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Enhancement of MultiSpectral Images of Ancient Manuscripts

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Abstract

This work is concerned with MultiSpectral Imaging (MSI) and image processing of ancient manuscripts. The writings imaged are partially in a bad condition, since they are partially faded-out or have been erased and overwritten. Therefore, a transcription by philologists belonging to our project team is aggravated. In order to increase the legibility, the manuscripts investigated have been imaged with a portable MSI system. While the imaging in selected narrow spectral ranges gained a legibility increase, post-processing techniques can be applied to the MSI data in order to gain a further contrast enhancement. For this purpose, three different dimension reduction techniques are applied to the manuscripts. A qualitative analysis shows that these techniques are capable of increasing the legibility of the ancient writings, compared to unprocessed multispectral images.

1. Introduction

This work is concerned with the imaging and post-processing of ancient manuscripts, which are of particular interest for philologists. The manuscripts are partially degraded, e.g. they are corrupted by mold or contain faded-out or even erased writings. In order to facilitate a transcription by scholars and to preserve this cultural heritage, the manuscripts have been imaged with a MultiSpectral Imaging (MSI) system. MSI has proven to be a valuable tool for the investigation of such manuscripts, since it is capable of enhancing the contrast of faded-out writings [LDSM08].

MSI has not only been used for the enhancement of faded-out writings, but also for the enhancement of erased texts contained in a palimpsest. The term palimpsest stems from the Greek word palimpsestos - meaning scraped again - and describes a manuscript, which originally contained a single writing that has been erased and overwritten with a younger text. The reason for the replacement of such original texts was that parchment was a precious material in former times. The original text is also named underwriting, whereas the younger writing is called overwriting. MSI can be used to recover such underwritings, as it has been demonstrated in the case of the famous Archimedes palimpsest [ECBK11].

Multispectral images can serve as a basis for further post-processing techniques, like image binarization or Optical Character Recognition (OCR). Such techniques are typically designed for grayscale images or RGB images and hence they cannot be applied directly on a multispectral scan of a document. Instead a single channel - or an RGB image - of the multispectral scan has to be selected or the dimension of the multispectral scan has to be lowered. Several authors - like [ECBK11] or [HC13] - have shown that by combining the information of several multispectral channels into a single or multiple images, the contrast of such degraded writings can be increased. For instance, Salerno et al. [STB07] have shown that dimension reduction techniques - like Principal Component Analysis (PCA) - can be used to lower the dimensionality of a multispectral scan of degraded writings. The authors show that by reducing the dimensionality, the contrast of the Archimedes palimpsest can be increased, compared to unprocessed multispectral images.

While PCA is an unsupervised dimension reduction tool, we propose the usage of a supervised dimension reduction technique, namely Fisher Linear Discriminant Analysis (LDA). Since LDA is a supervised technique it is necessary to select a subset of the multispectral observations and to label them as belonging to different classes. In our case we are searching for a discrimination between the foreground class, e.g. the writing, and the background class, e.g. unwritten

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parchment. In the case of palimpsests, a three-class problem is considered, whereby the younger overwriting is defined by the third class. Since the manual selection and labeling of multispectral samples is a time-consuming task, we propose an automated labeling strategy. The labeling strategy makes use of document image analysis methods in order to label selected samples. The method is evaluated by means of a qualitative analysis, which is performed by scholars. The evaluation shows that the enhancement technique proposed is partially superior compared to unsupervised dimension reduction techniques.

This work is structured as follows: In Section 2 an overview on the related work is given. In Section 3, the MSI setup used is introduced and in Section 4 the enhancement method is detailed. Afterwards, the method is evaluated and comparative results are provided. Finally, a conclusion is drawn in Section 6.

2. Related Work

The previously mentioned Archimedes palimpsest has been investigated by Easton et al. [ECBK11]. The authors imaged this particular codex in selected narrow spectral ranges. The different spectral ranges are provided by multispectral LED panels. Easton et al. report that the ancient palimpsest text, also called underwriting, is most visible in the UltraViolet (UV) range. The authors apply the PCA technique and report that this tool is capable of enhancing the contrast of the underwriting, compared to unprocessed multispectral images.

The Archimedes palimpsest is also investigated in [STB07]. Therein, the author apply the PCA technique and another unsupervised dimension reduction technique named Independent Component Analysis (ICA). The authors show that both techniques can be used for the separation of the over- and underwriting and additionally can be used to gain a contrast enhancement of the palimpsest text.

