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A procedure for the correction of back-to-front degradations in archival manuscripts with preservation of the original appearance

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Virtual restoration of digital copies of the human documental heritage is crucial for facilitating both the traditional work of philologists and paleographers and the automatic analysis of the contents. Here we propose a practical and fast procedure for the correction of the typically complex background of recto-verso historical manuscripts. The procedure has two main, distinctive features: it does not need for a preliminary registration of the two page sides, and it is non-invasive, as it does not alter the original appearance of the manuscript. This makes it suitable for the routinary use in the archives, and permits an easier fruition of the manuscripts, without any information being lost. In a first stage, the detection of both the primary text and the spurious strokes is performed via soft segmentation, based on the statistical decorrelation of the two recto and verso images. In a second stage, the noisy pattern is substituted with pixels that simulate the texture of the clean surrounding background, through an efficient technique of image inpainting. As shown in the experimental results, evaluated both qualitatively and quantitatively, the proposed procedure is able to perform a fine and selective removal of the degradation, while preserving other informative marks of the manuscript history.

Keywords: Ancient manuscript restoration; blind source separation; image inpainting.

1. Introduction

The virtual restoration of historical, archival manuscripts entails the correction of a complex, noisy background, where spurious strokes or other patterns interfere with the primary foreground text. Often, text binarization is proposed as a way to remove degradations from documents, especially when some enhancement is required prior tasks such as word spotting or character recognition. Binarization is thus performed to extract a mask of the interesting foreground text against all other features, considered noise as a whole. In the context of this approach, a large variety of methods have been developed for degraded document binarization.[1,2] Among the most recent, recurrent, convolutional or deep neural networks have been shown to cope, to some extent, with degradations such as uneven illumination, image contrast variation, changes in stroke width and connection, faded ink of faint characters.[3,4,5,6]

However, strong degradations due to interferences, especially occurring in ancient, historical manuscripts, cannot be normally removed by binarization alone, due to the significant overlap of the interfering patterns with the foreground text and the wide variation of their extent and intensity. Furthermore, binarization produces a boolean result, whereas the added value of virtual restoration is instead its capability to free the original contents from extra, foreign elements that have been added due to the ravages of time. In other words, virtual restoration should simulate on the digital images the process of physical and/or chemical restoration to be performed on the original, tangible manuscript. In fact, virtual restoration can represent the only viable way to restore the original appearance of precious and fragile historical manuscripts, when physical restoration is not practicable for safeguard reasons.

From the image processing perspective, virtual restoration should consist in substituting the noisy pixels with simulations of plausible background pixels, in such a way that the restored manuscript appears as much natural as possible. In most methods, this is accomplished in two steps: a first step where the unwanted motif is detected, and a second step where the detected motif is inpainted with proper values. The detection step is usually a three-classes segmentation problem, where the three classes are the background, the foreground text and the interferences. Hence, the unwanted class is replaced with values drawn form the estimated background class. For instance, in an earlier work,[7] where a recursive unsupervised segmentation is suggested to detect the manuscript components, the interfering component is replaced by the average of the detected background pixels. More recently, it was proposed to segment the distortion pattern through a conditional random field (CRF), and then replace it with background pixels randomly selected from the neighborhood.[8] However, these kinds of generic fill-in usually create visible artifacts when the background is textured.

In the case of the so called bleed-through effect, caused by the porosity of the paper that makes the ink penetrate the fiber and appear, more or less attenuated and smeared, also in the opposite side of the sheet, the availability of the extra information provided by the back page allows improvements in the segmentation step. Many examples can be found that use different strategies to obtain segmentation of the two texts by recto-verso data. For instance, classification has been performed by segmenting the recto-verso joint histogram with the aid of ground-truths,[9] or a dual-layer Markov Random Field (MRF) prior has been combined with a data term derived from user-labeled pixels,[10] and a model-based segmentation has been experimented as well, where the model is assumed non-stationary. [11] Successively, this latter approach has been completed by inpainting the bleed-through pixels through sparse image representation and dictionary learning.[12]

