Registration of Multi-spectral Manuscript Images as Prerequisite for Computer Aided Script Description

Martin Lettner[1], Markus Diem[1], Robert Sablatnig[1], Paul Kammerer[1], and Heinz Miklas[2]

[1]Pattern Recognition and Image Processing Group
Institute for Computer Aided Automation, Vienna University of Technology
lettner@prip.tuwien.ac.at,

[2]Institute for Slavonic Studies, University of Vienna
heinz.miklas@univie.ac.at

Abstract *This paper presents preliminary results of a collaboration of philologists and computer scientists devoted to the recording, investigation and editing of two medieval Slavonic manuscripts of extraordinary importance. The goal of the project lies in the development of techniques and tools for the recording, restoration and analysis of such sources in order to support the philological studies by automatically deriving the description and restoration of the relevant scripts. The algorithms developed shall enable the philologists to perform their tasks better and faster, while we do not aim to develop software that reads old handwriting automatically. First, the acquisition of multi-spectral images of the manuscripts give the basis to improve the readability of the texts. Image registration of the multi-spectral images and their enhancement are necessary steps for the subsequent computer aided script description and reconstruction. Here, an overview of the interdisciplinary project and preliminary results of the multi-spectral acquisition and registration are presented.*

1 Introduction

The study of handwritten sources covers a wide field reaching from the examination of the physical body up to the text and its contents, make-up and condition. Until the 1990ties this was mainly a domain of the humanities. Technical scientists were engaged predominantly in the recording and conservation of valuable objects. During recent years, however, interdisciplinary work has gained ground, concentrating not any more on a few special tasks, like the development of Optical Character Recognition (OCR) software, but comprising a growing amount of relevant items: the description of manuscripts, the Internet-publication of texts, the imaging and restoring of watermarks [1], palimpsests [2] and other latent texts [6], or a thorough description of writing systems and the identification of individual handwriting [24, 5]. Without overestimating the progress made so far, we can speak of a new era in the study of traditional written sources. And it may be expected that in the long run the decipherment, study and editing of such sources will be

- done predominantly based on images; a way that relieves the originals and makes their investigation independent of the place of preservation,
- enabled or improved by special recording methods like multi-spectral and radiographic imaging,
- more exhaustive, precise and less time consuming through automatic image analysis, and
- executed with a set of tools, obtainable in every computer shop and applicable by anyone interested in the matter with little training.

In this paper we give a survey of recent developments in image analysis for historical handwritten documents. Furthermore we present an overview of an interdisciplinary project where philologists and computer scientists will collaborate to enable a multifold progress in their fields both in time and substance. Finally we will show some preliminary results of a multi-spectral image acquisition system of historical manuscripts and a method for a fully automatic image registration. The registration process is necessary in order to align one spectral image to the other. Up to now the images of the different spectral ranges had to be registered manually.

Our project is devoted to the recording, investigation and editing of two medieval Slavonic manuscripts of extraordinary importance. Its second goal lies in the development of techniques and tools for the recording, restoration and analysis of such sources in order to support the philological studies. This scenario requires, on the one hand, the further improvement of traditional (philological and historical) methods and their transfer into technical methods of investigation, and, on the other, certain advances in the areas of recording, image-processing and image-analysis of handwritten and printed texts.

The objects to be edited are two Glagolitic [3] manuscripts with Cyrillic and Greek additions of the classical Old

[1]e.g. http://www.bernstein.oeaw.ac.at/

[2]A palimpsest is a manuscript page (particularly parchment) that has been written on, erased and used again.

[3]The Glagolitic alphabet is the oldest known Slavic script.

Church Slavonic (OCS) corpus, belonging to the new findings made in 1975 at St. Catherine's monastery on Mt. Sinai: *Euchologii Sinaitici pars nova* and *"Missale" (Sacramentarium) Sinaiticum* [18].

The project is subdivided into the following subtasks:

- Multi-spectral image acquisition
- Image registration and image enhancement
- Technical image analysis consisting of a computer aided script description and the reconstruction of broken character links
- Material analysis
- Philological image analysis and editorial steps

First, a multi-spectral acquisition of the manuscripts shall give the basis to improve the readability of the texts. Image registration, image enhancement, and a computer aided script description and restoration will then foster the philological work. A non-destructive material analysis will enable the definition of parchment, inks and pigments. The philological tasks include the decipherment, paleography and graphemics of the written material on the one hand, and the text constitution and text comparison, commentaries, a glossary and an introduction on the other.