Two different palimpsests are examined by Rapantzikos and Balas [RB05]. The system used is a hyperspectral imaging system, which enables an imaging in 34 spectral bands, ranging from UV to NearInfraRed (NIR) - namely from 360nm to 1150nm. The spectral ranges are provided by a tunable optical filter. The authors apply PCA and a supervised unmixing approach named Linear Spectral Mixture Analysis (LSMA). Example results show that the LSMA outcomes are partially inferior to the corresponding PCA outputs.

Lettner et al. [LDSM08] present an MSI setup that makes use of a filter wheel, providing 8 different spectral bands, ranging from UV to NIR. The system is used for the imaging of a single text, which is partially degraded since it contains faded-out characters and is corrupted by background clutter. Due to the bad condition of the manuscript, the authors apply the PCA transformation on the multispectral scans. Additionally, they propose an approach, which is based on Multivariate Spatial Correlation (MSC) [War85]. This approach is used to enhance text regions, which are found by a text line detection method. Resulting images show that the MSC method is superior compared to the PCA technique.

An enhancement method for historical documents and paintings is presented in [KDB11]. The method combines an RGB image taken in the visible range with multispectral images taken in the NIR range. The combination is performed in the gradient domain and the resulting images exhibit less artifacts than the original RGB images, while the original texture is preserved.

Hedjam et al. [HC13] propose an enhancement technique for documents that are corrupted by ink bleed-through, paper fluctuations etc. Such degradations are reduced, by combining information contained in the visible spectrum with information contained in the NIR range. The authors note that iron-gall based ink vanishes in the NIR range, while degradations are still visible in this spectral range. The method proposed makes use of this behavior in order to find degradations in the NIR range and to restore the affected regions by applying an image inpainting algorithm. The method is evaluated by applying binarization algorithms on enhanced images and on unprocessed multispectral images. The results show that a better binarization performance is gained on the enhancement results.

3. MSI System

Our MSI system is illustrated in Figure 1 (left). The MSI system used makes use of two cameras: (a) A grayscale NIR Hamamatsu C9300-124 camera that has a spatial resolution of $4000 \times 2672 px$ and a spectral response between 300 nm and 1000 nm. (b) A Nikon D4 SLR camera with a resolution of $4928 \times 3280 px$. The SLR camera is used for white light images and UV fluorescence photographs and the grayscale camera is used for MSI. 11 different spectral ranges are provided by two Eureka!Light^{TM}(Equipoise imaging, Archimedes project [EKCB03]) LED panels, whose spectra are shown in Figure 1 (right). By making use of LED illumination the heat and thermal stress put on the manuscripts is reduced compared to a broadband illumination - like tungsten illumination [CB12]. Additionally, by using narrow-band illumination, it is not necessary to filter the reflected light with optical filters, since the incident light is already filtered. However, in order to enable UV fluorescence and UV reflectography imaging, two filters are still required for filtering light with a wavelength below - respectively above - 400 nm. For this reason, these two filters are built in a filter wheel.

A portion of a palimpsest with the shelfmark 'Suppl. Gr. 200' is shown in Figure 2. The white light image exhibits mainly the overwriting. On the contrary, the underwriting is best visible under UV light. In the example shown the underwriting is most visible in the UV reflectography image,

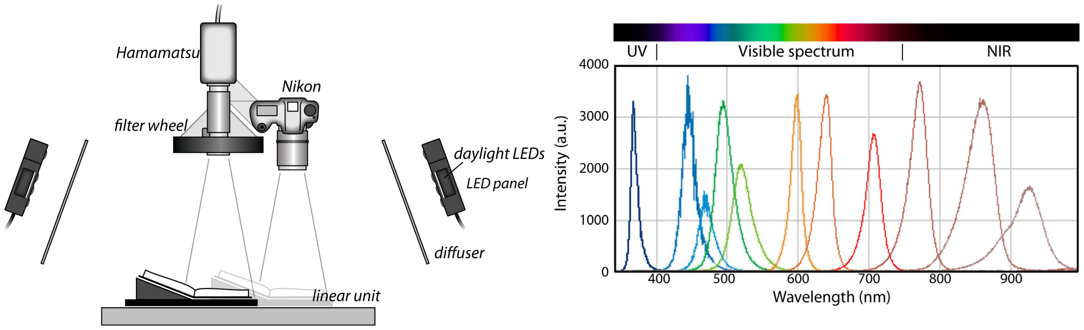

Figure 1: *(Left) Illustration of the MSI setup. (Right) Spectra of the multispectral LED panels.*

but also partially visible in the UV fluorescence image. Although the contrast of the underwriting is enhanced in the UV images, the legibility of the degraded text is nevertheless limited since it is not easily distinguishable from the remaining background. Therefore, enhancement strategies have been applied to the MSI data in order gain a further contrast enhancement.

