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Digital reconstruction of fragmented photographic glass plates: the case of archaeological photography

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Abstract

A recent digitalization project of the textual and iconographical fund of Department of Archaeology Library of the Catania University, one of the largest and oldest among Italian academies, presented the challenging problem of the iconographical resources on glass plates coated by silver halide. The Library has an archive of about 3,000 glass plates. Several of these are damaged and fractured. Acquisition of these images with a scanner or with a digital camera, after a manual recomposing of the sherds, leaves badly visible gaps and fracture lines. This happens because of an uncorrect alignment of the fragments or for the lost of the emulsion. To solve this problem and to introduce an efficient process to restore a large amount of fractured glass plates, we developed an automatic method for the virtual restoration of this large dataset based on the use of image processing techniques. The paper describes the proposed processing pipeline and discusses the results obtained insofar.

Keywords: `Glass plates, automatic reconstruction, inpainting.`

1. Introduction.

The Department of Archaeological, Philological and Historical Sciences (S.A.FI.St.) of Catania University has recently started a digitalization project of its textual and iconographical fund, one of the largest and oldest among Italian Academies. In this a difficult problem is presented by the glass plates coated by silver halide. The Library has an archive of about 3,000 of these glass plates produced between the two last decades of the '800 and the first half of the '900, depicting the masterpieces of Greek and Roman art. These plates were in part a teaching aid, but most of them are unique documents of the excavation activities of the Department in Sicily, North Africa, and Greece. In particular, in the first half of the 20th century,

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the archive was enriched thanks to Guido Libertini (1888-1953), a full professor of Classical Archaeology at Catania University since 1926, dean of the School of Classics studies between 1937-39 and 1944-1947 and Chancellor since 1947 to 1950. Several glass plates are related to the studies and excavations at Centuripe (Enna, Sicily), promoted by Libertini and later carried out by Giovanni Rizza [1], [2]. Among these plates some relevant examples have been selected as benchmark for the proposed restoration technique. This iconographic fund represents an important historical documentation of the past activities registered on a unique support [3]. The plates represents an important step forward in the evolution of photographic chemical support but, already at the time of its use at the Department of Archaeology [4], this technology was outperformed by the newborn roll-film using cellulose nitrate base, invented by George Eastman (1854-1932). However, it was still used in some specific disciplines, including archaeology, not withstanding the disadvantages related to its higher cost and the size of the photographic equipments, because of its incomparable rigidity of the support, essential feature to obtain sharp images, and by its chemical stability coupled to the impossibility of a spontaneous combustion. All these positive features came with a major disadvantage: the fragility of the support [5].

The use of the glass plates in the Catania University archive has been carried on, way after the introduction of celluloid support for photography. This is a fortunate case because of the greater chemical stability of glass. The trouble with images on glass plates is instead in their fragility and in the occasional peeling off of the emulsion. When a plate breaks the thin emulsion surface scratches and deforms itself especially in the proximity of the fracture. Even if plates are preserved in optimal conditions, tiny fragments and sherds are impossible to recover and gaps in the emulsion film are physically unavoidable.

Several of the plates in Catania fund are damaged and fractured, they cannot be used for reproduction and cannot be properly digitalized (Figure 1). Even after their acquisition with a scanner or with a digital camera, after a manual recomposing of the sherds, gaps and fracture lines will remain visible in the output because of an uncorrect alignment of the fragments or for the lost of patches of the emulsion. It is not advisable to further physically manipulate the fragments because of their extreme fragility.

In this paper we report the experience of the application of the algorithm presented in [6] to the case study of more than 3,000 glass plates. The algorithm in [6] is based on the use of image processing techniques developed in turn to reduce luminance artefacts originated by the interaction between the scanner light and the glass; to perform the image registration based on a roto-translation to align the different pieces; and to fill missing pixel

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(a) (b)

Figure 1. (a) Fragmented glass plate depicting a funerary painted urn (half of 3rd century BC) from the excavations at Centuripe (Enna, Sicily). (b) Overview of old town of Centuripe, on the right the Calvario hill.

values using inpainting techniques. The algorithm is easy to implement and to use, it is fast and it gives high quality reconstructions. Thanks to this methodology, with a synergic effort of experts in archaeology and image processing it has been possible to rescue a treasure of archaeological repertoires, otherwise lost, that represents an important part of the history of archaeological research of the Catania University.

The rest of the paper is organized as follows: Section 2 summarizes the algorithm proposed in [6], and Section 3 shows some experimental results. A conclusions Section ends the paper.

