schomaker's[8] writer identification method is a combination of textual and allographic features. The authors show that combining the features obtains better results than with single features. The manuscripts investigated were 70 medieval English documents. Brink et al.[9] introduced a method where the width and the directionality of the ink trace serve as features. This system was tested on historical English and Dutch documents.

Bar-Yosef et al.[10] have criticized the fact that binarization does not show proper results when it is applied to damaged historical manuscripts. They utilized a multi-step binarization method themselves. As a result, particular letters are recognized automatically and applied for writer identification. In order to manage the classification and attribution of the different texts to correct scribes, k-nearest neighbors and Bayes linear classifiers are evaluated. The authors note that the latter classifier achieves better performance than the k-nearest neighbors classifier.

Contrary to the above approaches, which are all based on binarized images, Bres, Eglin, and Volpilhac-Auger[11] used a model that works with grayscale images. They applied the Hermite transformation for denoising and identification of scribes and investigated 1438 historical manuscripts written by 189 different scribes.

Wolf et al.[12] approached the topic of writer identification in a broader sense. They designed a semi-automatic clustering method based on graphical models for the classification and identification of document fragments that once belonged to the same codex. They used the bag-of-words model to find image similarities. Using their technique, approximately 1000 previously unidentified relations could be detected.

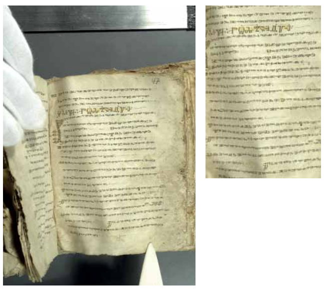

Fig. 7: Input and output images of the cropping procedure.

[7] Bensefia, Paquet, and Heutte 2003.

[8] Bulacu and Schomaker 2007.

[9] Brink et al. 2012.

[10] Bar-Yosef et al. 2007.

[11] Bres, Eglin, and Volpilhac-Auger 2006.

[12] Wolf et al. 2011.

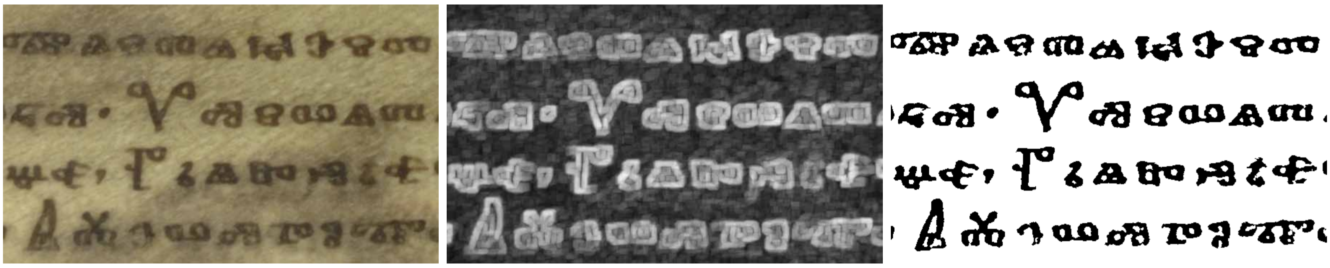

Fig. 8: binarization steps. Input image (left), contrast image (center), binarization result (right).

We propose a writer identification approach which is based on Fisher kernels and the utilization of scale-invariant feature transform (SIFT) features and Gaussian mixture models (GMM). This approach was originally developed to work on grayscale images of modern handwritings, i.e., with a uniform background. What happens when this method is applied on damaged historical documents is that SIFT features are also recognized on background clutter. In order to avoid this negative side effect, a binarization step is required as a form of pre-processing – a method that has already provided good results on binarized images of modern handwritings.

We applied our writer identification model on five Glagolitic manuscripts originating between the 10th and 11th centuries. These manuscripts had already been well-examined by scholars, so there were already paleographic results regarding the scribes.

Before the writer identification method is applied, the documents are cropped to images containing only the text of the manuscript. This is done by applying the text line detection method, which was mentioned in the preceding section.[13] Since this method only allows the extraction of rectangular regions, decorative elements such as initials can also be found in the cropped image (see fig. 7).

