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An application of image processing in the medieval mosaic conservation

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Abstract We present an application of digital image processing techniques in medieval mosaic conservation. The reconstructed art piece was The Last Judgment mosaic, situated on the wall of the St. Vitus cathedral in Prague, in the Czech Republic. The historical photograph of the mosaic from the 19th century was compared with the photograph of the current state in order to detect mutual differences. 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—mutual information and feature point correspondence. Finally, differences of the current and historical photographs were identified.

Keywords Art conservation · Change detection · Image registration · Image restoration · Mutual information

Introduction

Our paper demonstrates an application of digital image processing to the analysis of the accuracy of the medieval mosaic conservation. The splendid The Last Judgment mosaic is situated on the outer wall of the St. Vitus cathedral on the premises of the Prague Castle, in the Czech Republic (Fig. 1). It is made of almost 1,000,000 glass cubes and 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 high amount of agents contained in the glass, due to temperature fluctuations (the measured range of the temperature is from -28 to $+60$ degrees Celsius) and, recently, due to air pollution. A great deal of effort has been put into conserving and protecting the mosaic.

The last attempt started in 1992, when the Getty Conservation Institute of Los Angeles, jointly with Czech specialists, reconstructed the whole mosaic. The renovation was finished in September 2000. During the last conservation, an historical black and white photograph of the mosaic was discovered in the archives. It was taken on a glass plate by Jindrich Eckert, the famous Czech photographer, in 1879. This photograph captures the mosaic before its removal due to a great storm damage in 1890 (the renewed mosaic was returned to the cathedral wall in 1910). This photo gives us an unique opportunity to compare the current state of the mosaic with the state of the mosaic at the end of the 19th century.

The aim of our work was to reveal original patterns, captured in the historical photograph, which have 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 changes caused by several mosaic reconstructions realised since 1879.

For our experiments, we used the image of the current mosaic state taken by a digital camera (see Fig. 1 at the bottom) and the digitised negative (1200 DPI) of the Eckert's photograph (see Fig. 1 at the top). The special tonality of the historical image is caused by the low sensitivity of the employed photographic material to the red part of the visible spectra. The photograph has a high level of noise and blurring caused by various factors such as aging, chemical changes of the photomaterial and incorrect camera focus. The current photograph, depicting approximately the same parts of the mosaic as the historical image, was transformed to the greyscale space. For the presentation, the achieved results of the image restoration are shown on two severely blurred small areas (measuring 450×300 and 300×400 pixels). Image registration results are demonstrated on two larger mosaic parts, the Resurrection scene and the central part with Jesus Christ (see Figs. 2, 3 and 4).

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Fig. 1 The Last Judgment mosaic, situated on the outer wall of the St. Vitus cathedral. *Top*: The historical photograph of the mosaic by Jindřich Eckert, 1879. *Bottom*: The photograph of the current state taken by a digital camera

The next section describes the image restoration process applied primarily on the historical image. The restoration was necessary because of the degradation of the photograph (noise, blurring, etc.). The section Image registration provides information about used image registration methods which brought the images into geometric alignment. The comparison of the images, location of mutual differences, and the evaluation of the conservation are described in the Change detection section.

The photograph restoration

The quality of the historical photograph is poor; many scratches and dust are clearly visible at several places. An inaccurate camera focus (with large format cameras of that time, it was difficult to achieve a high precision of focusing) has caused image fuzziness. The aging effect (silver particles are subjected to the irreversible chemical process of diffusion) also has a profound impact on certain areas of the picture which manifest as additional blurring. Most of the components in black and white photography (fine-grained and superficial silver, with gelatin, albumin or collodium as a binding agent) are affected by environmental conditions and the stability of photographic pictures is limited by the properties of each of the substances.