2. The algorithm.

In this section we present the algorithm proposed in [6]. The reported method is our state-of-the-art technique for glass plate acquisition and restoration problem. It assumes that only affine transformations are needed and, hence, it reconstructs the original image using just roto-translations to align the pieces. The input for the algorithm is the digital acquisition of the glass fragments after a rough manual re-alignment. This is obtained using a consumer level flatbed scanner. Generally this stage leaves gaps between fragments in the final digital image. They are eliminated during the restoration phase of the algorithm.

2.1. *Detection.*

The method starts classifying the pixels of the digitalized image into those belonging to the fragments and those relative to the gaps. This step is relatively easy because of the way how the negatives are digitized. The areas relative to gaps indeed do not arrest the light of the scanner. Gaps, hence, originate areas that are much brighter than the rest of the image. Let I be the input image. A new image I' is created, where each pixel is labelled "white" if it is in the gap or "black" if it is outside the gap. Classification is obtained by thresholding with a very high threshold Th_1. A local filter is successively applied to I' to locate the fragments "border pixels" that are labeled as "gray" and that are used in the successive steps.

To extract *gray* pixels, we divide I' in overlapping blocks of size 2×2 and for each block we apply the rule:

if (#*white* pixels ≥ 1 *and* #*white* pixels < 4)
  black pixels *become gray* pixels
end

At the end of this simple classification stage the image I' been positioned into three classes labeled: *white*, *black*, and *gray*, corresponding respectively to a gap, a fragment, and a border of a fragment.

The algorithm proceeds creating a binary mask $BF_1, \ldots, BF_k$ for each fragment detected in the image where the border pixels assume the value 1 with respect to the background 0. The masks are obtained using a region growing segmentation techniques.

In the successive steps only pairs of two adjacent fragments are processed at each phase. After re-alignment those two fragments are merged and treated as unity. The procedure goes on merging to this new large fragment the other possible fragments until eventually all pieces are processed. For sake of clarity in the following only the merging of two fragments will be described in detail.

2.2. *Restoration.*

The algorithm restores the fragmented glass plate photographs in three steps. The first one is aimed to alleviate luminance problems; the second one performs a roto-translation to align the different pieces; the last one refines and fills possible residual gaps.

Step 1. The acquisition process of the plate requires that a light beam is projected from the scanner toward the glass pane. This is a relatively thick plate and luminance artefacts close to the border of the glass support are common, originating a "prism effect" and increasing the luminosity of the areas close to the gap. The algorithm in [6] proposes to apply a non linear filtering process centered in the *gray* pixels obtained in the previous detection phase that replace the altered luminance value with a better estimated value in its neighborhood. If the lighter pixels stay inside an area M close to the border of width m, to adjust them all the available information near the pixel are used. More precisely: for each pixel in $I_{ij} \in M$ we adjust the luminance according with this rule:

$N_{ij} = 3 \times 3$ neighborhood centred in I_{ij}
$S = \{I_{pq} \in N_{ij} : I'_{pq} \text{ is } black\}$
$if\ I'_{ij}$ is $gray$
  I''_{ij} = the nearest pixel $I_{pq} \in S$
$else$
  $if\ |I''_{ij} - I_{pq}| < Th_2$
    I''_{ij} = the nearest pixel $I_{pq} \in S$
  end
end

Here, Th_2 is a suitable threshold, set experimentally. The new image I'' obtained with the correction will give more realistic final restored results. This step discards the original pixels value even if it could contain some residual information. This lossy approach is reasonable since the low number of pixels belonging to this thin border area do not justify the study of an accurate photometric model of this material-light interaction [7].

Step 2. To obtain a good match between the pieces of the picture, the algorithm [6] divides the registration problem [8] in two different parts: rotation and translation. The first copes with the estimation of the rotation angle between fragments. The second part is the estimation of the displacement between the two pieces BF_1 and BF_2 of the photographic glass plate. We use the well-known phase-correlation technique that is exploited in several state-of-the-art motion estimation algorithms [9] and [10] and that makes use of the properties of the Fourier transform.

More in details, following the algorithm in [6], the rotation angle α between BF_1 and BF_2 can be estimated as follows:

- We denote as BF'_1 the centered version of the curve in BF_1.
- We define $BF_1'^{\delta}$, the image obtained by rotating BF'_1 in a suitable subset A of angles, δ, from 0 to 359.
- In order to reduce the computational cost, the decimated images $BF_1'^{\delta,d}$ and $BF_2^{\delta,d}$ have been considered instead of the original ones, $BF_1'^{\delta}$ and BF_2^{δ}.
- For each value $\delta \in A$ the cross correlation of the two images $BF_1'^{\delta}$ and BF_2^{δ} is evaluated.
- The maximum value M_δ of each cross correlation matrix – which indicates, for each angle, the best match between the two images– is stored in a vector M_{corr}.