The most challenging part of the project from the standpoint of image analysis lies in the description and reconstruction of the relevant scripts. Yet it has to be stressed that the algorithms to be developed shall only enable the philologists to perform their tasks better and faster. Figure 1 shows the flow chart of the project subtasks and the collaboration between them.

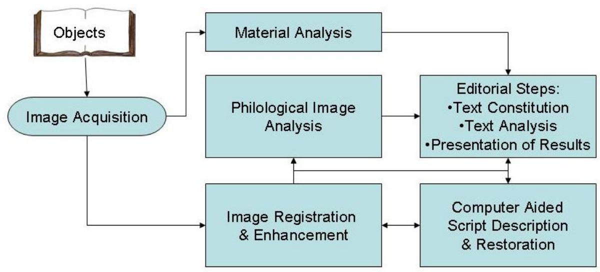

Figure 1: Flow Chart of the project subtasks.

This paper is organized as follows: The next section shows related work and gives an overview in the fields of image acquisition and technical image analysis for historical documents (manuscripts). Section 3 presents the methodology of the image analysis part within this project. The following sections cover the image acquisition (Section 4) and registration (Section 5) in more detail and show preliminary results. The last section gives a conclusion and an outlook.

2 Related Work

There have already been quite a few efforts in image analysis of historical documents. In general, differences between image analysis for ancient vs. modern documents accrue particularly from the aging process of the documents, the fading out of ink, or, e.g., environmental influences which complicate the analysis. Some major and several related studies in image analysis of historical documents will be covered in this section.

Multi- and hyper-spectral imaging has been used in a wide range of scientific and industrial fields including space exploration like remote sensing for environmental mapping, geological search, medical diagnosis or food quality evaluation. Recently, the technique is getting more and more applied in order to investigate old manuscripts. Two prominent representatives are the Archimedes Palimpsest [6] and Tischendorf's Codex Sinaiticus [7]. Easton et al. were the first to capture and enhance the erased writing of the famous Archimedes palimpsest by multi-spectral methods [6]. The system they propose is modeled on the VASARI illumination system developed at the National Gallery of London [17]. In the project it turned out that the adoption of spectral imaging produces higher and better readability of the texts than conventional thresholding methods. Balas et al. developed a computer controllable hyper-spectral imaging apparatus, capable of acquiring spectral images of 5nm bandwidth and with 3nm tuning step in the spectral range between 380-1000nm [1]. This device was selected as the instrument of choice for the Codex Sinaiticus Digitization Project conducted by the British Library in London [7]. Very good results in the enhancement of spectral images of palimpsests and other latent texts have also been achieved by the Italian company Fotoscientifica Re.co.rd.® [4] which provided for instance the pictures for the EC project *Rinascimento virtuale*, devoted to the decipherment of Greek palimpsest manuscripts [12]. The EC project IsyReaDeT developed a system for a virtual restoration and archiving of damaged manuscripts, using a multi-spectral imaging camera, advanced image enhancement and document management software [29].

For the enhancement of the readability Easton et al. used an unconstrained least squares algorithm for spectral unmixing and produced normalized and non-negative fraction maps of text and parchment [6]. The combination of these fraction maps can be used to highlight different classes, e.g. the underlying text and the overwriting. Rapantzikos and Balas separated the overwritten from the underwritten text-layer by means of the Principal component analysis (PCA) and a linear spectral mixture analysis [25]. Promising results are also obtained by Tonazzini et al. who applied an independent component analysis (ICA) to the spectral components at different bands to separate bleed-through and show-through texts as well as palimpsests [29]. The major advantage of this method is that no models are required (Blind Source Separation). For the extraction of "hidden information" of multi-spectral images, methods adapted from remote sensing applications are also appreciable, e.g. PCA, to emphasize information hidden in individual spectral bands. The generation of binary images out of ancient manuscripts is discussed by Bar-Yosef [2]. Since the behavior of different inks is different in multi-spectral bands

[4] http://www.fotoscientificarecord.com/

[15] the results depend on the method used for enhancing the digital images.

Some studies on historical documents cover not only the enhancement of the readability but also the analysis of the text contents in more detail. For instance, Manmatha and Rothfeder [16] as well as Feng and Manmatha [8] investigate several methods for the segmentation of words in historical documents, focusing on the whole word in order to avoid character segmentation which is difficult with degraded documents. Features for word spotting are also described by Rath and Manmatha [26] and Leydier et al. [13]. Text extraction from gray scale historical document images is investigated by Shi et al. [28], who use an adaptive local connectivity map to extract text from background. Blobs containing several instances of degraded characters are analyzed by Tonazzini et al. [30], but this study is already based on printed characters and not on medieval written sources.