The performance of the recto-verso based methods depends however on the alignment of the two images, which should ensure an accurate matching between the information carried on by corresponding pixels. In other words, the values of two opposite pixels must be the spectral signatures in the two sides of the same geometrical point. Accurate registration is difficult to achieve in this specific case, due to document skews, different image resolutions, or wrapped pages when scanning books. Furthermore, the intensity of corresponding foreground and bleed-through areas are usually very different, bleed-through might only occur sparsely across the page, and the binding of the page in case of books may have different degrees of curvature in the two sides. Thus, dedicated recto-verso registration algorithms have to be designed,[13,14,15] and joint registration and restoration has also been proposed.[16]

Single step enhancement methods have been proposed as well, under the requirement of multiple acquisitions of the same manuscript. These methods are based, for instance, on disentangling patterns that appear superposed in the degraded manuscript, according to a principle of mixing of source images. Thus, independent component analysis[17] and correlated component analysis[18] were experimented to separate the overlapped information layers from spectrally diverse acquisitions. Similarly, the information of the recto and verso images was exploited to uncouple the front and back texts via specular modelling and symmetric whitening decorrelation of the two images.[19] Other variants of source separation techniques have also been proposed.[20,21] With these techniques, it may happen that in some of the output images the foreground text dominates the grayscale whereas the interfering patterns tend to merge with the background, thus vanishing. However, often, some unpleasant imprints of the removed patterns remain in the enhanced, separated images, or discoloration of the inks can be observed in correspondence of the crossings between the foreground text and the spurious patterns.

The different approaches surveyed above have all merits and disadvantages. In this work we tried to catch their positive features to build an automatic procedure for the virtual restoration of RGB manuscripts degraded by back-to-front ink seeping. Our procedure aims at implementing a simple and fast processing pipeline that can facilitate the legibility of the intricate content of very damaged manuscripts, and consent a plainer readability of the main text, without destroying the peculiar features of the manuscript, related to its origin and history.

The approach above was first proposed, along with the sketch of the derived procedure, in a Conference paper.[22] In the present paper the procedure is described in deeper detail, and a quantitative analysis of its performance is also systematically conducted on the 25 pairs of recto-verso image of a public database containing ground-truths.[23,24] This analysis requested the inclusion of the whole Section 3.

The procedure is basically constituted of three main computational blocks: image enhancement and soft segmentation based on statistical decorrelation, detection and classification of the components based on binarization, and cancellation of the degradation class based on inpainting. The peculiar feature of the procedure, which significantly streamlines it, is that it does not require prior registration of the two sides. Indeed, we assume that, at local level, the misalignment between the recto-verso pair always reduces to a translation only, and hence, for each pair of image patches located at the same position in the two images, we compute their mutual shift to correct it. We then perform binarization of the two aligned recto-verso patches, after having decorrelated them through symmetric whitening. This specific type of source separation is particularly suited to reduce back-to-front interferences in either manuscripts or scanned printed documents,[19] while preserving all other marks genuinely belonging to each side. In practice, it performs a very fast and parameter-free soft segmentation that can significantly improve the results of a subsequent binarization. Through binarization of both the decorrelated sides we obtain, for each side, the three-class segmentation of each patch into foreground text, ink-bleed degradation, plus a background class that includes all other interesting patterns in the scene. The union of the detected foreground text and degradation pattern is inpainted in each side with the texture of the surrounding background, and then the pertinent, detected foreground text is replaced in the corrected background map. In this way, we obtain the selective removal of the unwanted interference alone, leaving unaltered the rest of the content.

The paper is organized as follows. In Section 2 we describe the procedure through the aid of a block diagram, and the salient mathematical details of the processing blocks are given. Section 3 contains the quantitative analysis of the method performance, based on the ground-truth images available in a public dataset.[24] Section 4 is devoted to the description and the qualitative analysis of some preliminary results obtained by applying the procedure to letters from the correspondence of Christoforus Clavius, conserved at the Historical Archive of the Pontificia Università Gregoriana in Rome. Finally, section 5 concludes the paper.

