Eurographics Italian Chapter Conference (2010)
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A framework for virtual restoration of ancient documents by combination of multispectral and 3D imaging

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Abstract

Historical documents often undergo various changes over time, that alter their original state and reduce their legibility. Digital techniques are widely applied for document preservation, archiving, analysis and dissemination over the Internet. The goal of restoration is to improve the document legibility for both human and automatic operators, to extract patterns and enhance colour reproduction. Our paper presents a framework for virtual restoration of ancient documents based on a combination of multispectral acquisition, 3D imaging and digital image analysis. The proposed framework consists of several steps. First, digital representations of the documents are acquired as multispectral images and 3D surface maps, the latter reconstructed by a structured light technique. A multispectral camera and a digital projector are used in triangular configuration for 2D and 3D data acquisition. Then the multispectral images are registered against possible misalignments, and the 3D surface representation is used to correct geometrical distortions. Document flattening is then performed by 3D surface parameterization and texture mapping. Statistical techniques of decorrelation are applied to extract individual context parts of the document patterns (stamp, text, etc.) and to attenuate interferences. The processed data are then binarized by the proper segmentation technique. The entire digital object history - all the acquisition and processing steps, with the corresponding parameters - is stored in metadata files. These data can be exploited in a future evaluation of the restoration process and can be used for either the creation of an expert knowledge database or the extraction of cross-document observations and conclusions.

Categories and Subject Descriptors (according to ACM CCS): I.4.9 [Image Processing and Computer Vision]: Application—I.7.5 [Document and Text Processing]: Document Capture—Document Analysis

1. Introduction

Ancient documents are often affected over time by changes that alter their original state. Manuscripts or printed documents can present damages due to ageing, atmospheric influences, inappropriate archiving and manipulations, interferences due to seeping of ink from the reverse side (bleed-through) or transparency of text through the page (show-through) [Dri06], and geometrical distortions like folding and bending [BSY*07]. At present, a virtual restoration of such documents is of great interest for preservation, digital archiving, study and dissemination on the Internet. The goal of virtual restoration is to obtain digital data that can be used for subsequent image processing tasks, such as patterns extraction (stamps, text, etc.), improvement of readability and aesthetics, Optical Character Recognition, or to bring the document back to its original appearance. Contactless and non-destructive imaging techniques, widely used for document analysis, provide 2D and 3D high-resolution and very accurate data. In particular, multispectral imaging yields additional information, spread across several channels, that cannot be seen in the common RGB images, while 3D imaging allows to reconstruct the shape of an object to analyse the surface topology. In this work we combine a whole-field 3D structured-light technique (fringe projection) with multispectral data to provide a restoration and analysis

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DOI: 10.2312/LocalChapterEvents/ItalChap/ItalianChapConf2010/001-007

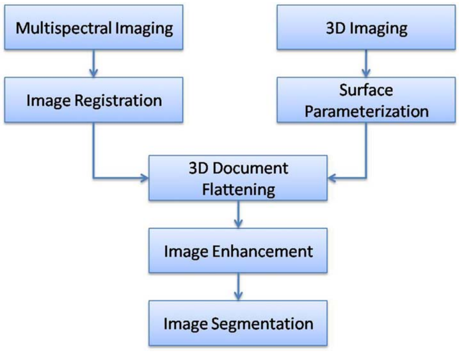


Figure 1: *Framework flow-chart to perform virtual restoration of ancient documents using multispectral and 3D data.*

tool for ancient documents. The imaging system we propose is composed of a multispectral camera and a digital projector, and does not require calibration. We used a multispectral camera equipped with a filter-wheel, that allows to select the optical filter and to acquire different wavelength ranges from infrared to visible radiations.