In the area of Philological and Computer Aided Script Description and Restoration there are also some publications which have to be mentioned. Although the subject has been treated in numerous publications, many of them comprised in the GICAS On-line Research Library[5], even for the description of Western writing systems no comprehensive, adequate model seems to exist so far. For Asian systems the GICAS project was started in 2001. It is to be hoped that this gap will be filled by a graphematic approach to the description of writing systems. While most efforts have been devoted to the recognition and analysis of modern individual handwriting in Latin scripts (cf. especially the results of the Graphonomic Society[6]), only a few recent projects concern the computer aided recognition and analysis of old handwriting. Recent developments of OCR software for historical manuscripts are presented for instance by Ntzios et al. who concentrate on ancient Greek handwritten texts [21]. A similar study by Clocksin and Fernando describes a method for the recognition of Syriac handwriting [4], and Yosef et al. present preliminary classification results when analyzing calligraphic styles of Hebrew handwriting [2]. Image analysis for paleography inspection is discussed by Moalla et al. [19]. They classify some different Latin writing styles into predefined classes but do not investigate the scripts in more detail. A detailed overview in the recognition of cursive Roman Handwriting is given by Bunke [3].

While image acquisition and enhancement have been treated quite often in computer science and serve for a better readability of latent texts, usually their results still have to be deciphered and analyzed by conventional philological methods. Consequently, the computer aided script description and reconstruction will be the major technical innovation in our project.

3 Methodology

From a pattern recognition point of view, the problem can be subdivided into two major goals: the image registration and enhancement on the one side, and the computer aided script description and reconstruction on the other.

When an image is to be utilized it is necessary to make corrections in brightness and geometry if the accuracy of interpretation is not to be prejudiced. Geometrical and radiometrical errors (i.e. vignetting, chromatic aberration and non linear geometric distortion) have to be detected (e.g. with test patterns) and corrected to achieve the desired accuracy [27]. The following registration process aligns one image to the other by establishing a coordinate transformation that relates the pixel coordinates from one image to another. Then the resulting images will be enhanced with various image processing techniques to further increase the readability of the text and to prepare it for the following computer aided script description.

To improve the legibility of the texts several methods, like contrast enhancement, independent component analysis [29], filters for background removal [9] or homomorphic filtering [23] are applicable. We will combine and improve these methods also in order to prepare the text images for the computer aided description (analysis) and reconstruction of individual scripts.

For specific tasks like ruling, line structure, and layout analysis, 2D projection techniques used in standard OCR will be reused, whereas primitive analysis tools must be developed and adapted. Furthermore, before extracting and defining single characters, the text structure (lines, paragraphs etc.) has to be analyzed; and unlike in standard OCR systems, the grammar and lexicon of OCS have not been studied yet.

The most challenging part of the project from the stand point of image analysis lies in the description and reconstruction of the relevant scripts, since even handwritten character recognition is still a huge research area and far from being solved. A recent study by Ntzios et al. devoted to the OCR of Greek minuscule manuscripts [21] will be of little help as in this case we have to do with OCS Glagolitic and Cyrillic and the Greek majuscule script.

After extracting the text from its background and establishing its features we are particularly interested in the analysis of graphical primitives. For this the comparison of primitives like majuscule-characters, punctuation and supralinear marks is of central concern: How was the primitive composed? In which direction was the stroke set? Which strokes were first? To answer questions like these, the primitives must be characterized with a statistical precision. Therefore it is necessary to automatically extract a relatively high number of identical primitives. Then statistical statements on the primitive parameters (size, shape, tilt angle, structure, density, number of strokes, directions, etc.) can be made. This also enables the isolation and classification of primitives, the results of which will be reused for their restoration in (partially) destroyed instances. Stroke detection is only practicable if an accurate model of a stroke is defined beforehand. The results of a stroke detection method based on a model incorporating parameters like length, width, curvature etc. are given by images of detected stroke segments in various orientations. These stroke segments are grouped into strokes by matching similar curvatures and orientations of neighboring stroke segments. If they match within certain tolerances, these stroke

[5] http://www.gicas.jp/

[6] http://www.cedar.buffalo/igs/

segments are connected forming the original stroke. The detected strokes are needed to carry out a structural analysis. The structure of the stroke segments allows the classification of the primitives. Since there are similar arrangements in all objects, we have to do with two different kinds of characteristics: scribe dependent characteristics given by the individual handwriting and scribe independent characteristics as a constraint from the shape of the character. The primitives extracted (characters) are then statistically analyzed in terms of stroke parameter deviation, stroke direction and angle with respect to the ruling angle, density and so on in order to uniquely identify and classify primitives. In this concept every primitive has a priori known parameters: shape, relative position and size. Based on the shape of the primitives, pattern recognition algorithms are then selected to detect the primitives in intensity images. Together with an object-specific shape based description, an analysis graph is instantiated to perform the recognition and classification.