- The position of the maximum value of M_{corr} determines in A the angle β that gives a first estimate for the correct value for α. To increase the precision we repeat the search procedure using the original images, within an interval of angles centered in β. The values of the peak in the cross correlation matrix are stored in the vector M^{β}_{corr}.
- The maximum value of M^{β}_{corr} is the best match, and it determines the rotation angle α which we are looking for.
- We rotate the fragment Fr_1 and the border image BF_1 by α degrees in order to obtain New_Fr_1 and New_BF_1.

According to the properties of the Fourier transform, it is possible to estimate the displacements between two images as follows:

- We denote $F_1 = \mathcal{F}\left(New\_BF_1\right)$ and $F_2 = \mathcal{F}\left(BF_2\right)$ as the Fourier transform of the two binary images New_BF_1 and BF_2.
- We estimate the following ratio:

$$\rho = \frac{F_1 \cdot F_2^*}{|F_1| \cdot |F_2|}$$

  where with $()^*$ we indicate the conjugate operator.
- Finally we estimate ϕ as the inverse Fourier transform of the ρ map:

$$\phi = \mathcal{F}^{-1}\left(\rho\right)$$

Due to numerical precision $|\phi|$ has to be evaluated instead of ϕ. In an ideal case, the ϕ map contains a Dirac delta in the position (dx, dy) where dx and dy denote the horizontal and the vertical displacement between the two input images. In a real case it is sufficient to consider the maximum peak of the map. Now we shift the fragment New_Fr_1 by dx in the horizontal direction and by dy in the vertical one.

Step 3. The image fragments are, at this point, as close as possible one to each other. It could happen however that some parts of the fragments are lost before the scanning. For this reason an inpainting phase has to be carried out to fill in the gaps. The algorithm in [6] suggest to use a simple average of pixels belonging in the fragment. Better results could be obtained using Poisson editing [11] or statistical image inpainting [12] but the following method is simple and fast.

for each pixel $P \in$ the gap G

$N = 3 \times 3$ neighborhood centred in P

$P =$ average of P_{ij} with $P_{ij} \in N$

$and\ P_{ij} \notin G$

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end

The image produced by this final step is the restored image to archive.

3. Experimental results.

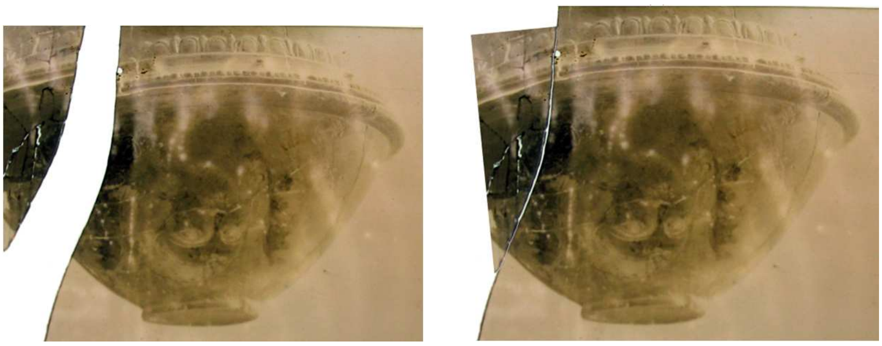
This section shows some results obtained applying the algorithm to old fragmented glass plate photographs. As expressed in Section 2 the method chooses only two fragments and it moves a fragment close to another. If the input images have more than two fragments, it is necessary to iterate the algorithm using the merged fragments as a new input fragment until all the fragments are processed. All the parameters adopted in our experiments are the same that were suggested in [6]: the threshold Th_1 for the detection is 245; the width m of the lighter border M is chosen equal to 2; and the threshold Th_2 is set equal to 20.

(a) (b)

Figure 2. (a) Original fragmented glass negatives. (b) Restored image with use of inpainting algorithm.

