APPLICATION OF IMAGE PROCESSING FOR THE CONSERVATION OF THE MEDIEVAL MOSAIC

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ABSTRACT

We present an application of digital image processing for the analysis of the medieval mosaic conservation. The reconstructed art piece was the "The Last Judgement" mosaic, situated on the wall of the St. Vitus cathedral in Prague, Czech Republic. The historical photograph of the mosaic from the 19^{th} century was compared with the photograph of the current state. The images were firstly preprocessed to increase their quality (noise reduction, deblurring). In the second stage, geometrical differences between images were removed by means of image registration techniques. Finally, differences of the current and historical photographs were identified.

1. INTRODUCTION

Our paper demonstrates an application of digital image processing for the analysis of the medieval mosaic conservation. The "The Last Judgment" mosaic is situated on the outer wall of the St. Vitus cathedral, Prague, Czech Republic (Fig. 1). It is made of almost 1 000 000 glass cubes and it was completed in 1371 under the reign of King Charles IV.

The dilapidation of the mosaic during the centuries was very severe, due to the lower quality of used glass, due to temperature fluctuations (the measured range of the temperature is from -28 to 60 degrees of Celsius) and, recently, due to the air pollution. Large amount of effort has been put to conserve and protect the mosaic. The last attempt started in 1992, when the U.S. Getty Conservation Institute jointly with Czech specialists reconstructed the whole mosaic. The renovation was finished in September 2000.

During the last conservation an historical bw photograph of the mosaic was discovered in the archive. It was taken on a glass plate by famous Czech photographer J. Eckert in 1879. This photograph captured the mosaic before its temporal removal in 1890 (due to the storm damage).

Our aim was to reveal original patterns, captured on the historical photograph, which already disappeared from the mosaic and which are not apparent on the photograph due to the high level of present noise and blurring. Moreover, we were asked to evaluate the mosaic reconstruction process. Having the images of the historical and current state of the mosaic (taken by a digital camera), the goal was to compare them and to find the mutual differences.

Section 2 describes the image restoration applied primarily on the historical image. It was necessary because of present noise and blurring, caused by various factors such as aging, chemical changes of the photo material and wrong focus of the camera. Section 3 provides information about used image registration methods, which brought the images into geometric alignment (the photographs were not taken from the same position so their geometry differ from each other). Without the image alignment, the following comparison of the images and the location of mutual differences would be difficult to realize.

2. PHOTOGRAPH RESTORATION

The quality of the historical photograph is poor, many scratches and dust are clearly visible at several places. The wrong setting of the camera focus (with large format cameras of that time, it was difficult to achieve high precision of the focusing) has caused image blurring. Moreover, the aging effect (silver particles are subject to the irreversible chemical process of diffusion) has a profound impact on certain areas of the picture where it manifests as blurring. In general, most of the components in bw photography (fine-grained and superficial silver, gelatin, albumin or collodium as a binding agent) are affected by many environmental conditions, and the stability of photographic pictures is limited by the properties of each of the mentioned substances.

The removal of these degradations on the historical mosaic photograph requires an appropriate image restoration technique which would decrease the noise impact and in-

Historical photograph: 1879

New photograph: 2001

Fig. 1. The Last Judgement Mosaic

crease the image sharpness.

Most of the image degradation processes can be, at least locally, successfully modeled by linear shift invariant system

$$g = f * h + n,$$

where g, f, h, and n represent an acquired degraded image, original image, point spread function (PSF) and additive noise, respectively. The operator $*$ stands for the convolution. We assume that the effects, vividly apparent on the historical photograph, can be sufficiently approximated by this model.

For the noise suppression, three different methods were applied to decrease the noise level: wavelet-based denoising with automatic noise level estimation [1], adaptive nonlinear filters [2], and iterative denoising based on Mumford-Shah's functional [3]. These methods were chosen as examples of different approaches to noise reduction that simultaneously preserve edges and fine details. In our experiments,