The following points summarize the specific goals of the image analysis part of the project:

1. High resolution, multi-spectral image acquisition
2. Geometrical and radiometrical corrections
3. Image registration and image enhancement to increase the readability of latent texts
4. Incorporation of OCR knowledge and philological parameters for the description of scripts and writing systems:
   - Layout analysis (shape and size of page layout)
   - Ruling analysis (position, number and angle of lines with respect to borders)
   - Line structure analysis (number of primitives per line)
   - Automatic extraction of primitives for statistical evaluation
   - Primitive analysis and classification
   - Representation of character primitives for database applications
   - Scribe analysis on the basis of variations of primitives in different parts
   - Reconstruction of missing links of primitives (characters) in enhanced images

4 Image Acquisition

The first step enabling the technical and philological image analysis is the digitization of the manuscripts. Since photographic techniques in the visible range (film, digital camera) have proven to be insufficient with the objects given, spectral imaging will have to be applied. Like in the field of Art Research and Conservation, multi- and hyper-spectral imaging techniques have become a powerful tool in the scientific analysis and documentation of old manuscripts with “latent” (degraded, disintegrating and overwritten) texts, since images in different wavelengths provide information that the human eye cannot see [25]. Applied in the spectral range from ultra-violet (UV), visible light range (VIS) up to the infrared (IR) range, these techniques combine conventional imaging and spectrometry to acquire both spatial and spectral information from an object. They produce three dimensional images or spectral image cubes where the third dimension contains spectral information for each pixel. According to the number of spectral channels we distinguish between multi-spectral for fewer channels and hyper-spectral for a large number of spectral channels.

For the acquisition of the manuscripts we use a Hamamatsu C9300-124 camera system, furnished with additional equipment. The C9300-124 is a high resolution camera with 10 Mega pixels using a high-speed interline transfer CCD chip. Its spectral response lies between 330 and 1000nm (similar to the hyper-spectral MuSIS^{TM}camera system [1]). To obtain multi-spectral data a set of optical filters is used to select the best specific ranges from the spectrum. Easton et al. used 4 different spectral bands to improve the readability of the Archimedes palimpsest [6]. A lighting system provides the required illumination (UV, VIS and IR) for the multi-spectral images, and filters fixed on the lens of the camera select specific spectral ranges. Figure 2 shows the acquisition system.

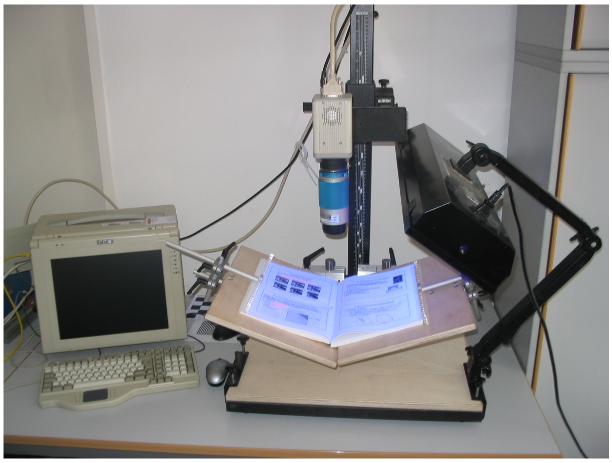

Figure 2: Acquisition System.

For the investigation of old manuscripts several methods have been developed. It is known that especially in the UV range additional information appears which is invisible for the naked eye [10, 15]. The near UV (400 nm - 320 nm) excites in conjunction with specific inorganic and organic substances visible fluorescence light [15]. For our preliminary studies we have recorded historical manuscripts with UV fluorescence and UV reflectography, showing palimpsests of ancient handwritings:

UV reflectography to visualize retouching, damages and changes through e.g. luminescence. Therefore the visible range of light has to be excluded in order to concentrate on the long wave UV light. This is only achievable with a difficult technical effort.