The data set coming from the imaging system is then processed by our restoration and analysis software. Fig.1 shows the software modules that perform restoration. Most of them are either automatic or require a limited human intervention. The multispectral images are aligned by a registration method based on log-polar mapping. Each set of images is acquired by the multispectral camera, while a sinusoidal fringe pattern is projected on the document surface. Recorded images are then analysed to evaluate the phase-map of the object, which contains the shape information. The 3D model obtained is used to correct the geometrical distortions. To achieve this goal, we flatten the document by conformal parameterization, which allows us to handle arbitrary rigid deformations (preserving surface geodesic). An image of the flattened document is then obtained by establishing a correspondence between points of the registered multispectral images and the flattened surface, through image warping and texture mapping techniques. Statistical techniques of data decorrelation are employed to separate individual patterns (background, foreground, interferences) to extract symbols, stamps, etc., and to attenuate the degradations Finally, an image binarization algorithm can be applied to fully isolate the pattern of interest. All the imaging and processing tasks applied to the document, along with the related parameters, are stored in a subsequent metadata module. Subsequently a database is created for further data management, where each document is represented by metadata that take into account both the original information on the physical document and the history of its digital processing. As this is a work in progress, we have described in detail each step of the framework, as at present there are no experimental results of the entire flowchart ready. We tested each image processing technique, measuring its impact on documents, and defined the experimental set-up.

This paper is structured as follows: Section 2 deals with the related works, in Section 3 we present the imaging techniques applied to study the ancient documents; in Section 4 we describe the image registration method to align the multispectral images. In Section 5 the surface parameterization to map a 3D surface in a plane is described. Section 6 deals with the statistical techniques of decorrelation used to enhance and extract patterns from the documents, Section 7 shows how the image segmentation is used to separate the main text from the background and Section 8 describes the storage of the collect data into a metafile. Finally, in Section 9 we make some considerations about our framework, and in Section 10 we have the conclusions.

2. Related Works

Many studies have proposed techniques for document restoration such as image enhancement to improve the readability of a text or attenuate the degradations, image registration for geometrical alignment [LDSM08], and segmentation for document binarisation [TT95]. Statistical techniques of signal decorrelation based on Blind Source Separation (ICA, PCA, Symmetric Orthogonalization, [TSB07]) have proved to be able to extract patterns [TBS04], improve the readability of palimpsests [EKCB], and attenuate degradations in the cases of both single- and double-sided (recto-verso) scans [BBT*09, DP01]. Further processing (e.g., thresholding) can be applied to separate degradation patterns from the principal text (e.g. Sauvola [SP00]). Document restoration can also take into account 3D shape information to correct possible geometrical distortions [BSY*07], such as the ones that may appear in scans of folded sheets, or due to various damages caused, for example, by bad environmental conditions. In previous works, a structured-light system (laser scanner) with a high-resolution camera [BSY*07] or a stereo vision system [YKKM04] have been used to acquire the document shape. The acquired texture images are then mapped on the 3D model and the document is flattened by surface parameterization or by a physically based modeling approach. So far, the problems of document restoration from multispectral scans and from 3D models have been addressed separately. A combination of multispectral and 3D imaging has also been used for architecture applications, relying on a system composed by a spectrograph and a laser scanner [BCF*06]. Pelagotti et al. [PDMUR09] propose an automated multispectral texture mapping of 3D models of artwork objects acquired by photogrammetry or laser scanner In Mansouri [MLM*07] a camera with a motorized filter-wheel captures images in different spectral bands and a LCD-projector projects a light-sheet to scan an object, The above mentioned works aim to acquire a 3D model of an object on which the texture obtained by multispectral images is applied. This requires the use of both a multispectral cam-

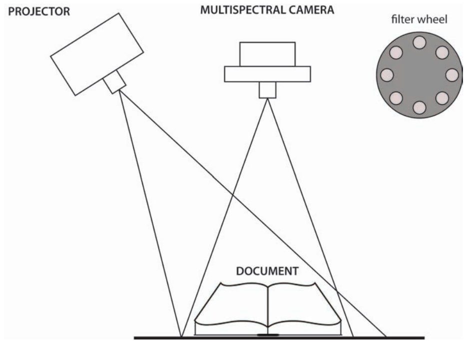


Figure 2: *Imaging system for data acquisition of ancient documents.*

era and a 3D scanner, or to integrate a camera with a filter-wheel and a projector in a unique apparatus. As our goal is different, we don't need to acquire the whole 3D mesh of the object - we aim to obtain the 3D information just to improve the flattening process. Therefore, our system projects just one pattern to acquire the 3D shape, reducing considerably the acquisition time with respect to the multi-frame acquisition needed in sheet-light scans.