The removal of these degradations on the historical mosaic photograph requires an appropriate image restoration technique which would decrease the noise impact and increase the image sharpness. Most of the image degradation processes can be, at least locally, successfully modelled by a linear shift invariant system:

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

where g, f, h, and n represent the 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 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 non-linear 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, the wavelet-based denoising (Fig. 5a and Fig. 5b) gave the most favourable results. Several methods for image sharpening were considered in the image pre-processing stage. First, we have chosen an iterative reconstruction algorithm based on total variation (TV) [4]. This method belongs to the group of blind deconvolution techniques and does not require any prior knowledge of the PSF. However, blind single-channel reconstruction with either weak constraints or no constraints is an ill-posed problem (this is the case of the historical mosaic image), and, therefore, 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. The solution of the heat equation is the convolution of the original with a Gaussian function. The inverse heat equation can be applied to reverse the effect of the diffusion process. However, this technique lacks numerical stability and requires extra denoising at the end. Once we accept the assumption that blur can be modelled by a Gaussian function, one can use, after estimating its variance, classical non-blind deconvolution techniques, e.g., the Wiener filter (see Fig. 5) or constrained least square methods.

The most satisfactory results were obtained by means of the TV-based reconstruction method [4] applied in a nonblind framework, i.e., the Gaussian function was used as a model of the PSF. The TV norm is essentially the L_1 norm of the image gradient which is an appropriate regularisation functional that allows discontinuities in functions and thus preserves

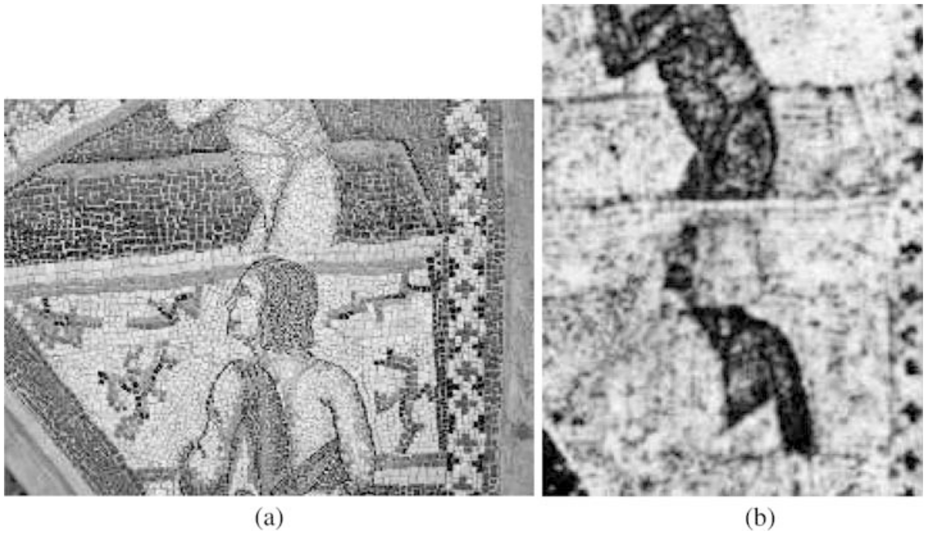


Fig. 2 The Resurrection scene, used as a test-site for image alignment and change detection. **a** The current photograph; **b** The historical photograph

edges in images. Some modifications of the TV norm are necessary to avoid difficulties associated with the non-differentiability of the Euclidean norm at zero. This leads to a constrained minimising problem of the following form:

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

where σ^2 is the error (noise) level and β is a small positive parameter. An equivalent unconstrained optimisation problem can be obtained by means of Lagrange multipliers. Several linearisation schemes were proposed to deal with the nonlinearity of the associated Euler-Lagrange equations: a fixed point iteration scheme [5, 6], a primal-dual method [7] or a more general half-quadratic regularisation scheme proposed by Geman and Reynolds in [8]. We have followed the approach of Chambolle and Lions [9] which introduces an auxiliary function and is similar to the half-quadratic regularisation scheme. Fig. 5 illustrates the results achieved by this method on the chosen samples.

The results of restoration (Fig. 5) show a 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 of the original non-enhanced data.