UV fluorescence shows only changes in the upper script (paint) layer. In principle, grabbing the visible fluorescence of objects is possible with every camera.

Thus we have two different images of one and the same manuscript: the UV reflectography image and the UV fluorescence image. These are only some preliminary test images (espacially to develop the registration process) but we are going to expand the number of the spectral images with a couple of spectral filters (cf. [6]).

5 Image Registration

Following the acquisition of the manuscript images the images have to be registered. Image registration is a fundamental task in image processing used to match two or more pictures taken under different conditions. For instance, during the acquisition of images in different bands the objects or the camera may be affected as a result of filter changes. Up to now the images had to be registered manually using commercial image processing software.

Image registration is the process of estimating the ideal transformation between two different images of the same scene taken at different times and/or different viewpoints. It geometrically aligns images so that they can be overlaid. There is a wide variety of different methods (especially in remote sensing and medical imaging applications) like the use of corresponding structures or mapping functions [27] which can be adapted for this application. An overview of image registration methods is given by Zitova and Flusser [32].

The image registration process proposed in this paper and in the majority of registration methods [32] can be separated in four steps:

Feature detection Features are detected automatically in the so-called reference image. For further processing, these features are represented by a point which is placed in their center and denominated as control point.

Feature matching The correspondence between the feature of the reference image and an area in the sensed image is established. The similarity measurement is calculated by the normalized cross correlation.

Transform model estimation The parameters of the mapping function, aligning the sensed image with the reference image, are estimated using the previously computed corresponding control points.

Image resampling and transformation The sensed image is transformed by means of the local weighted mean transformation which is a local mapping function [11]. Non-integer coordinates are interpolated.

5.1 Feature detection

Incipiently the input images are prepared for registration by means of low level image processing. These steps include homomorphic filtering [23], non-linear diffusion [20, 31] and thresholding [22] in order to detect features (e.g. characters) that allow a best possible cross correlation. The homomorphic filtering and the non-linear diffusion are intended for reducing noise in images so that the cross correlation compares exclusively characters. Additionally a binary image of the reference image is generated by Otsu's thresholding approach [22]. Thus, the shapes of detected features can be calculated with little efforts.

Characters as well as punctuations etc. recur within lines and paragraphs. If their visual information is sparse (e.g. an "i" or a point in the Latin font), the mistake rate of the cross correlation will be high. Therefore, in order to be selected for cross correlation the features have to satisfy a minimum magnitude.

5.2 Cross Correlation

The features detected in the images can be matched by means of the image intensity values in their close neighborhood, the feature spatial distribution, or the feature symbolic description. Cross correlation is an area-based method which does not need features of images which have to be registered. As previously mentioned the established algorithm detects features exclusively in the reference image in order to avoid false correspondence.

The cross correlation calculates the difference of two display windows by means of a modified euclidean distance. The so-called template image is an image detail of the reference image. Its image size corresponds to the bounding box of the afore found feature. According to the disparity of the reference and the sensed images the magnitude of the display window, taken from the sensed image, is defined. Having defined the display windows which have to be compared, the template image is shifted over the entire detail of the sensed image. For each shift the correlation between the template and the display window is computed. The resultant function indicates the strongest correspondence of the template image and the display window by the absolute maximum. Hence the control point of the sensed image is seated at the coordinates of the absolute maximum.

The cross correlation is variant to changes in the image amplitude caused, e.g., by changing lighting conditions. Consequently, the correlation coefficient normalizing the template as well as the display window of the sensed image is computed. According to the templates magnitude, the proportion of the template and the display window, the computation is performing better in the frequency domain than in the spatial domain.

5.3 Transformation

Having determined the control points, the parameters of the mapping function are computed. Images which possess only global distortions (e.g. rotation) may be registered with a global mapping function. Likar and Pernuš mentioned that the global rigid, affine and projective transformations are most frequently used [14]. As a consequence of non-rigid distortions such as the changing lenses, illumination or curvature of a single page, the images have to be registered using a curved transformation. Using a global mapping function is practicable only when a low number of parameters defining the transformation is needed (e.g. for rigid or affine transformations). Curved transformations are defined by numerousness parameters, which results generally in a complex similarity functional that has a large amount of local