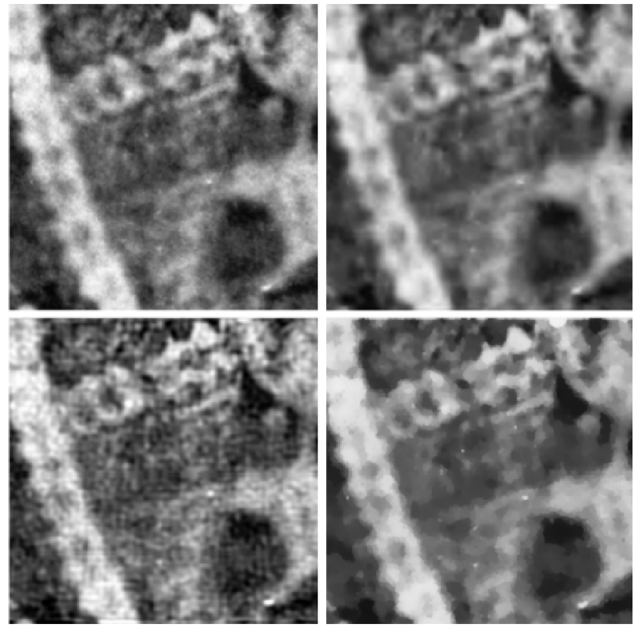


Fig. 2. Restoration results (detail of the historical image): original - (top left); wavelet-based denoising - (top right); Wiener filter sharpening and denoising - (bottom left); total variation sharpening and denoising - (bottom right).

the wavelet-based denoising gave the most favourable results, see Fig. 2*(a) – top right*.

Several methods for image sharpening were considered in the image preprocessing stage. As the first method we have chosen an iterative reconstruction algorithm based on total variation [4]. This method belongs to the group of blind deconvolution techniques and does not require any prior knowledge about the PSF. However, blind single - channel reconstruction models with no or too few constraints are very ill-posed (this is the case of the historical mosaic image), so the obtained results were unsatisfactory. In another applied approach, a PSF estimation preceded the image sharpening. The partial differential equation known as *the heat equation* well describes the chemical process of diffusion that contributes to the overall blurring effect. It is the well-known fact that the solution of the heat equation is the convolution of the original with a Gaussian function. The inverse heat equation could be applied to reverse the effect of the diffusion process. The main drawbacks of this method are its low stability and the necessity of extra denosing at the end of the processing. Once we accept the assumption that blur can be modelled by Gaussian function, one can use, after estimating its variance, classical nonblind deconvolution techniques like e.g. Wiener filter (see Fig. 2*(c) – bottom left*) or constrained least square methods.

The most satisfactory results were obtained by means of the total variation (TV) based reconstruction method mentioned above ([4]) but in a non-blind framework, i.e. the Gaussian function was used as the representation of the PSF. The TV norm is essentially the norm of the image gradient which is an appropriate regularization functional that allows discontinuities in functions and thus preserves edges in images. Some modifications of the TV norm are necessary to avoid difficulties associated with the nondifferentiability of the Euclidean norm at zero. This leads to the constrained minimizing problem of the following form

$$\min_f \int \sqrt{|\nabla f|^2 + \beta^2} \text{ subject to } \|h * f - g\|^2 = \sigma^2 \quad (1)$$

where σ^2 is the error (noise) level and β is a small positive parameter. Equivalent unconstrained optimization problem can be obtained by means of Lagrange multiplier. Several linearization schemes were proposed to deal with the nonlinearity of the associated Euler-Lagrange equations: fixed point iteration scheme [5], primal-dual method [6] or more general half-quadratic regularization scheme proposed by Geman and Reynolds in [7]. We have followed the approach of Chambolle and Lions [8] which introduces an auxiliary function and is similar to the half-quadratic regularization scheme. Fig. 2*(d) – bottom right* shows the result achieved on the chosen sample.

The results of applied restoration methods (Fig. 2) show slight but not demonstrative improvement. The methods produce images with less noise and/or with sharpened details. Each of the applied methods has its particular advantages and disadvantages. Unfortunately, the overall impression is not significantly better than the original non-enhanced data.

3. GEOMETRICAL ALIGNMENT AND LOCATION OF DIFFERENCES

Before any effort to detect mutual differences can start, geometrical correspondence of images has to be assured. Since the images were taken from different locations of the camera their geometry is different. After the alignment, all objects which did not change their position in the scene, will be at the same part of the images. Then, by means of simple image overlaying, we can easily identify places, where the mosaic was changed with respect to its state in 1879.

There are various methods that removes geometrical differences of images (good overview is in [9]). The big difference between our images due to the violation of intensity values correspondence, blurring, scratches, noise, etc. demand a feature-based registration approach which does not use directly the image functions but extracted features and their estimated correspondence. Salient point pairs (easily distinguishable points on both images, such as corners and edge endings) were detected and their correspondence is used for the computation of parameters of the geometric transform, present between images.