In the next step, the images are binarized using a binarization method designed specifically for historical documents by Su, Lu, and Tan.[14] First, a contrast image is calculated which encodes local gray-value differences. These differences are especially high at stroke boundaries, and the algorithm is based on the detection of stroke boundaries. An example of this type of contrast image is given in fig. 8 (center). After computation of the contrast image, high-contrast pixels are identified by applying Otsu[15] thresholding on the contrast image. These high-contrast pixels are usually located at stroke boundaries and are used in the final step of the binarization process. At this stage, each pixel of the input image is considered and is classified as a foreground pixel if the following conditions are met: firstly, the pixel must be near a sufficient number of high-contrast pixels, whereby the required number of high-contrast pixels is a user-defined parameter; secondly, the gray value of the pixel considered must be smaller than or equal to the average gray value of pixels in its local neighborhood, which are marked as being high-contrast pixels. A sample output of the algorithm is shown in fig. 8.

The writer identification model proposed is based on the Fisher kernels.[16] The starting point is to calculate the SIFT features using the scale-invariant feature transform (SIFT)[17] on a training dataset. In order to recognize Glagolitic characters correctly, the features were adopted in our examination, as suggested by Diem and Sablatnig:[18] if an angle occurs which is larger than 180°, the orientation of the key-point is mirrored. This is because the upper and lower level of features within the writing is a discriminative feature for Glagolitic character recognition. Other modifications we performed were heightening the contrast threshold (due to a lot of noise) and reducing the edge threshold (due to a high number of edge-similar features).

The calculation results of two Glagolitic letters and the corresponding histograms are depicted in fig. 9.

Where the two Glagolitic characters are concerned, the relevant features are found in the circles and at the corners. The histograms clearly show that if the SIFT features are calculated based on rotational invariance, both letters are impossible to distinguish.

[13] For a detailed description, see Fiel et al. 2014 (forthcoming).

[14] Su, Lu, and Tan 2010.

[15] Otsu 1979.

[16] Perronnin and Dance 2007; improved by Perronnin, Sanchez, and Mensink 2010.

[17] Lowe 2004.

[18] Diem and Sablatnig 2010.