4. Enhancement

The enhancement method proposed makes use of Fisher LDA. Therefore, the underlying statistical theory is briefly introduced in the following. Since LDA is a supervised dimension reduction it is necessary to select a subset of the multispectral observations and to label the observations as belonging to different classes. For this purpose an automated labeling strategy is suggested that makes use of spatial information. The labeling and enhancement procedures are explained in Section 4.2.

4.1. Linear Discriminant Analysis

The LDA is seeking for a projection $\mathbf{W}$ that is maximizing the within-class scatter and the between-class scatter. The within-class scatter is defined as

$$\mathbf{S}_W = \sum_{i=1}^{c} \sum_{\mathbf{x_k} \in \mathbf{X_i}} (\mathbf{x}_k - \mathbf{m}_i)(\mathbf{x}_k - \mathbf{m}_i)' \tag{1}$$

where c depicts the number of classes, $\mathbf{x}_k$ is a sample belonging to a class X_i and $\mathbf{m}_i$ is the mean of the class. The between-class matrix is defined by

$$\mathbf{S}_B = \sum_{i=1}^{c} N_i (\mathbf{m}_i - \mathbf{m})(\mathbf{m}_i - \mathbf{m})' \tag{2}$$

where N_i depicts the number of samples in the class X_i and $\mathbf{m}$ is the total mean vector over the mean vectors $\mathbf{m}_i$. The projection $\mathbf{W}$ is found by maximizing the criterion function:

$$\mathbf{J}(\mathbf{W}) = \frac{\mathbf{W}'\mathbf{S_B}\mathbf{W}}{\mathbf{W}'\mathbf{S_W}\mathbf{W}}. \tag{3}$$

It is noted in [DHS01] that the PCA transformation finds components that are useful for the representation of the data, whereas the LDA is searching for components which are convenient for discrimination. In the case of palimpsest texts, we are considering a three class problem ($c = 3$) and we are searching for a discrimination between the underwriting class X_1, the background class X_2 and the overwriting class X_3. For this purpose, a subset of all multispectral observations $\mathbf{x}$ is used for the calculation of $\mathbf{W}$. The subset consists of several multispectral observations $\mathbf{x}_k$, whereby the length of each observation is equal to the number of channels in a particular multispectral scan.

It should be noted that in the following, the restoration of palimpsest texts is described. However, the method can also be applied to degraded manuscripts, which contain only a single writing. In this case, a two class problem ($c = 2$) is considered: Therefore, the labeling step for the overwriting is omitted and solely the degraded writing is labeled and enhanced in a procedure that is similar to the underwriting detection, detailed in Section 4.2.2.

4.2. Enhancement Method

The LDA based enhancement method for palimpsests is searching for a discrimination between the overwriting, underwriting and background class. Therefore, it is necessary to detect and afterwards label several selected samples. For this purpose, document image analysis methods are employed. In a first step, the overwriting is detected by applying a simple procedure. Afterwards, the underwriting is detected in an iterative procedure. Both tasks are explained in the following.

4.2.1. Overwriting Detection

The detection of the younger writing X_3 is performed on a single multispectral image, since the overwriting is usu-

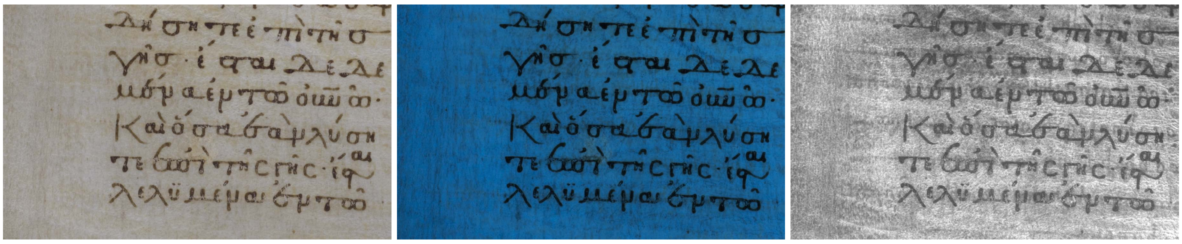

Figure 2: *Suppl. Gr. 200 manuscript portion. From left to right: Image taken under white light. UV fluorescence image. UV reflectography image.*

ally in a better condition than the underwriting and recognizable in the visible range. In the case of the 'Suppl. Gr. 200' manuscripts, we noticed that the overwriting is visible in RGB images taken under white light, while the underwriting is barely visible in these images. Therefore, the overwriting is detected on the red channel of RGB images, by applying a simple binarization approach.