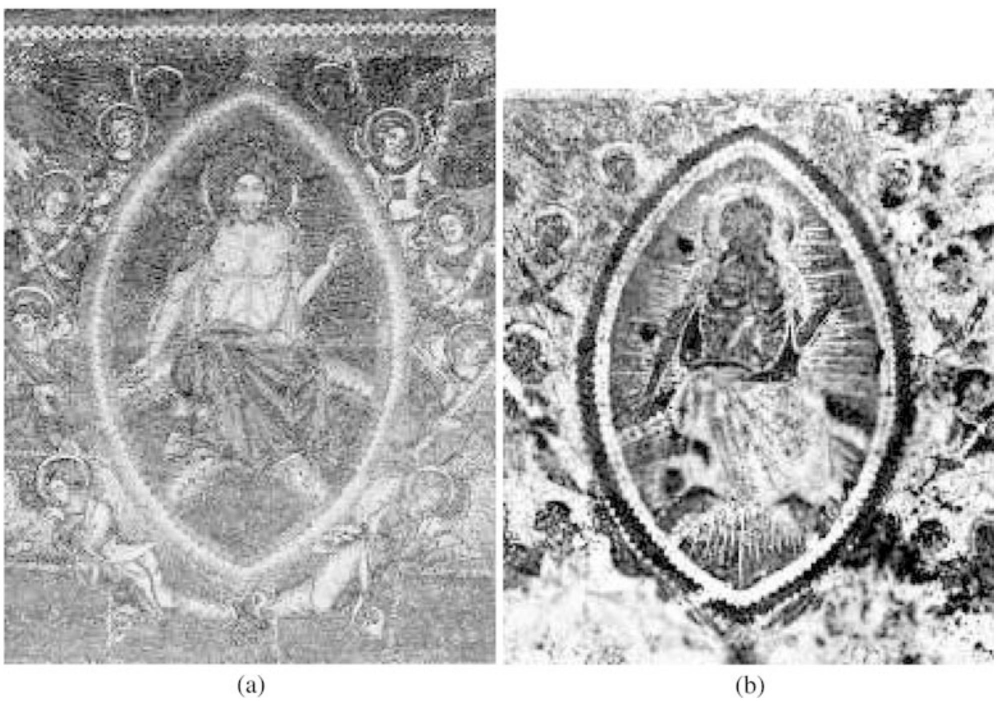


Fig. 3 The Jesus Christ scene, used as a test-site for image alignment and change detection: **a** The current photograph; **b** The historical photograph

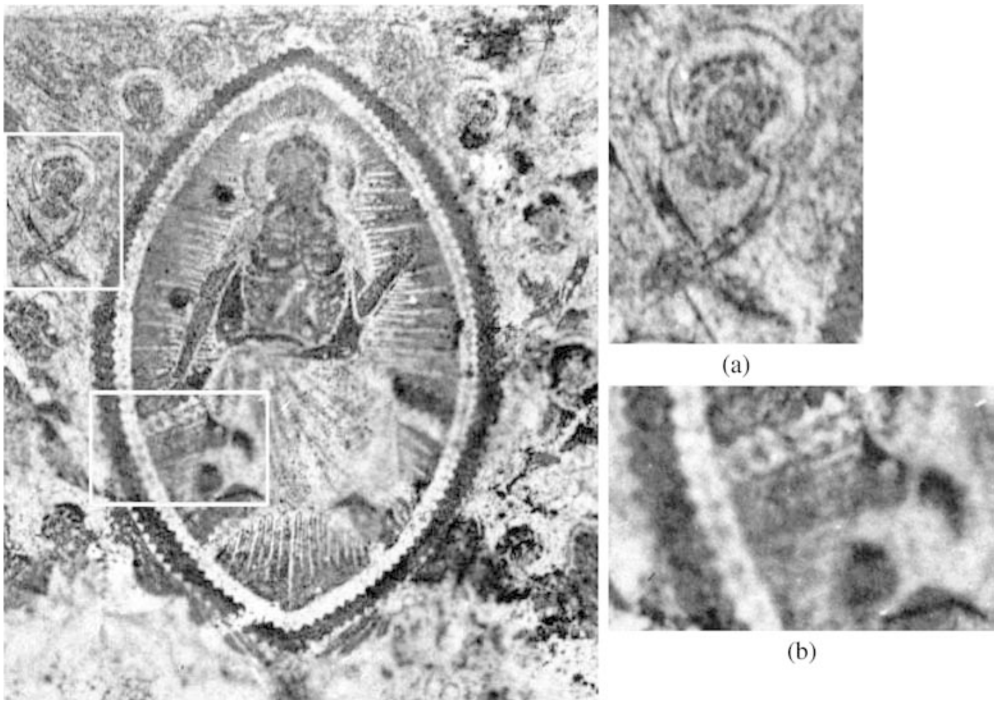


Fig. 4 Two areas (see the rectangles on the left image) which were selected as test sites for image restoration **a** 300×400 pixels; **b** 450×300 pixels

Image registration

Before any effort to detect mutual differences can start, the geometrical correspondence of images has to be assured. This process is called *image registration*. 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 parts where the mosaic was changed with respect to its state in 1879.