2. The virtual restoration procedure

The virtual restoration procedure that we propose is illustrated in Figures 1 and 2. Figure 1 summarizes the local mechanism by which the procedure operates. The two images in input are subdivided into subsequent patches, each pair of homologous recto and verso patches are processed together in order to obtain the restored version of the recto patch. After the elaboration of the whole recto image, the two inputs are inverted, and the procedure is repeated again to obtain the restored verso image. The two output images maintain the geometry of the corresponding input ones, in that no registration between the recto and the verso is performed. Hence, as a consequence, the resolution of the images is not reduced by any interpolation process.

Figure 2 illustrates the procedure at the level of each pair of patches. This is constituted of three main steps: pre-processing, segmentation, and degradation removal, which, in turn, are subdivided into a number of consecutive phases, namely patch alignment (A - alignment), patch decorrelation (SW - symmetric whitening), patch binarization (B - binarization), background map estimation (I - inpainting), and foreground text repositioning (R - restoration).

2.1. *Phase A - alignment*

In Phase A, given a recto patch, the corresponding patch in the mirrored verso that best matches it is searched for. We observed that, at the local level, the geometric transformation between a recto patch and its corresponding verso patch can be approximated by a simple translation, when the patch size is not too big and the global deformation is moderate, although even non-rigid, as in the cases of book bindings or undulations of the sheet.[16] The value of the shift can be found by the maximizer of the cross-power spectrum of the two homologous recto-verso patches (same size and same position in the two sides).

In the mathematical formalism, given two patches f_1 and f_2 such that, in a common support, it is $f_1(x + \Delta x_0, y + \Delta y_0) = f_2(x, y)$, the following relationship

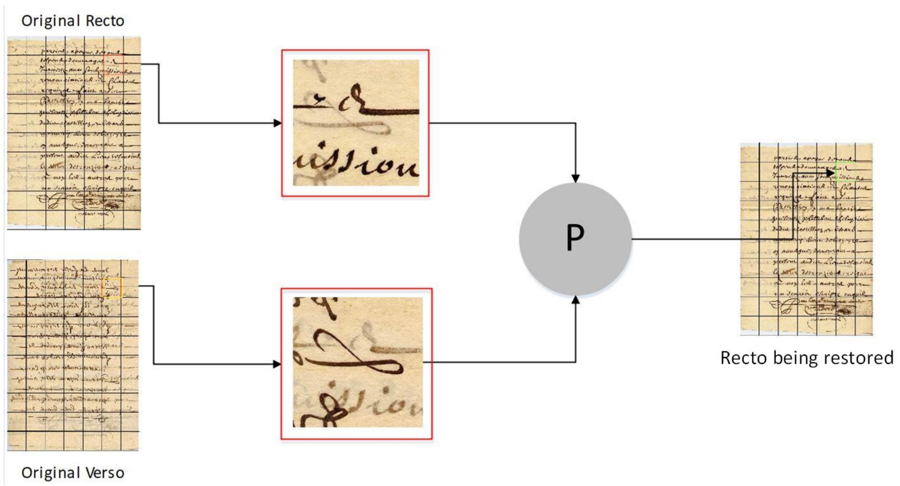


Fig. 1: Image-level procedure: patch-by-patch processing.

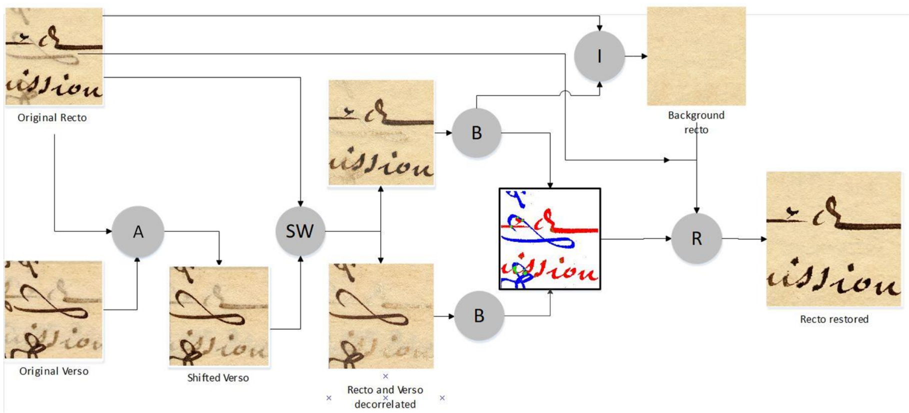


Fig. 2: Patch-level procedure: elaboration of each pair of opposite patches.