3. Imaging

Data acquisition by means of imaging techniques is the first step to obtain a digital representation of a document. In particular, we use an imaging system, composed by a multispectral camera and a digital projector, that allows to acquire both 2D and 3D data (Fig. 2).

3.1. Multispectral imaging

A multispectral camera Chroma CX3 C1600E, equipped with a monochrome CCD (Charge Coupled Device), a 35 mm lens and a 6-filter wheel, is used to acquire images in different spectral bands (infrared, visible, ultraviolet). Using different filters allows to capture a gray-level image for each band by selecting a different wavelength range of the spectrum. An infrared filter (IR) selects the band with wavelengths between 720 nm and 880 nm, while the visible spectrum is covered by three filters(Red, Green, Blue). Each RGB channel is digitized separately, so the colorimetric accuracy is greater than the one obtained by three-channel devices [Mar96]. While IR and RGB images are acquired by reflectography, the ultraviolet (UV) wavelengths are acquired by fluorescence of UV light, in the range 350 - 400 nm, using a Wood lamp. In this latter case the acquisition is performed without the use of filters. The infrared and ultraviolet imaging can reveal details undetectable through common RGB capture. In Tab. 1 multispectral images of an ancient manuscript affected by degradations are shown. The diversity of information spread across the different channels is apparent. apparent.

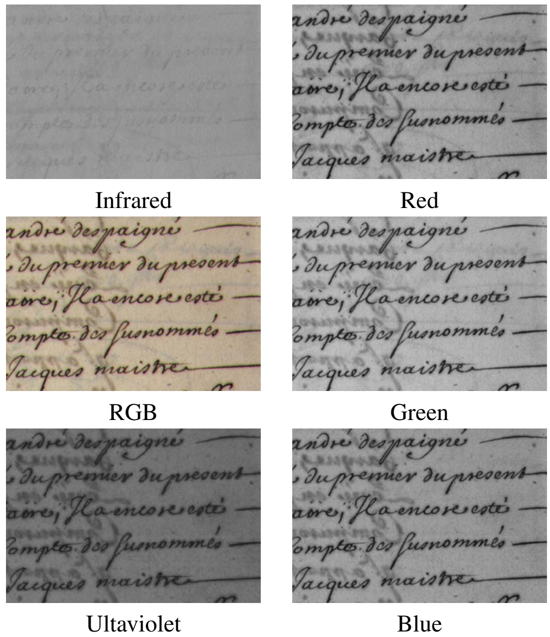


Table 1: *Document images acquired in different spectral bands.*

3.2. 3D imaging by fringe projection

A digital projector is used in triangular configuration with the camera, in a geometrical setup with crossed optical-axes (Fig. 2) to perform 3D imaging by fringe projection technique [GR10]. One sinusoidal pattern is projected on the document and acquired by the multispectral camera, without filters. As a result, we have obtained images of a fringe pattern projected on a reference plane and on the document's surface, that are subsequently elaborated by Wavelet Transform Profilometry [ZW04]. Considering a 2D image of sinusoidal fringe pattern as a signal with a carrier which depends on the fringe period , the Wavelet Transform allows to extract the phase map, that is related to the shape object. The phase-map obtained from signal processing technique is discontinuous (wrapped phase-map), thus it has to be unwrapped to calculate the continuous phase-map (unwrapped phase-map) [GP98]. For this purpose, we use the Matlab code of Dias and Leitão, that implements the ZpM algorithm for unwrapping [DL10]. Finally, we can relate height to phase by a linear relationship, since the object height is much smaller than the distance between the object and the camera or the projector. As the 3D surface can simply be reconstructed by direct interpretation of the phase-map, it is not necessary to calibrate the system if the measurements of the object are not required, so the acquisition time becomes shorter. The fringe projection technique is a whole-field structured light technique and provides a 3D shape (Fig. 3) quickly and with high accuracy.