There are various registration methods that remove geometrical differences of images (extensive overviews are in [10, 11]). The big differences between our images due to the discrepancy of intensity values, blurring, scratches, noise, etc. preclude using of classical correlation-like methods. Feature based methods, which use extracted features and their estimated correspondence, or up-to-date multimodal area based techniques [12, 13] are appropriate candidates for the solution of our task.

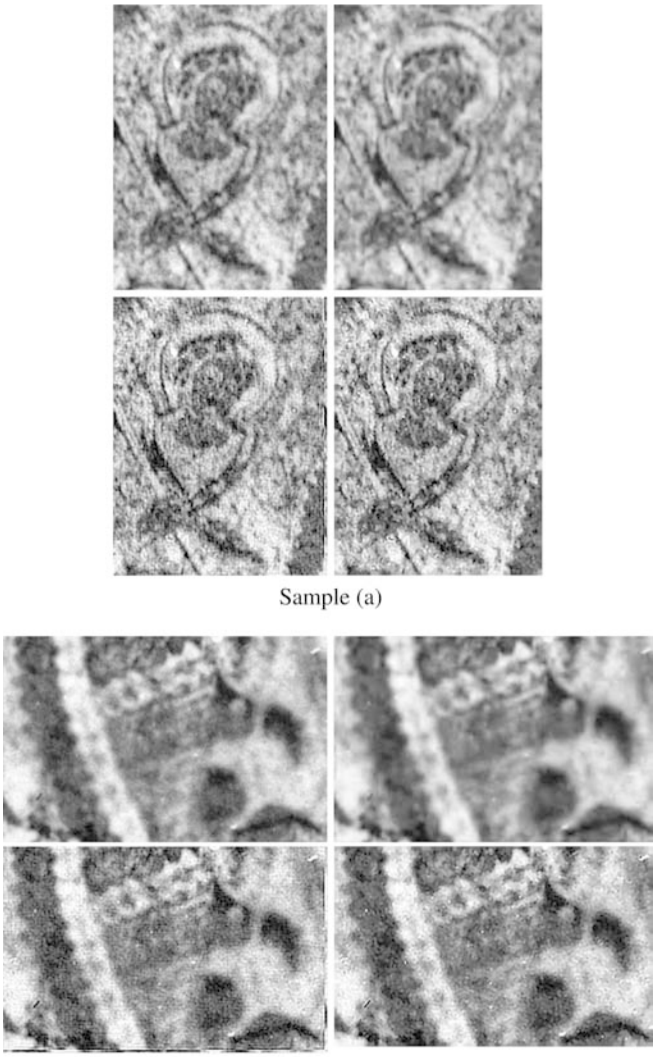
The proposed approach combines both of the abovementioned categories. Firstly, the features, i.e., salient point pairs (easily distinguishable points on both images, such as corners and edge endings), were manually selected; their correspondence was used to estimate the scale difference between images, and the images were re-scaled to the same scale.

20 point pairs which were manually selected are shown in Fig. 6. In general, the feature point selection is a difficult task due to the differences between the images (blur, noise, intensity changes), but the accuracy of feature selection can strongly influence the quality of the resulting registration. Thus, locations of identified salient points in the historical image were improved by means of the mutual information (MI) method [12]. MI is a measure of statistical dependency between two data sets (images), which originates from information theory. Contrary to traditional correlation-based methods, which use directly image intensities, the MI criterion is not explicitly dependent on image functions, which makes it particularly suitable for registration of images from different modalities. This was exactly our case because the historical photograph has low sensitivity to the red and green spectral bands. MI between two random variables X and Y is defined in terms of entropy H as:

$$I(X,Y) = H(X) + H(Y) - H(X,Y).$$

The entropies are estimated from image histograms. For registration purposes, MI is evaluated for all possible translations of the images and its maximum indicates optimal matching position. We computed the MI between the point pairs locally using the window neighbourhood around the particular feature points. Positions of the shifted windows, which refer to the maximum value of the MI criterion, were regarded as the refined coordinates of the salient points in the historical image. For 75% of the pairs the MI criterion has well localised peeks and gives us more accurate positions of the feature points (see Fig. 7 for two examples). In the rest of points, the maximum was reached too far from the initial point or even was not found at all and thus we did not apply it to refine the point locations.