between their Fourier Transforms (FT) holds true:

$$F_2(\omega_x, \omega_y) = F_1(\omega_x, \omega_y)e^{j(\omega_x \Delta x_0 + \omega_y \Delta y_0)} \tag{1}$$

from which:

$$\frac{F_2(\omega_x, \omega_y)}{F_1(\omega_x, \omega_y)} = e^{j(\omega_x \Delta x_0 + \omega_y \Delta y_0)} \tag{2}$$

Then, theoretically, the inverse FT of the ratio in Eq. (2) will return a Dirac impulse located in $(\Delta x_0, \Delta y_0)$. Nevertheless, due to the presence of random noise, dissimilar parts and gain changes, inverse filtering produces a very noisy map, where a trustable peak cannot be located. A more robust estimate of the cross correlation between f_1 and f_2 is given by the inverse FT of the cross power spectrum:

$$\frac{F_2(\omega_x, \omega_y) \cdot F_1^*(\omega_x, \omega_y)}{|F_2(\omega_x, \omega_y)| \cdot |F_1^*(\omega_x, \omega_y)|} = e^{j(\omega_x \Delta x_0 + \omega_y \Delta y_0)} \tag{3}$$

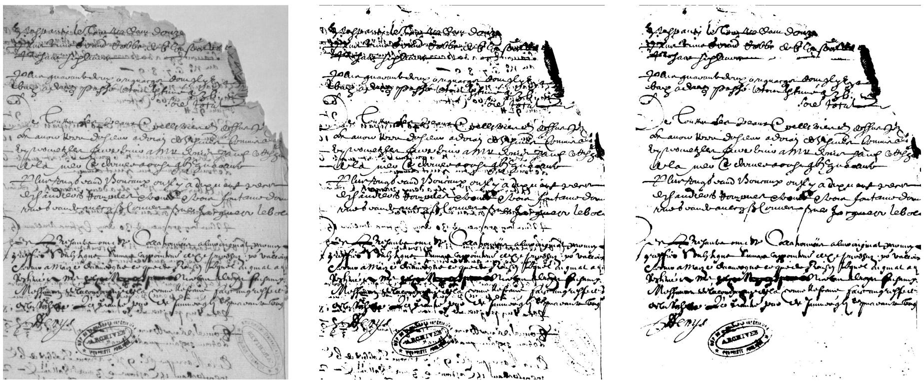
where $*$ denotes the complex conjugate. The location of the well emerging peak of the cross-correlation function computed using Eq. (3) defines the relative translation between the two patches. Using FFT, this computation is very fast.

2.2. *Phase SW - symmetric whitening*

Back-to-front degradations have the peculiarity that, when the images of the two opposite sides are perfectly registered, the location of the main text in one side corresponds to that of the degradation in the other, and the background is given by the area outside the union of the two texts. Thus, if satisfactory text binarization can be achieved in each side, the two binarized front and back images automatically provide the three classes that constitute each side, i.e. pure background, foreground and interfering pattern.

To improve binarization, noise filtering and contrast enhancement are often applied as a pre-processing.[25] In our procedure, image enhancement is performed in Phase SW, where the two aligned recto-verso patches are first decorrelated via symmetric whitening, in order to reduce the degradation coming from the opposite side.

The rationale for using decorrelation lies in considering the recto and verso images, in presence of ink seeping, as different observations of a same scene, where the different texts and, possibly, other features (paper texture and watermarking, stains, stamps, pencil annotations, etc.) appear as overlapped layers of information. Diversity of the acquisition modality is constituted by the different intensities of a same text pattern in the two observations. To describe this fact, a linear, instantaneous overlapping model has been proposed.[19] This is a 2×2 model, whose mixing matrix is related to the percentage of ink seeping from one side to the other. Since it is reasonable to assume that the ink penetrates the paper in the same way from recto to verso and from verso to recto, the mixing matrix can be assumed symmetric. In the mathematical formalism, let $r(t)$ and $v(t)$, $t = 1, 2, ..., T$, be the pair of