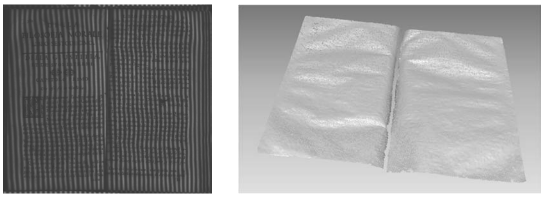


Figure 3: *At the left, fringe pattern projected on the document surface and the 3D model obtained (at the right) by fringe projection technique.*

4. Image registration

Multispectral images can suffer of misalignments due mainly to two factors: 1. application of multispectral filters that slightly shift the image focal plane; 2. accidental geometrical displacements of the document in multi-temporal acquisition. This can negatively influence the quality of the recomposed images and the subsequent processing steps, that require the pixel-by-pixel correspondence between channels. Thus we have to preregister the multispectral images. Among the possible automatic registration methods [ZF03], we propose to apply a method based on Fourier-Mellin transform [RC96] that provides good results, also for double-sided documents [BBT*09, TBS09]. We assume that a similarity transformation is sufficient to model the geometrical misalignments. The main idea lies in applying the Fourier theorems for similarity transform, and the log-polar coordinate transformation. In particular, the shift theorem of Fourier Transform ensures that the phase of the cross-power spectrum is equivalent to the phase difference between two images. Since spatial shifts affect only the phase representation of an image, it's possible to calculate the translation parameters by phase correlation of cross-power spectrum. Thus the Fourier transform magnitude is a translation invariant. The basic translation invariants may be converted to rotation and scale invariants through log-polar mapping. In particular, scaling can be reduced to a translational movement by converting the axes coordinate to logarithmic scale. Moreover, by converting the axes to polar coordinates, rotation is transformed to a translation. Then we can calculate the cross-power spectrum in logarithmic and polar coordinates to obtain the scale and rotation factors, respectively. Once all the transformation parameters are computed (rotation, translation, scale), the images are remapped to the reference system. Fig. 5 presents an example of registration of two channels (green and infrared).