An interesting result was obtained for the salient point shown in Fig. 8. The corresponding point in the historical image was identified incorrectly during the



Sample (a)

Sample (b)

Fig. 5 Results of the historical photograph restoration (samples a and b): original (*top left*), wavelet-based denoising (*top right*), Wiener filter sharpening and denoising (*bottom left*), total variation sharpening and denoising (*bottom right*)

manual selection since human perception automatically fills missing patterns, which was misleading in this case. On the other hand, the MI method takes into account the whole region and therefore has found a more accurate position. The graph of MI criterion for this neighbourhood is in Fig. 7.

The refined point positions were then used for the computation of the transformation model parameters. According to the expected difference in the camera position, we applied the affine model:

$$u = a_0 + a_1 x + a_2 y,$$
$$v = b_0 + b_1 x + b_2 y$$

and the projective model:

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

for the 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 tried the thin-plate spline model [14] too, to be able to eliminate possible local deformations. However, the affine transform proved to be sufficient.

The current image was transformed and resampled by means of the bilinear interpolation. Examples of the registered parts together with the historical originals are shown in Fig. 9.

Change detection

Finally, by transforming and overlaying the registered images of the historical and current mosaic state, many differences, not visible before, became apparent. Examples of the identified differences can be seen in Fig. 9, where two test parts of the mosaic are presented. In the Resurrection scene, examples of the differences include the following: the haircut of the figure has an extra wave (difference No. 1), the ornamental patterns on the right side are corrupted and have a different shape now (difference No. 2) and a part of the coffin edge is missing (difference No. 3). In the Jesus Christ scene, the rays under Jesus Christ are missing (difference No. 1), the shape of Jesus' beard is changed (difference No. 2) and the collar of one of the angels is different (difference No. 3), to name a few.

The task was very difficult due to the low image quality and missing colour 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.

Conclusions

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

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

The main aim was to identify differences and to affirm patterns, which were not changed. Moreover, this experiment was the test case as to whether 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

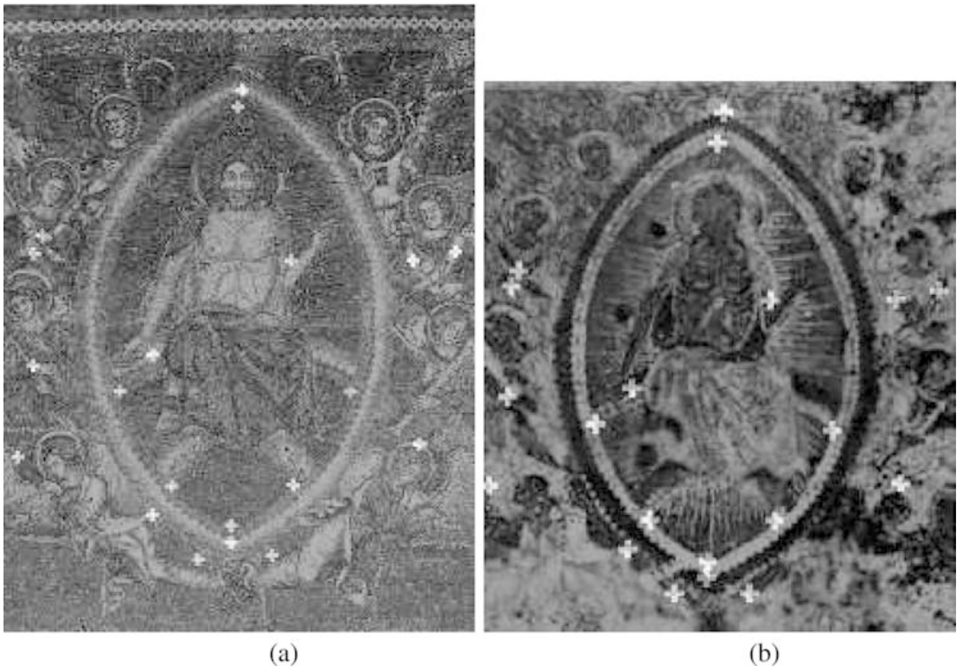


Fig. 6 The Jesus Christ scene, with selected feature points marked by crosses. **a** Current image; **b** Historical image