(a) (b) (c)

Fig. 3: Application of Sauvola binarization before and after symmetric whitening of the two sides of a typical archival manuscript: (a) original recto; (b) binarized original recto; (c) binarized recto after decorrelation of the recto-verso pair.

the acquired (mirrored and registered) images, with t the pixel index. We consider $r(t)$ and $v(t)$ as a linear combination of the two images $s_1(t)$ and $s_2(t)$, $t = 1, 2, ..., T$, representing the clean main texts in the recto and the verso, respectively. We can write:

$$\begin{aligned} r(t) &= A_{11}s_1(t) + A_{12}s_2(t) \\ v(t) &= A_{21}s_1(t) + A_{22}s_2(t) \end{aligned} \tag{4}$$

where $A_{12} = A_{21}$. Viewing s_1 and s_2 as the sources, and A as the unknown mixing matrix, Eq. (4) turns out to define a 2×2 blind source separation (BSS) problem.[26,27]. In the assumption of mutually independent sources, both the sources and the mixing coefficients can be estimated from the data alone, through techniques such as independent component analysis (ICA).[27] In our case, as the mixing matrix is expected to be symmetric, decorrelating the data through symmetric whitening is equivalent to ICA,[26] and much faster and simpler.

2.3. *Phase B - binarization*

In most cases, after decorrelation a more effective binarization of the pertinent foreground text can be performed in each side.

As an example, Figures 3 (b) and (c) show the results of the binarization of the recto side of an archival manuscript degraded by ink seepage (see Figures 3 (a)), obtained with the Sauvola algorithm[28] before and after decorrelation of the two sides.

In our procedure, the individual binarization of the decorrelated recto and verso patches is performed in Phase B, with the aim, as said, to segment the foreground text of each side. The procedure can use any of the many degraded document binarization algorithms proposed in the literature. At present, we have included the Sauvola algorithm.[28]

Binarization of the two sides detects also a safe background area in the recto, from which to drawn samples for filling in the complementary area, i.e. the area of the union of the two texts. This is highlighted in the map shown in the diagram of Figure 2, where the blue mask corresponds to foreground, the red mask to bleed-through, and the green pixels are the crossings between the two texts. Since the bleed-through text of the recto is estimated from the corresponding foreground text of the verso, it is likely that the former is underestimated, because of the effect of diffusion of the penetrating ink. We then dilate its mask to account for this fact.

2.4. *Phase I - inpainting*

In Phase I, the white pixels of the map are replaced with the values of the corresponding pixels of the safe background of the original recto, and the masks in color are inpainted with samples drawn from the closest safe background region itself. In this way, a full-image background map is generated, which simulates the empty page, that is the texture of the paper prior the writing. To do that, we tested various state-of-the art still image inpainting techniques, and selected as the best one for our purposes an exemplar-based image inpainting technique implemented in Matlab, also for its relative simplicity, and the standardized code. Specifically, we used the function *inpaintExemplar* introduced in Matlab R2019b, Image Processing Toolbox, which combines the exemplar-based methods proposed by Criminisi[29] and by Le Meur.[30]

2.5. *Phase R - restoration*

Finally, Phase R produces the final restored recto, by placing the original foreground text in the simulated background map. At present, we use the binarized recto to locate the pixels to be replaced with the proper values. However, a finer estimation of the foreground map, to be used at this stage, could be obtained with other approaches, for example by the model based segmentation already mentioned.[11]

3. Experimental results and quantitative analysis

We tested our procedure on a database of high resolution images of ancient documents affected by bleed-through, which has been published online a few years ago and that became a benchmark in the field [23,24]. It comprises 25 registered recto-verso sample RGB image pairs, taken from larger high resolution manuscript images, with varied degrees of bleed-through. In addition, for each image a binary ground-truth mask of the foreground text is provided. Although in these ground-truth images the foreground text is labeled manually, they are commonly used for a quantitative analysis of the results.

Fig. 4: Comparison between the results of our procedure and the results of another recent non-blind method, the method in Ref. [9]: (a) original recto; (b) original verso; (c) ground-truth recto; (d) ground-truth verso; (e) recto restored with the method in Ref. [9]; (f) verso restored with the method in Ref. [9]; (g) recto restored with the proposed procedure; (h) verso restored with the proposed procedure.