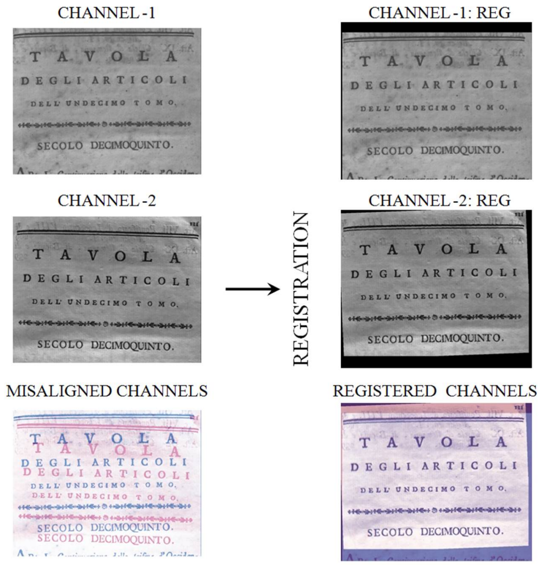


Figure 4: *Example of registration of two multispectral images.*

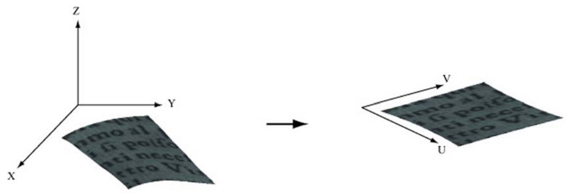


Figure 5: *Mapping of a 3D shape in a plane.*

5. 3D document flattening

Flattening consists in mapping a 3D surface into a plane (Fig. 6). The rectification of a 3D surface can be performed in many ways. In our work we use the conformal mapping approach, introduced by Brown [BSY*07]. The 3D surface is triangulated to produce a 3D mesh, then each triangle is mapped into a 2D plane preserving its angles. If the surface is developable (with zero Gaussian curvature), it can be flattened into a plane without distortions. A similarity mapping allows the 3D triangle to be modified through translation, rotation, and scale. Therefore, a set of 2D coordinates are solved to minimize the error in the piecewise similarity mappings for each triangle in the 3D mesh to a location in the 2D coordinate space, while maintaining the mesh topology. The mapping that globally minimizes this error will be taken as the conformal map. In case that non-rigid deformations are negligible, i.e. the distance between points remains the same after a deformation if measured on the surface, we can develop the surface to the plane without stretching or compressing. Otherwise, another approach is needed, which takes into account the mechanical properties of the material. This information is not always available. In this phase, the image data are registered and the 3D variations are removed by warping the document on the basis of the flattened 2D map. Here we do not consider photometric corrections of images, because we suppose that the multispectral data are taken under uniform illumination.

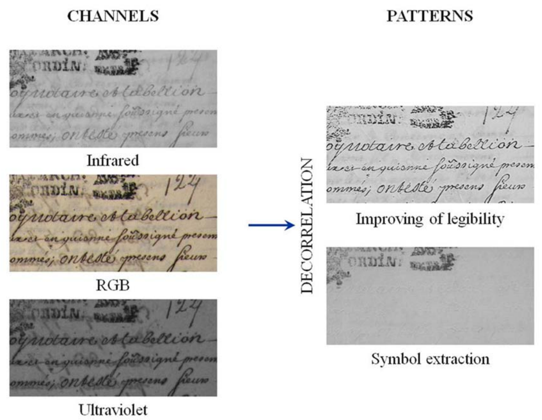


Figure 6: *An example of document patterns obtained by decorrelation of different channels.*

6. Image enhancement

Statistical decorrelation techniques such as ICA (Independent Component Analysis), PCA (Principal Component Analysis), or SO (Symmetric Orthogonalization), can be used to extract patterns from the warped images. We assume that our document is made of a mixture of distinct "patterns": this mixture is obtained through some physical processes that we can hypothesize, but are actually unknown. Not all the patterns may be immediately visible or identifiable in the document (interferences, symbols, etc). Some of the patterns we are interested in may be visible and distinguishable in some channel captured in multispectral modality. Indeed, by observing that the individual patterns overlapped in a degraded document are much less correlated than the acquisition channels, we argue that channel decorrelation can yield a new representation of the document whose channels can coincide with the separated patterns. Then we can hypothesize some mutual statistical relationship betweem the patterns, and process all the parts of the data cube by some statistical technique. In this way, some outputs of the processing can reproduce some of the individual patterns that form the data image. A suitable number of selective acquisitions can thus produce a selectivity in the patterns that can be revealed. This technique often gives excellent results when applied to the visible channels (R, G, B). Even better results can be achieved by also relying on channels from non-visible spectral bands, which are usually less correlated from each other. In Fig. 7, we show the foreground (main text), background and degradation patterns obtained by using decorrelation of multispectral images.

7. Image segmentation

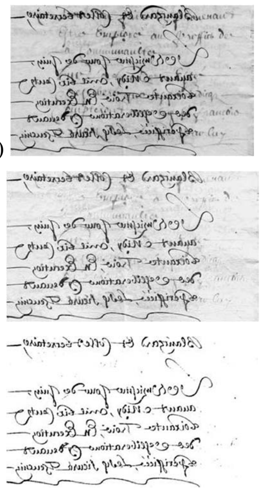
Image segmentation techniques are usually applied to grayscale images, aiming to localize a threshold gray value that allows to separate, for example, the textured background from the foreground text, i.e. to isolate the written words from the artifacts. The output of segmentation is a binary image, where text pixels and background pixels are labeled, and can be processed through OCR techniques. Among various global and local methods presented in the literature, we propose to use the local method by Sauvola and Pietaksinen [SP00]. We also have demonstrated [BBT*09] that the results are improved if the method is applied to decorrelated data (Fig. 8).