The binarization approach chosen has been suggested by Su et al. [SLT10] and is especially designed for ancient text documents. The algorithm considers the image contrast, which is defined by the intensity maximas and minimas within local neighborhoods. These local intensity extrema are used for the generation of a contrast image, which is defined as:

$$D(x,y) = \frac{f_{max}(x,y) - f_{min}(x,y)}{f_{max}(x,y) + f_{min}(x,y) + \varepsilon}, \quad (4)$$

where $f_{max}(x,y)$ and $f_{min}(x,y)$ are the maximum and minimum intensity values in a local neighborhood. The denominator consists of an infinitely small number ε, which prevents a division by zero, and a normalization term $f_{max}(x,y) + f_{min}(x,y)$. This normalization term is used in order to lower the influence of background variations and to enable a detection of faded out characters. In Figure 3 (left) the contrast image is shown that is gained by applying the method on the parchment portion shown in Figure 2.

The algorithm proceeds with an identification of the stroke boundaries. It is assumed that the local contrast is especially high at stroke boundaries - compared to the background - and the character boundaries are detected by applying a global Otsu threshold. The foreground pixels found at this juncture are called high contrast pixels. The overall segmentation is concluded by a detection of the foreground pixels, which are in the near of the high contrast pixels. A pixel is classified as a text pixel if the following conditions are met: On the one hand the pixel must have at least a certain number of high contrast pixels in its local neighborhood. On the other hand the intensity value of the pixel must be equal or smaller than the average intensity value of the high contrast pixels within the same neighborhood window. The output of the method is shown in Figure 3 (right). The entire foreground pixels found are labeled as belonging to the class X_3.

Figure 3: *Binarization. (Left) Contrast image. (Right) Binarization result.*

4.2.2. Underwriting Detection

While the detection of the overwriting is straightforward, the detection of the underwriting is more complicated since the text is often barely visible in the MSI scan - as it has been shown in Figure 2. Therefore the underwriting is not detected on multispectral images, but instead on images that are gained by applying the PCA transformation. Those images are hereafter denoted as PCA images. Figure 4 shows the first four PCA images that are obtained after applying PCA on the multispectral images shown in Figure 2. It can be seen that the underwriting is partially better visible in the PCA images compared to multispectral images. Similar to [LDSM08], we observed that the degraded writing is emphasized by multiple Principle Components (PC) and it is not predefined, which PC enhances the underwriting.

Since the underwriting can be emphasized by multiple PC's the first k PCA images have to be considered. It was experimentally found that for the 'Suppl. Gr. 200' manuscript, the underwriting is usually enhanced by one or more of the first four PC's. Therefore, the following labeling procedure is applied on each of the first four PCA images.

While the overwriting can be successfully detected by applying a binarization algorithm, a labeling of the underwriting by binarization is error-prone due to the smaller contrast and the presence of background clutter. Instead, we noticed that the text line scheme is better recognizable in the PCA images than the faded-out characters. Therefore, a subset of the multispectral samples is labeled as belonging to a text line region or an intermediate region between two text lines. In order to detect text line and intermediate regions a text line detection method is applied on the PCA image. The text line detection method is similar to the one suggested in [YHKD09] and is based on Local Projection Profiles (LPP). The algorithm is based on the assumption that vertical projection profiles assume local minima at text line positions and local maximas between text lines. The algorithm does not require a binarization of the input image, which makes it applicable to the palimpsest images investigated. The interested reader is referred to [YHKD09] for a detailed explanation of the text line detection algorithm. Before the algorithm is applied on a PCA image, a simple preprocessing step is required: Since the PCA images show partially the overwriting, it is necessary to modify the images: Therefore, the overwritten regions in a PCA image are simply filled with the median gray value of the remaining image.

Afterwards, the text line detection algorithm is applied. The multispectral samples contained in the text line regions are labeled as belonging to class X_1, the samples in the intermediate regions are labeled as belonging to the background class X_2 and the output of overwriting detection step is labeled as belonging to class X_3. The labeled samples are then used for the training of an LDA classifier by applying Equation 3. Afterwards, all multispectral samples - including labeled and unlabeled samples - are projected on the hyperplane found by the classifier. Thus, the dimensionality of the multispectral scan is lowered and two resulting images are obtained, whereby the first image enhances the underwriting and the second image emphasizes the overwriting. These resulting images are hereafter referred to as LDA images.