We first compared qualitatively our procedure with a method that, as ours, exploits the information of the verso side, the method proposed in Ref. [9]. Sometimes, the methods exploiting both sides of the manuscript are named *non-blind methods*. Conversely, the methods that work on a single side can be mentioned as *blind methods*.

As an example of the performance of our procedure and of that of the method in Ref. [9], Figure 4 shows the respective results on one pair of manuscripts of the database. The results of the method in Ref. [9] are available in grayscale, because the method itself has been devised for single channel pairs. It is possible to observe that the results of our very simple procedure are comparable with the ones of this more sophisticated method, and that the appearance (color and paper texture) of the original acquisitions has been conserved quite well.

Successively, we included in the comparison also the blind method based on CRF.[8] Also this method is more complex than ours, however, it exploits less information, because the verso side is not used. Again, we basically found that the qualitative performance of the two methods is very similar.

Panel in Figure 5 gives an overall picture of the performance of the three compared methods. Note that also the CRF methodof Ref. [8] has been designed for grayscale images. The first column (Figure 5 (a)) contains portions from some of the original recto images of the database. The results of the proposed method are

(a) (b) (c) (d)

Fig. 5: Comparison between the results of our procedure and the results of methods in Ref. [8] and Ref. [9]: (a) original recto; (b) recto restored by method in Ref. [9]; (c) recto restored by method in Ref. [8]; (d) recto restored by the proposed method

shown in the last column, Figure 5 (d). As it can be clearly appreciated, on average, the three methods are competitive, in terms of foreground text conservation, bleed-through removal, and plausibility of the inpainted background texture. Some variability can be observed in dependence of the specific image at hand. Again, we confirm the extreme simplicity of our procedure, and highlight the fact that it is naturally able to straightforwardly handle RGB images.

To quantitatively evaluate the performance of a bleed-through removal method, two complementary features are usually taken into account: i) the fidelity of the reconstructed foreground text to the original, and ii) the ability of cancelling as much as possible of the bleed-through pattern, that is the noise in the data. To this purpose, when a ground-truth for the foreground text is available, three different metrics are typically used, namely Precision, Recall and F-measure. The three metrics are defined as following:

$$Precision = \frac{Sum(FT_R \cap FT_{GT})}{Sum(FT_R)}$$

$$Recall = \frac{Sum(FT_R \cap FT_{GT})}{Sum(FT_{GT})}$$

$$F-measure = \frac{2 \times (Precision)(Recall)}{Precision + Recall}$$

where FT_R is the binary map of the foreground text in the restored image and FT_{GT} is the foreground text in the related binary ground-truth mask. It is to be noted that, while the ground-truth mask is fixed, different binarization algorithms can be used to extract the binary mask of the foreground text from the restored images, so that the resulting metric values can be affected by this choice. For the non-blind method[9] and the blind, CRF method[8] we report here the values that were found in the respective papers.

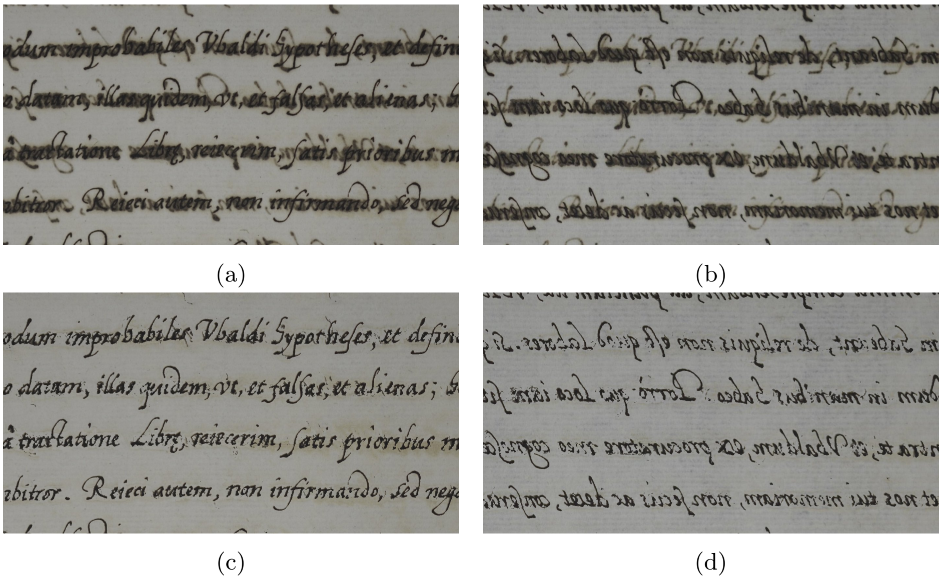
Thus, the average values for the three metrics on the whole dataset are shown in Table 1.