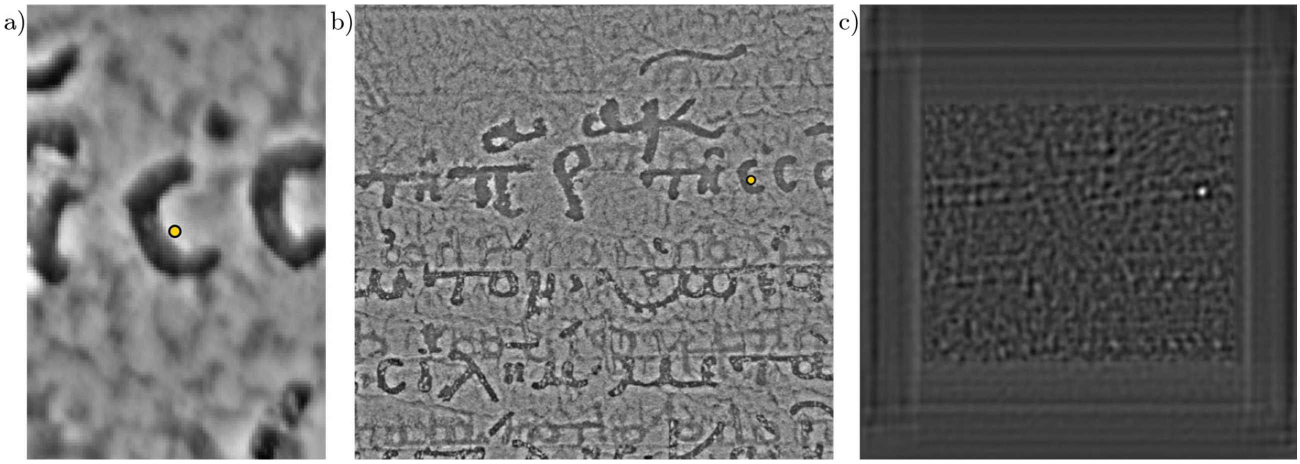

Figure 3: A control point at the center of the template image (a). Display window of the UV reflectography image with the corresponding control point (b). Normalized cross correlation with the absolute maximum (c).

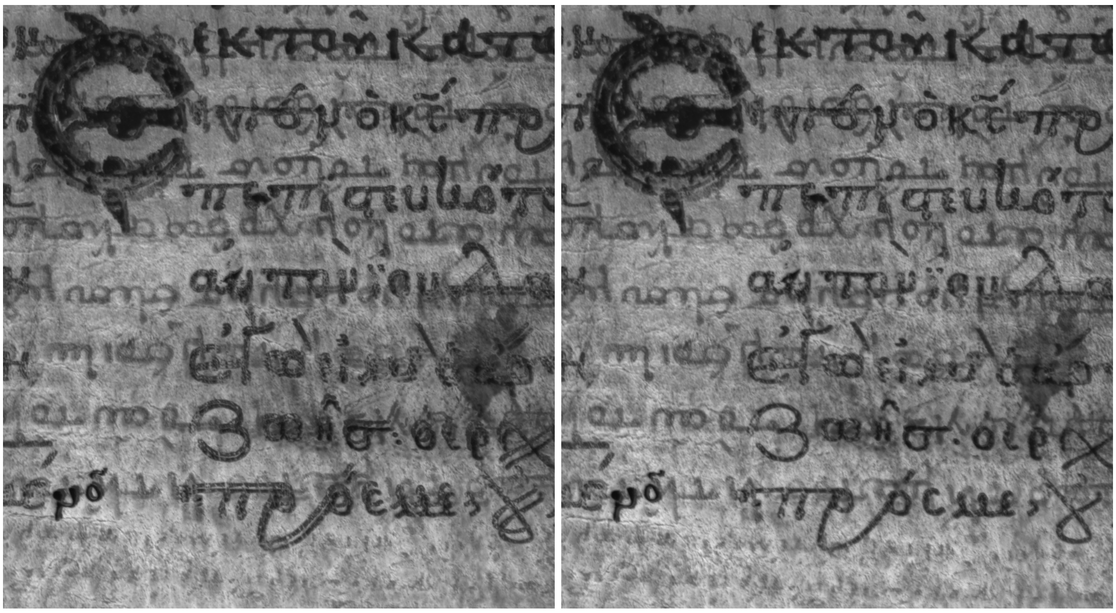

Figure 4: UV fluorescence image registered to the UV reflectography image using an affine mapping function (left). Registration with the same control points using a local weighted mean transformation (right).

optima. To overcome this problem a local mapping function is applied. The local weighted mean method [11] is a local sensitive interpolation method. It requires at least 6 control points which should be spread uniformly over the entire image. Polynoms are computed by means of the control points. Thus, the transformation of an arbitrary point is computed by the weighted mean of all passing polynomials. Besides, a weighting function is defined which guarantees that solely polynomials near an arbitrary point influence its transformation.