Figure 5 shows the LDA images enhancing the underwriting. The images are obtained, by applying the procedure mentioned on the PCA images shown in Figure 4. It can be seen that the underwriting is visible in each LDA image. This can be attributed to the fact that each PCA image is at least showing vestiges of the underwriting. Therefore, the text line detection algorithm is able to recognize the text line scheme and the underwriting is enhanced in the resulting LDA image.

In order to obtain a single image showing the underwriting, the PCA transformation is afterwards applied on the LDA images showing the palimpsest text. Since the underwriting is visible in the majority of the LDA images it is emphasized by the first PC. This image is used in the final step: Again, the LPP based text line detection algorithm is applied on the resulting image and the output is used for a further application of the LDA based dimension reduction. Figure 6 shows the final outputs of the method proposed. It can be seen that the overwriting image - shown in Figure 6 (left) - has a high foreground to background contrast and

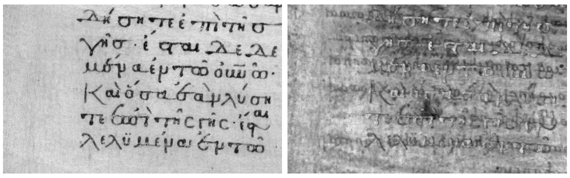

Figure 6: *Overall result of the LDA based enhancement method. (Left) Image showing the overwriting. (Right) Image showing the underwriting.*

that the image contains barely vestiges of the underwriting. The underwriting image - shown in Figure 6 (right) - has a lower foreground to background contrast and the image is blurred. This can be attributed to the fact the labeling of the underwriting is solely based on text lines instead of characters. Thus, a certain amount of foreground pixels are labeled falsely as belonging to the background.

A more accurate labeling could be gained by applying the binarization approach on the LDA image showing the underwriting. Unfortunately, due to the bad condition of the 'Suppl. Gr. 200' codex the binarization algorithm cannot be applied successfully. Nevertheless, if we compare the underwriting image with the multispectral images and the PCA images, we can see that the underwriting is better recognizable in the LDA image.

5. Results

To the best of our knowledge there is no direct performance measurement for the enhancement task existing. Therefore, we provide exemplar results in order to allow for a qualitative comparison between results obtained with the method proposed and results gained by other techniques. The method is compared to two unsupervised dimension reduction techniques, namely PCA and ICA. The ICA implementation used is the FastICA [HO00] algorithm, which is also used in [STB07] for the enhancement of palimpsests that are captured by a MSI system [ECBK11]. The output of the FastICA algorithm depends on a random initialization and on several parameters. More details on the parameter dependency can be found in [STB07]. Hence, we applied the algorithm several times with different parameters and selected the best outcome for the evaluation task. For the evaluation of the PCA performance, the best PCA outcome was also selected manually, because a writing can be emphasized by multiple PCs.

Figure 7 shows the PCA, ICA and LDA results gained on the MSI data provided in Figure 2. It can be seen that underwriting is best visible in the LDA based enhancement technique. A further comparison between enhancement results is given in Figure 8. In this case the underwriting is again best visible in the LDA image. However, it should be noted that it is not guaranteed that the LDA outcome is superior to

Figure 4: *PCA images. The images are sorted based on the corresponding eigenvalues, which are sorted in a descending order.*

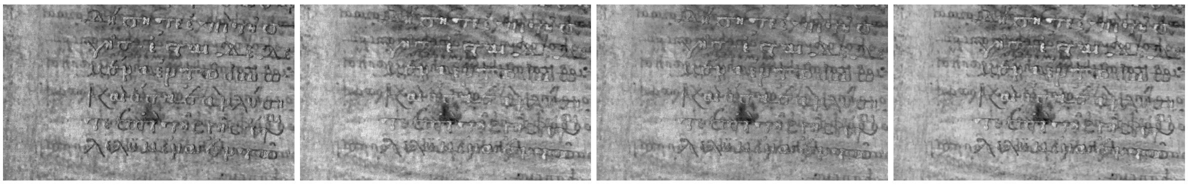

Figure 5: *LDA images.*

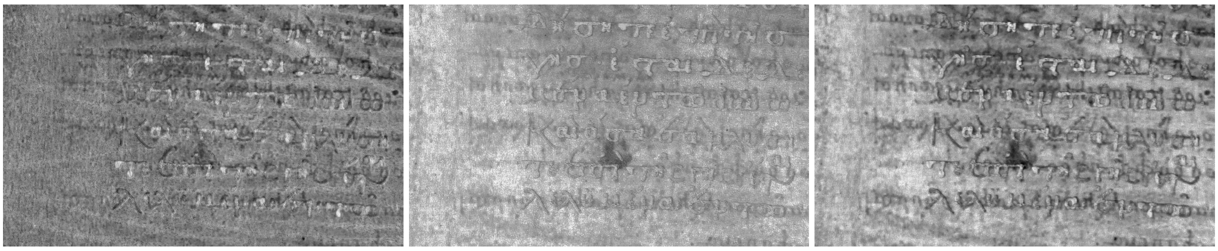

Figure 7: *Comparison between different enhancement results. From left to right: PCA image. ICA image. LDA image.*