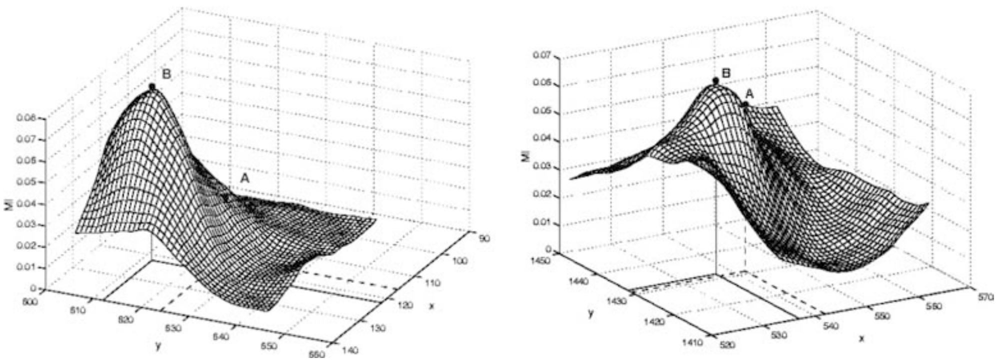


Fig. 7 The mutual information criterion for two different point pairs. A represents the position selected manually in the historical image, B marks the improved position of the point using mutual information. The graph on the left-hand side corresponds to the point pair shown in Fig. 8. The distance between A and B is 13 pixels

but due to the very complex nature of image degradations no impressive results were achieved. The increase of the quality is not significant; however, small improvements in denoising and sharpening have been achieved. The second part, the image registration and location of differences, gave much better results. Using the feature-based registration approach combined with the mutual information for the feature accurate localisation, the geometrical deformations due to the non-corresponding positions of the cameras during the image acquisition were removed and the differences, not apparent before, were revealed. The digital image processing substantiates itself as a useful tool, applicable in the areas of art protection and conservation, which is 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.

Originality and contributions

In this work, we demonstrate how up-to-date image restoration and registration techniques can be utilised to validate such delicate conservation tasks as the reconstruction of the 14th century mosaic. Our aim was to compare the current state of the mosaic with its former state and localise any differences. The uniqueness of the described application lies in the fact that this splendid marvel made by medieval artists was captured on an old photograph just before it was severely damaged and had to be removed in the second half of the 19th century from its original location. The old photograph is of poor quality due to the aging effects of old photographic materials. Nevertheless, the photograph provides us with precious information that enables us to compare the current renovated mosaic with its former state and evaluate any discrepancies introduced by several conservation efforts in the last 120 years. Using modern image processing methods for denoising, deconvolution and image registration, we were able to successfully identify pattern differences that were overlooked by restorers. We claim that digital image processing can provide important complementary data for scholars and should be thus considered as a verification tool for such restoration tasks.

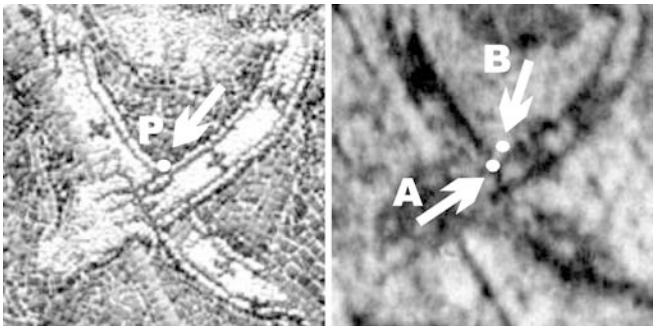


Fig. 8 The improvement of the control point position. In the historical image, point A was manually selected as the counterpart of point P from the current image. Its position was refined by mutual information method (see point B). The person who selected the points misjudged the shape of the straps, which was changed during the mosaic conservations

About the authors

Barbara Zitova received her M.Sc. degree and Ph.D. degree in computer science from Charles University, Prague, Czech Republic. Since 1995, she has been with the Institute of Information Theory and Automation, Academy of Sciences of the Czech Republic, Prague. She also gives tutorials on image processing and pattern recognition at the Czech Technical University and participates in courses on digital image processing at the Faculty of Mathematics and Physics, Charles University. Her current research interests include image processing, geometric invariants, image enhancement and image registration. She has co-authored and authored more than 25 research publications in these areas.