5.4 Results

Resulting images of the previously mentioned algorithms are presented in Figure 3 and Figure 4. Figure 3a shows the UV fluorescence template image with a control point located in its center. The display window with the corresponding control point of the UV reflectography image is shown in Figure 3b. Computing the normalized cross correlation of these two images results in the third image (see Figure 3c) where the white blob shows the absolute maximum.

The local weighted mean method was compared to a global interpolation method (see Figure 4). As a consequence of the global mapping function the registered images correspond only to certain parts of the images. Hence, the farther the points are away from the corresponding area, the more they differ. That is why a local mapping function was used to compute the transformation.

6 Conclusion and Outlook

This paper introduced an interdisciplinary project of computer scientists and philologists. The main goals of the project are the preparation of a edition of two medieval Slavonic manuscripts of extraordinary importance where the technical image analysis supports the philological studies. The methodology of the image processing part is as follows. First, a multi-spectral image acquisition will improve the readability of the manuscripts. Then a registration process aligns the images of the different spectral bands. Preliminary results of the registration process are already presented in this paper.

In this paper we demonstrated some preliminary results for the registration process of two different spectral bands of digital images from ancient manuscripts. We registered an UV reflectoggraphy image and an UV fluorescence image in order to avoid a manual registration which causes errors. For the registration of the multi-spectral images we are going to compare the method proposed to some others (e.g. [14]) and we also will evaluate the method when applied on synthetic images.

The next steps of the project will cover the enhancement of the readability of the text. For this we will perform a PCA or comparable methods in order to find the most effective method for our purposes. Then page segmentation and the segmentation of the primitives (characters) will be exhaustively analyzed as a basis for the philological studies. The major goal of the project from the standpoint of image analysis lies in the description and reconstruction of the relevant scripts which might also be the most challenging one.

References

[1] C. Balas, V. Papadakis, N. Papadakis, A. Papadakis, E. Vazgiouraki, and G. Themelis. A novel hyper-spectral imaging apparatus for the non-destructive analysis of objects of artistic and historic value. *Journal of Cultural Heritage*, 4(1):330–337, January 2003.

[2] I. Bar-Yosef, K. Kedem, I. Dinstein, M. Beit-Arie, and E. Engel. Classification of Hebrew Calligraphic Handwriting Styles: Preliminary Results. In *1st International Workshop on Document Image Analysis for Libraries (DIAL 2004)*, pages 299–305, Palo Alto, CA, USA, January 2004.

[3] H. Bunke. Recognition of Cursive Roman Handwriting - Past, Present and Future. In *7th International Conference on Document Analysis and Recognition (ICDAR 2003)*, pages 448–460, Edinburgh, Scotland, UK, August 2003.

[4] W.F. Clocksin and P.P.J. Fernando. Towards automatic transcription of Syriac handwriting. In *12th International Conference on Image Analysis and Processing, ICIAP 2003*, pages 664–669, Mantova, Italy, 2003.

[5] M.E. Dehkordi, N. Sherkat, and T. Allen. Handwriting style classification. *International Journal on Document Analysis and Recognition*, 6(1):55–74, 2003.

[6] R.L. Easton, K.T. Knox, and W.A. Christens-Barry. Multispectral Imaging of the Archimedes Palimpsest. In *32nd Applied Image Pattern Recognition Workshop, AIPR 2003*, pages 111–118, Washington, DC, October 2003. IEEE Computer Society.

[7] And the word was made flash. *The Economist*, March 23rd 2005.

[8] S.L. Feng and R. Manmatha. Classification models for historical manuscript recognition. In *Eighth International Conference on Document Analysis and Recognition (ICDAR 2005)*, pages 528–532, Seoul, Korea, August 2005.

[9] K. Franke and M. Köppen. A computer-based system to support forensic studies on handwritten documents. *International Journal on Document Analysis and Recognition*, 3(4):218–231, May 2001.

[10] R. Fuchs, R. Mrusek, and D. Oltrogge. Spektrale fenster zur vergangenheit - ein neues reflektographieverfahren zur untersuchung von buchmalerei und historischem schriftgut. *Naturwissenschaften*, 82:68–79, 1995.

[11] A. Ghostasby. Image registration by local approximation methods. *Image and Vision Computing*, 6:255–261, 1988.