Table 1: Quantitative evaluation

Method	*Precision*	*Recall*	*F-measure*
non-blind 2013[9]	0.92	0.87	0.89
blind 2016[8]	0.89	0.86	0.87
Proposed	0.93	0.82	0.87

It is to be noted that the values for the CRF method are computed on the recto sides only. With respect to possible comments on these values, we may observe that both the two non-blind methods have higher precision values, that is they are more robust against false-positive FT pixels. In other words, they should be more effective in cancelling the noisy bleed-through pixels. And indeed, for example, in the image of the third row of Figure 5, especially in the second text line, our result is more clean than that of the CRF method. Our method has a lower precision value, which means that some FT pixels in the character borders can get lost. This effect it is apparent, e.g., in the result of the fourth row image of Figure 5. On the other hand, on this same image, the non-parametric method strangely is unable to remove a good deal of the bleed-through pattern.

Finally, we would like to highlight that the three metric above, when applied in the document processing field, are certainly suitable for an effective evaluation binarization/classification task. Neverteless, for a virtual restoration task, the quality



(a) (b) (c) (d)

Fig. 6: Application of the whole procedure, a detail of the results: (a) original recto; (b) original verso; (c) recto restored; (d) verso restored. Original images (a) and (b): reproduction by courtesy of The Historical Archive of the Pontificia Università Gregoriana, APUG 529/530, c. 131r/v (Fondo Clavius).

of the reconstruction of the background, which replaces the bleed-through pattern, is also of great importance, and it is related to the effectiveness of the inpainting algorithm used. At present, this estimate of the background texture is evaluated qualitatively.

4. Some results on the correspondence of Christoforus Clavius

We show here the results of the procedure on pairs of recto-verso letters from the correspondence of Christoforus Clavius, conserved at the Historical Archive of the Pontificia Università Gregoriana in Rome (APUG 529/530 - Fondo Clavius).

Figure 6 shows a details of a very damaged manuscript letter. Comparing recto and verso, it is possible to appreciate the significant misalignment introduced during the acquisition. This misalignment appears also in the restored images, since the procedure does not require image registration. Although the results are not perfect, the improvement of readability is impressive, in that the two completely overlapped texts, almost indistinguishable in the originals, have been fully and correctly separated. We expect that better results can be obtained by refining binarization through performing state-of-the-art algorithms specifically designed for degraded documents.

Figures 7 and 8 show the full page and a detail, respectively, of the verso side of another letter.