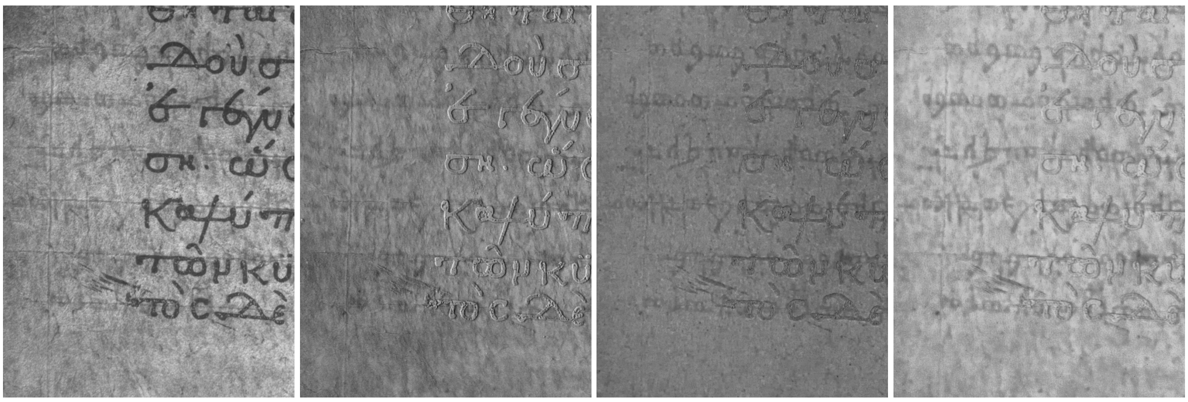

Figure 8: *Comparison between different enhancement results. From left to right: UV reflectography image. PCA image. ICA image. LDA image.*

the PCA and ICA images. Therefore, we suggest to apply all techniques and to decide, which output is most appropriate.

A further enhancement result gained on the 'Suppl. Gr. 200' is provided in Figure 9. The top row shows image portions captured under white light and UV light. The left image at the bottom row shows the corresponding UV reflectography image. The right image at the bottom row of Figure 9 shows a pseudo color image that is generated based on the LDA enhancement results. The pseudo color image is obtained by inserting the image, which shows the overwriting, into the red channel. The image showing the underwriting is put into the remaining channels of the pseudo color image. Easton et al. [ECBK11] report that scholars favored such pseudo color images, since they show the over- and underwriting at a glance.

While the enhancement results presented have been gained on manuscripts containing palimpsest texts, the algorithm has also been applied on manuscripts containing a single writing. These manuscripts are written in a Slavic script and one of the two books, named 'Missale Sinaiticum', is especially degraded, since the color of the ink discolored partially from black to white [MGK*08]. An example for this circumstance can be seen in Figure 10: The writing is barely visible in the white light image. In contrast, the writing is only partially visible in the UV fluorescence image. The text is also partially visible in the NIR image, whereby the text regions are brighter than the remaining background regions. The corresponding enhancement results are given in the bottom row of Figure 10. It can be seen that the contrast of the writing is enhanced by all methods, whereby the PCA output is clearly inferior to the LDA and ICA outputs. It should be noted that in contrast to the palimpsest examples presented, the degraded text in the 'Missale Sinaiticum' is not always best visible in the UV range. Instead, the writing is partially better recognizable in the NIR range or in the visible range. In this cases, the legibility of the text can be increased by taking images in spectral ranges that are above the UV range.