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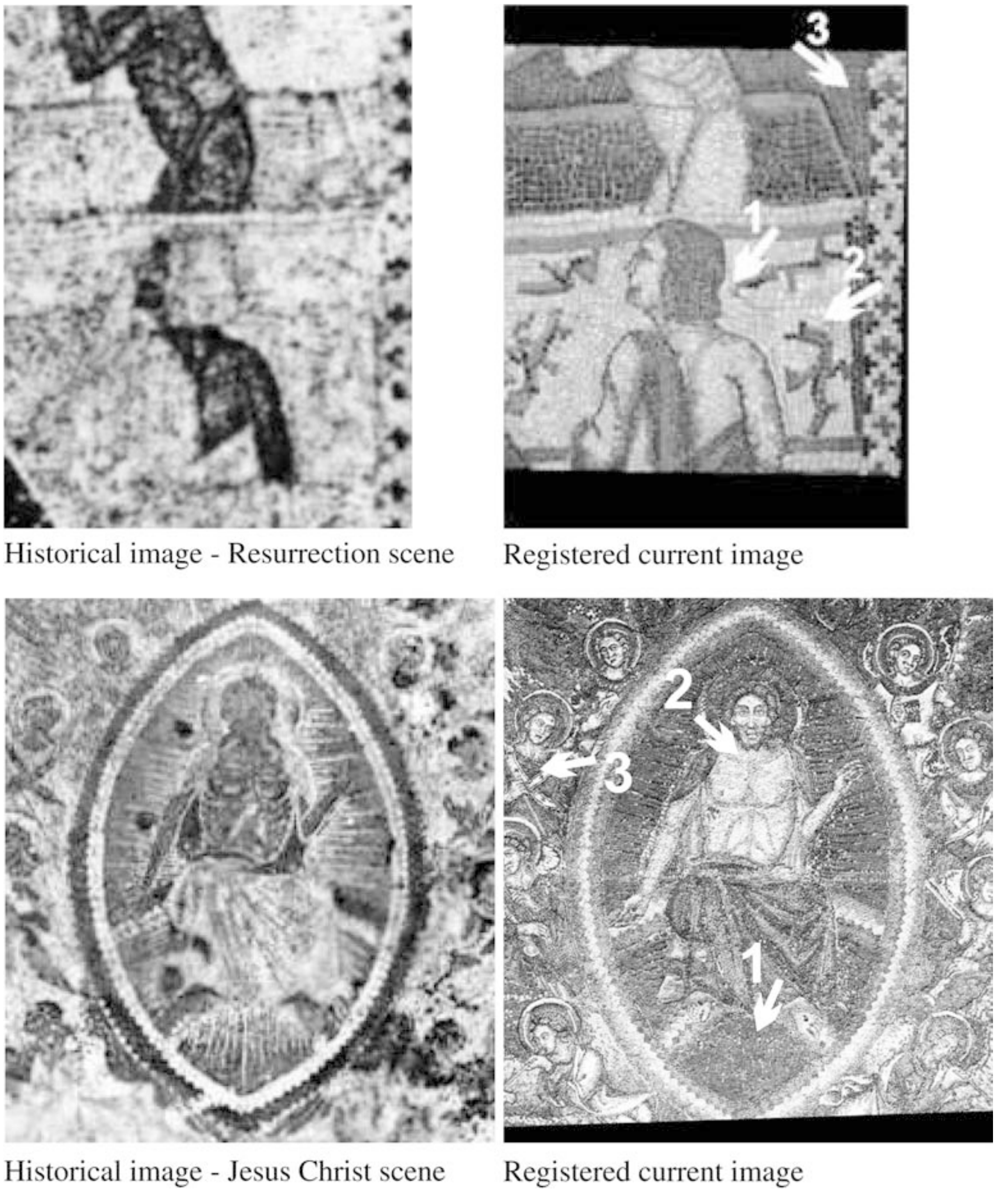

Fig. 9 Examples of identified differences between the registered images. Resurrection scene (*top row*): (1) haircut (2) ornamental patterns (3) coffin edge. Jesus Christ scene (*bottom row*): (1) rays (2) beard (3) collar

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