[12] D. Harlfinger. Rinascimento virtuale. Digitale Palimpsestforschung. Rediscovering written records of a hidden European cultural heritage. In Dieter Harlfinger, editor, *Berichtband der Konferenz des Netzwerks Rinascimento virtuale zur digitalen Palimpsestforschung*, pages 28–29, Wien, 2002.

[13] Y. Leydier, F. Le Bourgeois, and H. Emptoz. Omnilingual segmentation-freeword spotting for ancient manuscripts indexation. In *Eighth International*

Conference on Document Analysis and Recognition (ICDAR 2005), pages 533–537, Seoul, Korea, August 2005.

[14] B. Likar and F. Pernuš. A hierarchical approach to elastic registration based on mutual information. *Image and Vision Computing*, 19:33–34, 2001.

[15] F. Mairinger. *"Strahlenuntersuchung an Kunstwerken"*. Bücherei des Restaurators, Band 7. E.A. Seemann, 2003.

[16] R. Manmatha and J.L. Rothfeder. A scale space approach for automatically segmenting words from historical handwritten documents. *IEEE Trans. Pattern Anal. Mach. Intell.*, 27(8):1212–1225, 2005.

[17] K. Martinez, J. Cupitt, D. Saunders, and R. Pillay. Ten years of art imaging research. In *Proceedings of the IEEE*, volume 90, pages 28–41. IEEE Computer Society, 2002.

[18] H. Miklas. Die slavischen Schriften: Glagolica und Kyrillica. In Wilfried Seipel, editor, *Der Turmbau zu Babel. Ursprung und Vielfalt von Sprache und Schrift. Ausstellungskatalog des Kunsthistorischen Museums*, volume 3a, pages 243–249, Wien, 2003.

[19] I. Moalla, F. Lebourgeois, H. Emptoz, and A.M. Alimi. Contribution to the discrimination of the medieval manuscript texts: Application in the palaeography. In *7th International Workshop on Document Analysis Systems, DAS06*, pages 25–37, Nelson, New Zealand, 2006.

[20] P. Mrázek. *Nonlinear Diffusion for Image Filtering and Monotonicity Enhancement*. PhD thesis, Czech Technical University, 2001.

[21] K. Ntzios, B. Gatos, I. Pratikakis, T. Konidaris, and S.J. Perantonis. An Old Greek Handwritten OCR System. In *Eighth International Conference on Document Analysis and Recognition (ICDAR 2005)*, pages 64–69, Seoul, Korea, August 2005.

[22] N. Otsu. A threshold selection method from grey level histograms. *IEEE Transactions on Systems, Man, and Cybernetics*, 9:62–66, 1979.

[23] X. Pan, M. Brady, A.K. Bowman, C. Crowther, and R.S.O. Tomlin. Enhancement and feature extraction for images of incised and ink texts. *Image and Vision Computing*, 22(6):443–451, 2004.

[24] R. Plamondon and S.N. Srihari. On-line and off-line handwriting recognition: A comprehensive survey. *IEEE Trans. Pattern Anal. Mach. Intell.*, 22(1):63–84, 2000.

[25] K. Rapantzikos and C. Balas. Hyperspectral imaging: potential in non-destructive analysis of palimpsests. In *International Conference on Image Processing, ICIP 2005*, volume 2, pages 618–21, 2005.

[26] T.M. Rath and R. Manmatha. Features for word spotting in historical manuscripts. In *7th International Conference on Document Analysis and Recognition (ICDAR 2003)*, pages 218–222, Edinburgh, Scotland, UK, August 2003.

[27] J.A. Richards and X. Jia. *Remote Sensing Digital Image Analysis : An Introduction*. Springer, 1999.

[28] Z. Shi, S. Setlur, and V. Govindaraju. Text extraction from gray scale historical document images using adaptive local connectivity map. In *Eighth International Conference on Document Analysis and Recognition (ICDAR 2005)*, pages 794–798, Seoul, Korea, August 2005.

[29] A. Tonazzini, L. Bedini, and E. Salerno. Independent component analysis for document restoration. *International Journal on Document Analysis and Recognition*, 7(1):17–27, March 2004.

[30] A. Tonazzini, S. Vezzosi, and L. Bedini. Analysis and recognition of highly degraded printed characters. *International Journal on Document Analysis and Recognition*, 6(4):236–247, 2003.

[31] J. Weickert. *Anisotropic Diffusion in Image Processing*. PhD thesis, University of Kaiserslautern, 1996.

[32] B. Zitová and J. Flusser. Image registration methods: a survey. *Image and Vision Computing*, 21(11):977–1000, 2003.