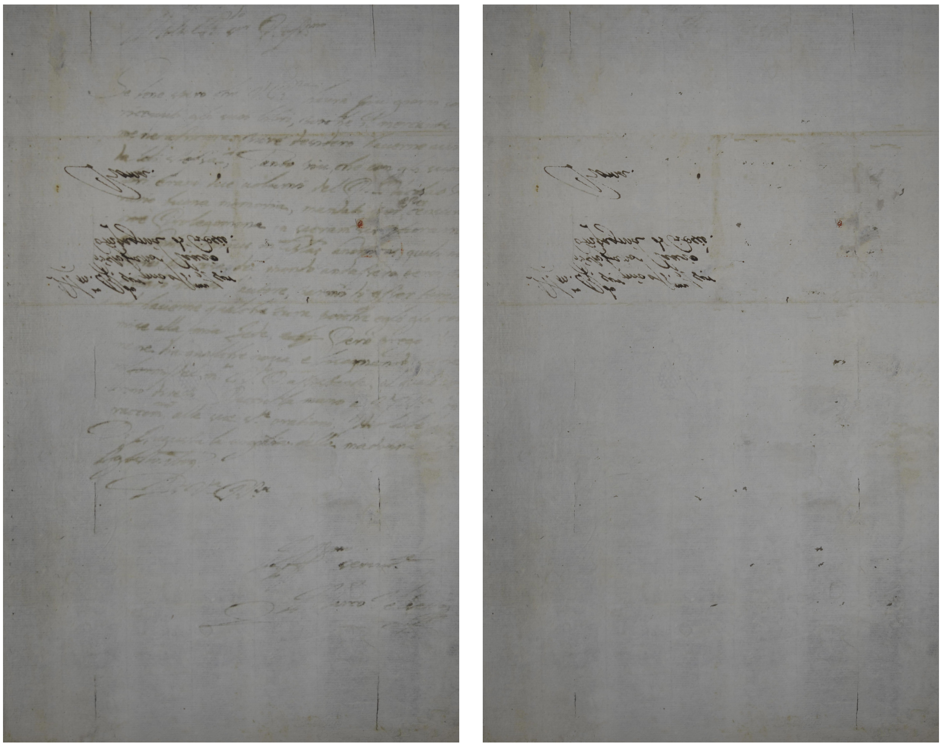


Fig. 7: Application of the whole procedure: (a) original verso; (b) verso restored. Original image (a): reproduction by courtesy of The Historical Archive of the Pontificia Università Gregoriana, APUG 529/530, c. 071r/v (Fondo Clavius).

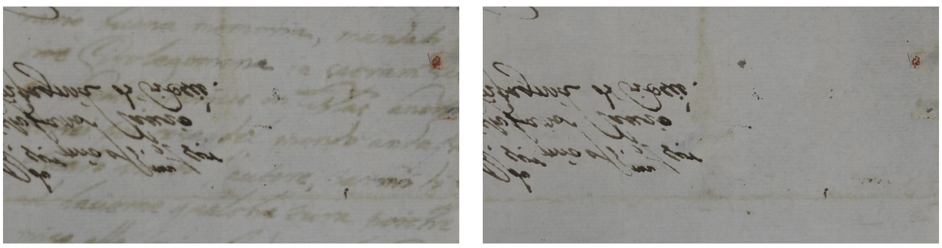


Fig. 8: A detail of the images shown in Figure 7: (a) original verso; (b) verso restored.

Note that the non-periodic texture of the paper and other local marks on the support have been preserved, and now they appear even enhanced, whereas only the seepage has been exclusively removed.

5. Conclusions

As opposite to the popular approach of completely removing the complex background, e.g. through binarization, we proposed to virtually restore degraded, archival manuscripts by removing the unwanted interference alone, while preserving the fine details related to the original appearance. To this aim, exploiting the information contained in the verso side is crucial, in that it allows a very fine discrimination among features due to ink seepage or originally present in the side at hand. In this paper, we proposed a procedure that does not require prior registration of the two sides, and exploits joint binarization of only mutually translated opposite patches to perform a three-classes segmentation of the manuscript contents into main foreground text, pattern interfering from the back side, and pure background. Restoration is then obtained by inpainting the region containing the union of foreground and interference with the texture of the surrounding background, and repositioning the original foreground text in the so estimated background map.

The qualitative and quantitative analysis conducted on a popular, public database of recto-verso archival manuscript has highlighted that the proposed method, despite its conceptual simplicity and computational efficiency, is competitive with recent, more complex methods. A significant part of the efficiency and competitiveness of our method is also due to the alignment step, fully integrated with the local virtual restoration process, without requiring a real registration between the two sides of the manuscript.

Experimental results obtained on historical manuscripts demonstrate the potentiality of the procedure for a significant improvement of the quality of even highly degraded manuscripts, and its large scale usage in historical archives. From a quantitative point of view, the performance of the procedure can be boosted by the choice of more effective degraded document binarization and inpainting algorithms. As both fields of research are very active, with specialized contest being held annually, we plan to carry on a large comparative experimentation.

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