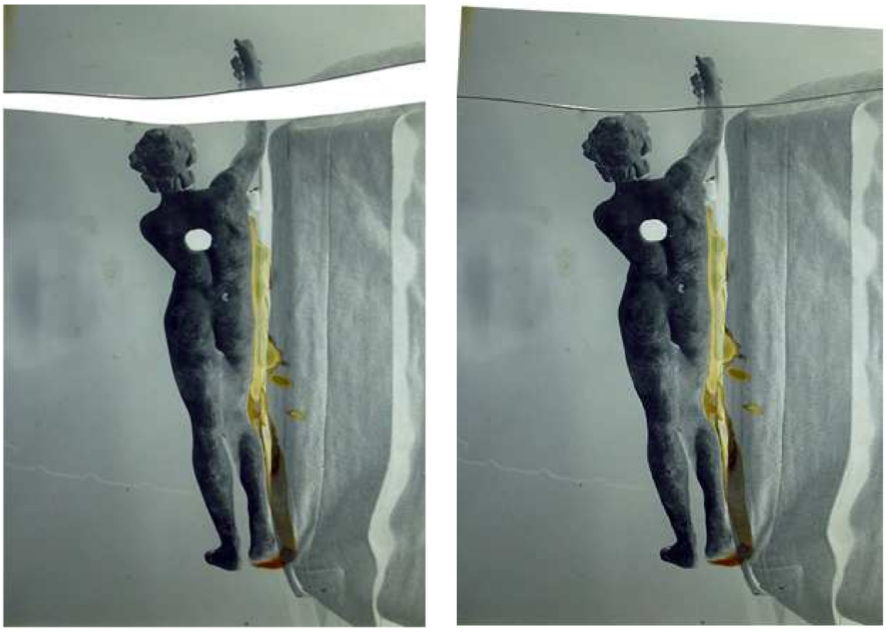
The image in Figures 2, 3, 4, 5 and 6 are obtained using the approach described above. Figures 2(a), 3(a), 4(a), 5(a) and 6(a) report the original digitalized fragments. In Figures 2(b), 3(b), 4(b), 5(b) and 6(b) the obtained alignments are reported. In all of them the alignment obtained is good.

In particular, Figure 2(b) shows a restoration where the complete pipeline is applied. The lines are perfectly restored and the result is of high quality. The inpainting step is an accessory step of the proposed processing routine. It has typically not been carried out in our experiments (as shown in Figures 3, 4, 5 and 6) because the responsible of the archive choose a more rigid philological approach in the restoration and asked not to mask out the fractures of the plates.



(a) (b)

Figure 3. (a, b) Example of application of the algorithm on the fragmented glass plate with the Hellenistic funerary painted urn of Figure 1(a).



(a) (b)

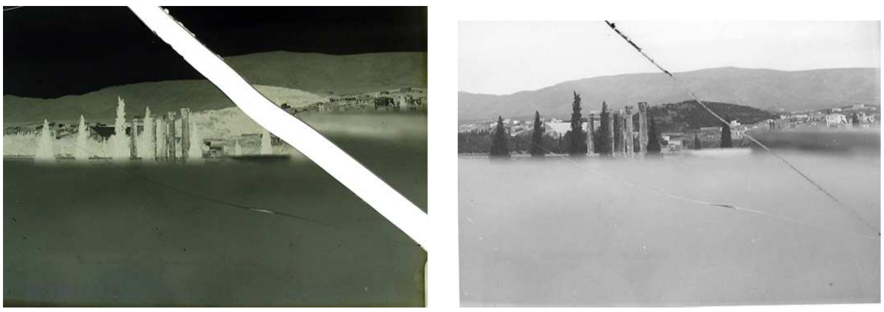
Figure 4. (a, b) Example of application of the algorithm on the fragmented glass plate depicting a bronze mirror handle in shape of naked boy (half of 3rd century BC) from Centuripe.

All the experiments have been obtained using Matlab 7.6 R2008a, us-

(a) (b)

Figure 5. (a, b) Example of application of the algorithm on the fragmented glass plate depicting the overview of Centuripe of Figure 1(b).

ing a CPU Core 2 DUO processor, E8500, 3,16 GHz, RAM memory 6GB. Table 1 reports the performance statistics of the algorithm. In particular, the second column reports the average run-time required for each step and the third column shows the percentage over the total.



(a) (b)

Figure 6. (a, b) Example of application of the algorithm on the fragmented glass plate depicting the Corinthian columns of the scene of the Hellenistic - Early Roman theatre of Taormina (Messina, Sicily).

Table 1. Average time used by the algorithm.

	second	%
Detection	6.13	5.68%
Color correction	3.72	3.44%
Rotation	93.21	86.29%
Translation	2.71	2.51%
Interpolation	2.25	2.08%

4. Conclusions.

In this paper we have presented an algorithm for the automatic restoration of digitalized photographic glass plates. The experimental results we achieved on the case study represented by the found of Department of Archaeology Library have demonstrated the reliability of this method in a real and large dataset. Furthermore, thanks to the application of the proposed algorithm it was possible to print new restored copies of the damaged and fragmented glass plates, otherwise unusable.

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