In order to evaluate the performance of the LDA based enhancement technique, a quality assessment has been performed by humans. Since such a quality assessment is a subjective issue, it was performed by two philologists experienced in ancient Slavic scripts. Therefore, 7 test panels belonging to two ancient Slavic manuscripts have been extracted. Both manuscripts are not containing palimpsest texts, but instead single and degraded writings. By emphasizing a certain character, the visual quality of another character within the same portion might be worsened if the letter has a different spectral signature. Hence the scholars did not evaluate entire image patches, but single characters instead. A grouping into categories of visual quality was not used, due to high variety of the enhancement results. Instead, the scholars were asked to compare single characters, which were produced by different techniques, pairwise. The techniques evaluated are PCA, ICA and LDA. Additionally,

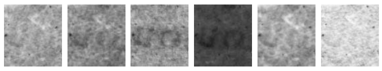

Figure 11: *Example of the test set. The scores assigned are from left to right: 1, 3, 5, 4, 2 and 0.*

Table 1: *Average scores gained on test panels*

Panel #	PCA	ICA	MSI	LDA
1	0.5/0.5	1.2/1.5	1.3/1.2	**2.7/2.5**
2	0.4/0.8	**2.1**/1.7	1.7/**1.9**	1.8/1.2
3	1.3/1.7	1.7/1.9	0.9/0.5	**2.1/2.0**
4	2.3/1.4	2.6/1.9	0.5/0.2	**3.9/3.1**
5	**3.7/3.0**	2.5/2.6	2.8/2.6	2.0/1.3
6	1.4/1.9	2.6/2.9	0.8/1.1	**3.8/3.9**
7	2.6/2.2	2.8/1.8	2.6/4.3	**4.0/4.4**

the multispectral image, which showed the writing best was added to the test set. The philologists were not told which method was used for the enhancement of a particular character. For each compared letter pair, the scholars decided which letter was found more legible and assigned a one to the superior result image and a zero to the inferior counterpart. Afterwards, the sum of the assigned scores was calculated.

An example of the test set and the assigned scores are provided in Figure 11. The average scores gained are provided in Table 1. The first column shows the numbers of the test panels and the remaining columns show the score gained by the enhancement methods. The fourth column titled MSI contains the assigned score to the multispectral image, which showed the text best.

It can be seen that the method proposed achieves on 5 out of 7 test panels the highest average score. On the contrary, in the fifth test panel the algorithm gained a relative low score of 2.0. This can be attributed to the fact that the line detection failed on several PCA images, because the background within those PCA images is highly varying and is partly darker than the dominant foreground color. Thus, the enhancement method emphasizes the background variations instead of the writing. It should be noted that the method is highly depending on the output of text line detection step. Hence, if the document is strongly degraded by background clutter the algorithm fails. Additionally, in the case of decorative elements - such as initials - the method is often not capable of detecting the text line regions correctly.

6. Conclusion

This work is concerned with the enhancement of ancient documents that are captured by MSI systems. The imaging in selected narrow band spectral ranges is capable of enhancing the contrast of degraded writings, compared to white light illumination. However, the manuscript portions

Figure 9: *Enhancement of a portion belonging to the 'Suppl. Gr. 200' manuscript. Top row: (Left) Image taken under white light. (Right) UV fluorescence image. Bottom row: (Left) UV reflectography (Right) Pseudo color image.*