8. Archiving

The last module of our framework is dedicated to the archiving of the raw and processed data, along with a metadata description of all the imaging and processing tasks applied to each document. Each document-related image is represented by metadata, characterizing the history of the elaboration process and the document intrinsic information. Such information can be exploited in a future evaluation of the digital restoration process and for the creation of an expert knowledge database for the extraction of cross-document observations and conclusions about the document production process, the ageing process, etc., which are important for both historians and restorers. The metadata schema is composed of four main entities: the Creation entry, which provides metadata describing the very art object, the Collection entity, which depicts the physical location where the cultural heritage object is located, the Digital Representation (DR) entity, which represents the digitized versions of the Creation entity (multispectral images, registered images, enhanced images, etc.), and the Operator entity, which describes persons or organizations primarily responsible for creating the content of the record. The proposed metadata schema links a set of attributes to each entity. For example, DR is associated with acquisition attributes, parameters of image registration, relationships between recto and verso images, to name a few. The type and number of attributes and relations is not predefined, so the model is flexible enough to support unforeseen representations. This rich description of acquisitions and of image processing results will support the archiving of acquired images and their retrieval based on the characteristics of the processing. At the same time, the availability of traditional descriptive metadata associated to the Creations, will support content based search, as is usually done in a Digital Library.

9. Considerations

This paper presents the layout of the framework that is currently under development in the AMMIRA project [AMM10]. The novelty of this framework lies in in the possibility to have an unique environment in which all the operations needed to acquire, enhance and archive a digital copy of an ancient document can be performed through the most recent techniques available in literature. Each phase of this process has its own issues and peculiarities. Moreover, this



a) b) c)

Figure 7: *Segmentation result (c) of a decorrelated image (b). In a) one of the original multispectral channels.*

framework takes several steps to restore an ancient document affected by alterations. Certainly, the aforementioned image processing techniques are widely used in literature, but our goal is to suggest some tools to analyse and study the document degradations that can be employed also by untrained users: each step of our process is automatic or requires a limited human intervention. Moreover, the proposed imaging system is an innovative solution to boost the performances of a multispectral camera, by adding a digital projector to project structured light. The purpose is to acquire the document 3D surface in order to solve the flattening problem. With respect to previous works, we have used for the first time ever the fringe projection technique in document analysis. Thanks to the architecture of our system, it's not necessary to spend time in performing a calibration.. Moreover, since we use a still camera, we have to perform a frame-by-frame acquisition, so we chose to apply the Wavelt Transform Profilometry, a fringe projection technique that requires only one pattern to extract the shape information.

10. Conclusions

We propose a framework for virtual restoration of ancient documents affected by various alterations, based on multispectral and 3D digital representations. This approach provides several advantages in the analysis. The framework consists of seven steps, in which we apply image processing techniques, widely used in this context. Many of these steps are automatic or require little operator intervention. A new fast imaging system is proposed for multispectral and 3D data acquisition that consists of a multispectral camera and a digital projector, arranged in a triangular configuration. Concerning 3D shape reconstruction by fringe projection, the system does not require calibration. However, calibration can be performed it real size information is required. The experimentation is not complete yet. We are analysing ancient documents that present bleed-through degradation, blurs due to humidity, and shape deformation.

Acknowledgements

This work is a part of the AMMIRA project (www.ammira.eu) partially financed by Regione Calabria, Italy, under the POR 2007-2013 program (PIA2008 project no. 1220000119). Partial support is also acknowledged to the Czech Ministry of Education under Project 1M0572 (Research Center DAR) and by the Grant Agency of the Czech Republic under Project 102/08/1593.

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