Considering the expected difference in the camera position, we applied the affine model

$$\begin{aligned} u &= a_0 + a_1 x + a_2 y \\ v &= b_0 + b_1 x + b_2 y \end{aligned}$$

and the projective model

$$\begin{aligned} u &= \frac{a_0 + a_1 x + a_2 y}{1 + c_1 x + c_2 y} \\ v &= \frac{b_0 + b_1 x + b_2 y}{1 + c_1 x + c_2 y} \end{aligned}$$

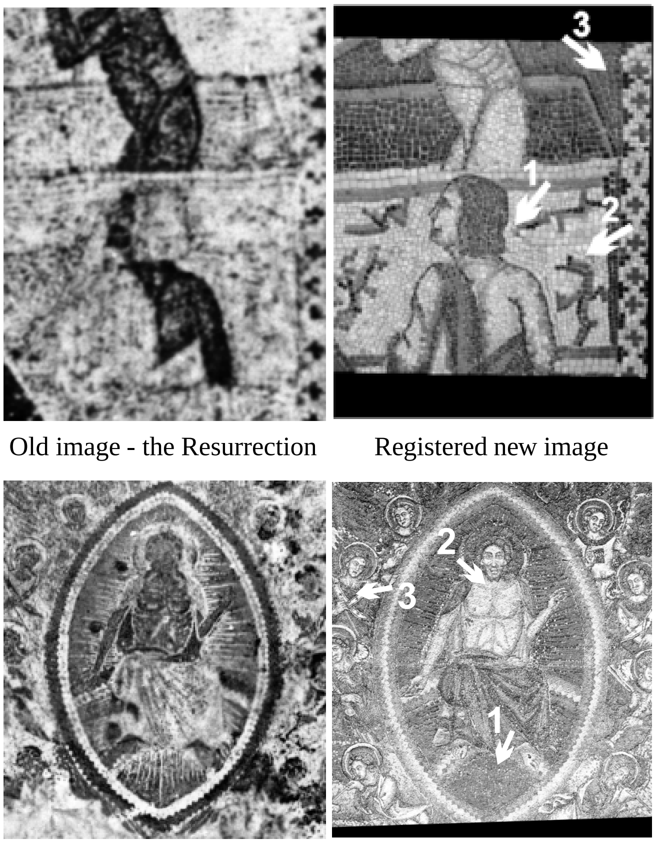
for the mutual geometrical transformation of the images. Here, (u, v) and (x, y) are the coordinates in the original and the to-be-registered images, respectively. We have tried the thin-plate spline model [10] too, to be able to eliminate possible local deformations. However, the affine transform proved to be sufficient.

Finally, by transforming and overlaying the registered images of the historical and new mosaic state, many differences, not visible before, became apparent. Examples of the identified differences can be seen in Fig. 3, where two details of the mosaic are presented. In the Resurrection scene, examples of the differences are following: the haircut of the person has an extra wave (the difference No.1), the ornamental patterns on the right side are corrupted and have different shape now (the difference No.2), the part of the coffin edge is missing (the difference No.3). In the Jesus Christ scene, the shine rays under Jesus Christ are missing (the difference No.1), the shape of the Jesus beard is changed (the difference No.2) and the collar of one of the angels is different (the difference No.3), to name some. The task was very difficult due to the low image quality and missing color information on the historical photograph, however, we were able to identify differences, which could bring new ideas to the understanding of the mosaic and which were appreciated by art historians.

4. CONCLUSION

The fast development of computers and algorithms during last decades can influence even such distant area to the computer technology as the art conservation is. The aim of conservators, saving the heritage of the past for the next generations, can be facilitated using the high–tech devices and methods.

Our task was to use modern image processing methods for the evaluation of the conservation, realized on the medieval mosaic ”The Last Judgement”. We were asked to compare the historical photograph from the end of the 19^{th} century, very much destroyed by aging, noise, and blurring, with the digital photograph of the mosaic current state. The



Old image - the Resurrection   Registered new image

Old image - Jesus Christ   Registered new image

Fig. 3. Examples of identified differences (details: the Resurrection and Jesus Christ scenes). The Resurrection scene (top row): (1) the haircut, (2) the ornamental patterns, (3) the coffin edge; Jesus Christ scene (bottom row): (1) the shine rays, (2) the beard, (3) the collar.

main aim was to identify differences and to affirm patterns, which were not changed. As well this experiment was the test case if digital image processing can be of any use for the conservation of art pieces of this kind .

We applied several image restoration methods to improve the quality of the historical photograph but due to the very complex nature of the image degradation no impressive results were achieved. The increase of the quality is not significant, however, small improvements in denoising and sharpening have been realized.

The second part, the image registration and location of differences, gives much better results. Using the feature-based registration approach, the geometrical deformations due to the non-corresponding positions of the cameras during the image acquisition were removed and the new differences, not apparent before, revealed.

The digital image processing substantiates itself as a useful tool, applicable in the area of art protection and conservation and able to supply information not available otherwise. However, because of the complex interdisciplinary nature of the problem, the image processing techniques applied in such cases are not likely to work fully automatically. Human assistance of computer scientists as well as art historians will be always required.

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