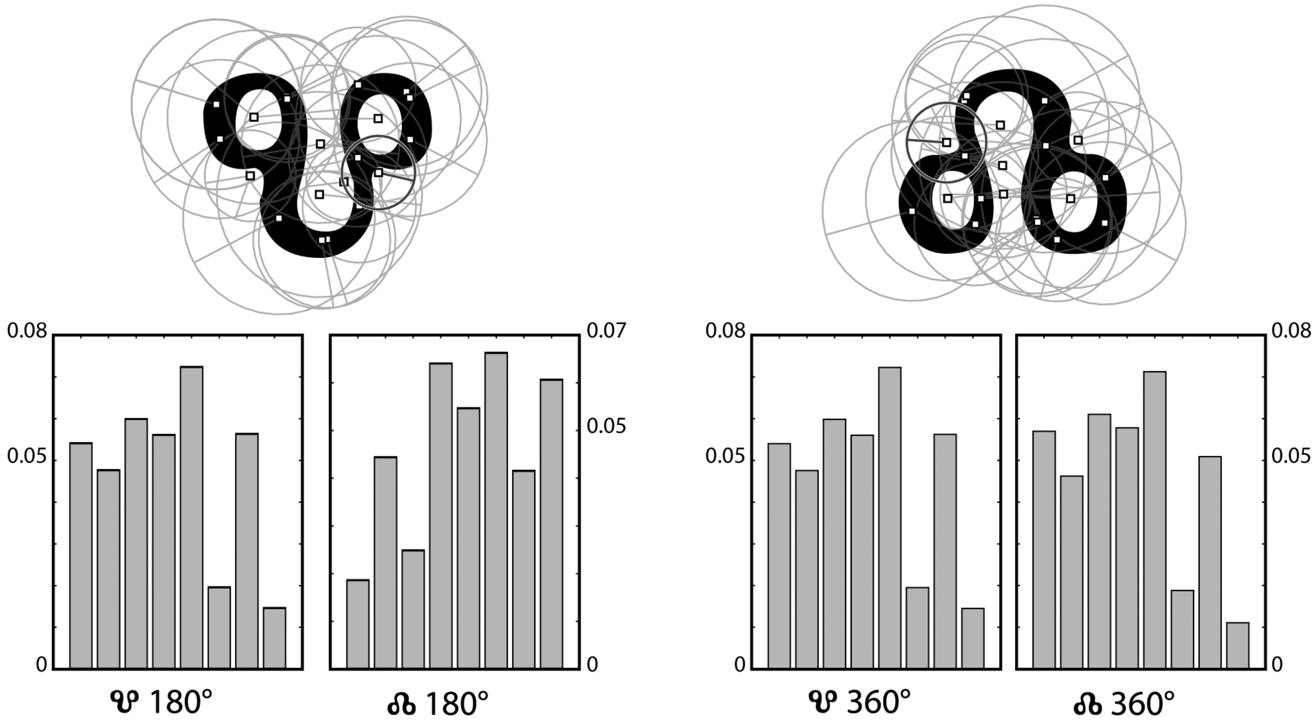

Fig. 9: the top row shows two Glagolitic characters with their SIFT features, while the bottom row shows generated histograms of the two marked features (blue). In the bottom row on the right, the calculation of the SIFT features is rotation-invariant, thus they both generate a similar histogram. On the left, the calculation is rotation-dependent, which makes the two characters distinguishable.

The objective of the next step is to create a visual vocabulary. For evaluation reasons, a different training dataset is used than in the SIFT procedure. First, a PCA is employed on the features to reduce the dimensionality from 128 to 64. Each SIFT feature in the training set can be seen as an observation of a Gaussian mixture, and the parameters of this density function can be estimated using an expectation maximization algorithm. The number of Gaussian has to be set in advance, and experiments have shown that 100 distributions have the highest performance. When identifying the writer of a new page, the SIFT features of the relevant page are calculated and the Fisher kernel for each GMM is applied. The resulting vectors for each distribution are then concatenated. The cosine distance of the resulting vector to the features of known writers is calculated, and the writer with the smallest distances is assigned as the writer of the particular document.

The documents are then ordered by their similarity to a reference document, and the evaluations are carried out using the k-nearest neighbors algorithm. The evaluation method is based on the model of the ICDAR 2011 Writer Identification Contest.[19] Each document in the database is used as a reference document for the evaluation, and the distances to the remaining documents are calculated. These distances can then be used to compute several criteria, particularly the Top 1 criterion, meaning that the document with the smallest distance to the reference document has to be by the same writer as the reference document. For this criterion, the method gained a rate of 98.9% on binarized images. The identification rate on grayscale images was 87.6% for the Top 1.[20]

5. Conclusion and outlook

Interest in the digital imaging of ancient documents has significantly increased in the past decade. There can be no doubt that study and processing of this cultural heritage in the future will be done predominantly by means of those image products. MSI is a useful technique for the non-invasive investigation and preservation of ancient documents. It has been proven that MSI is a successful method for enhancing the legibility of damaged historical documents, and applying UV light is especially effective for deciphering faded text or palimpsests. Since the approach is still relatively young, we also plan in future to focus on MSI research within our

[19] Louloudis, Stamatopoulos, and Gatos 2011.

[20] For the interested reader, a detailed evaluation can be found in Fiel et al. 2014.

interdisciplinary project. This will enable us to collect further qualitative data about the imaging of degraded historical manuscripts and palimpsests in order to make new scientific findings.

This article has also dealt with the enhancement of degraded manuscripts that have been captured by MSI. The supervised dimension reduction technique of LDA was shown to be able to further heighten text legibility. The method is organized as follows: first, the data is labeled in text line regions and intermediate regions using a text line detection technique, since the condition of the manuscript investigated is extremely bad. We then apply a procedure to label a subset of the multispectral data as foreground and background. Finally, a finer labeling method is employed by applying a binarization technique. The results show that this enhancement method is partially superior to the unsupervised methods of PCA and ICA. However, our method has not been successful in cases where there were dark and bright areas in the background, since the text line detection algorithm fails to work. We are currently working on a solution to this issue by manual refinement of the text line detection output.

In this article, we also reported on the first application of automated writer identification on Glagolitic manuscripts. Our approach uses Fisher kernels on visual vocabularies. The documents are initially cropped to images containing only text. In the next step, the SIFT features are calculated on the image. The Fisher kernel is then generated with the aid of the GMM. The documents are organized by their similarity into a reference document, and the evaluation uses the k-nearest neighbors algorithm. The best performance was achieved by applying binarization to the image. We plan to improve the cropping method in future. Since the current method only allows the extraction of rectangular regions, decorative elements such as initials are also found in the cropped image. This means that the SIFT features are calculated on non-text regions, too, which makes a correct identification of the writer harder.

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