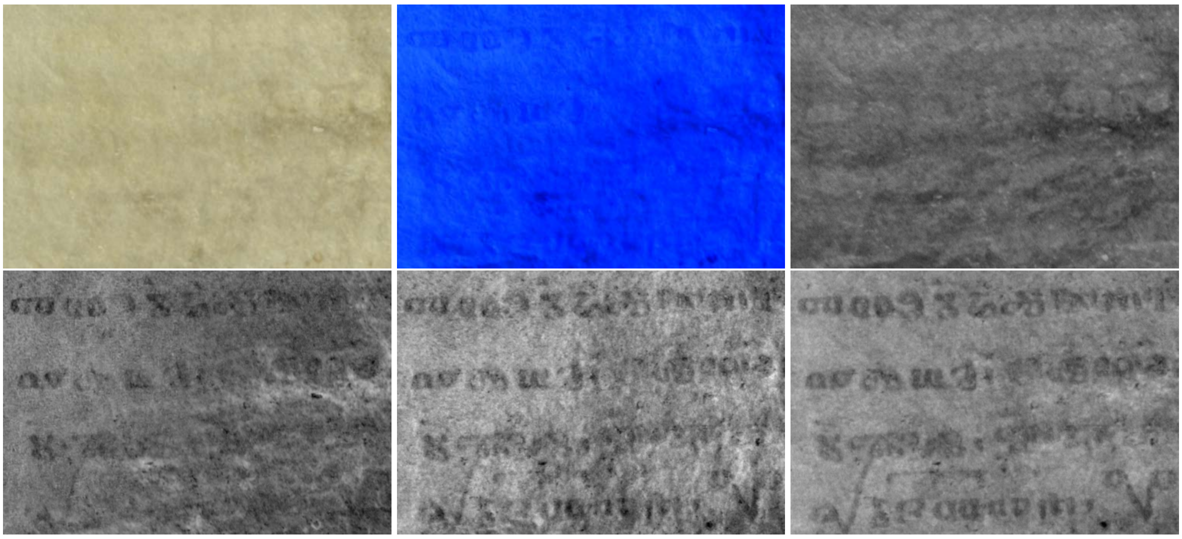

Figure 10: *Portion belonging to the Missale Sinaiticum manuscript. From left to right: (Top row) White light image. UV fluorescence image. IR reflectography image, with a long pass filter at 800nm. (Bottom row) PCA image. ICA image. LDA image.*

are partially illegible, even in the multispectral images. Dimension reduction techniques can be used to lower the dimensionality of the multispectral scan and to gain a further contrast enhancement. This work makes usage of LDA based dimension reduction. Since LDA is a supervised dimension reduction, it is necessary to label a subset of the data as belonging to different classes. For this purpose, an automated labeling strategy has been proposed that makes use of spatial information. It has been shown that the method is capable of enhancing the contrast of degraded writings, compared to unprocessed multispectral images. Thus, the legibility of the writings is enhanced and the resulting images can serve as preprocessing step for further document analysis methods.

7. Acknowledgement

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References

[CB12] CHRISTENS-BARRY W. A.: LED Imaging of the Archimedes palimpsest, accessed 2012. http://archimedespalimpsest.org/imaging_experimental3.html. 2

[DHS01] DUDA R., HART P., STORK D.: *Pattern Classification*, 2 ed. Wiley-Interscience, New York, 2001. 3

[ECBK11] EASTON R., CHRISTENS-BARRY W., KNOX K.: Spectral Image Processing and Analysis of the Archimedes Palimpsest. In *19th EUSIPCO* (2011), pp. 1440–1444. 1, 2, 5, 7

[EKCB03] EASTON R., KNOX K., CHRISTENS-BARRY W.: Multispectral Imaging of the Archimedes Palimpsest. In *32nd Applied Image Pattern Recognition Workshop, AIPR 2003* (Washington, DC, October 2003), IEEE Computer Society, pp. 111–118. 2

[HC13] HEDJAM R., CHERIET M.: Historical document image restoration using multispectral imaging system. *Pattern Recognition 46*, 8 (2013), 2297–2312. 1, 2

[HO00] HYVÄRINEN A., OJA E.: Independent component analysis: algorithms and applications. *Neural Networks 13*, 4-5 (2000), 411–430. 5

[KDB11] KIM S. J., DENG F., BROWN M. S.: Visual enhancement of old documents with hyperspectral imaging. *Pattern Recognition 44*, 7 (2011), 1461–1469. 2

[LDSM08] LETTNER M., DIEM M., SABLATNIG R., MIKLAS. H.: Registration and Enhancing of Multispectral Manuscript Images. In *16th EUSIPCO* (2008). 1, 2, 4

[MGK*08] MIKLAS H., GAU M., KLEBER F., DIEM M., LETTNER M., VILL M., SABLATNIG R., SCHREINER M., MELCHER M., HAMMERSCHMID E.: St. catherine's monastery on mount sinai and the balkan-slavic manuscript-tradition. *Slovo. Towards a Digital Library of South Slavic Manuscripts* (2008), 13–36. 7

[RB05] RAPANTZIKOS K., BALAS C.: Hyperspectral imaging: potential in non-destructive analysis of palimpsests. *ICIP 2* (11-14 Sept. 2005), II–618–21. 2

[SLT10] SU B., LU S., TAN C. L.: Binarization of historical document images using the local maximum and minimum. In *DAS* (2010), pp. 159–166. 4

[STB07] SALERNO E., TONAZZINI A., BEDINI L.: Digital image analysis to enhance underwritten text in the archimedes palimpsest. *IJDAR 9*, 2-4 (2007), 79–87. URL: http://dx.doi.org/10.1007/s10032-006-0028-7, doi:10.1007/s10032-006-0028-7. 1, 2, 5

[War85] WARTENBERG D.: Multivariate Spatial Correlation: A Method for Exploratory Geographical Analysis. *Geographical Analysis 17*, 4 (1985), 263–283. 2

[YHKD09] YOSEF I. B., HAGBI N., KEDEM K., DINSTEIN I.: Line segmentation for degraded handwritten historical documents. In *ICDAR* (2009), pp. 1161–1165. 5