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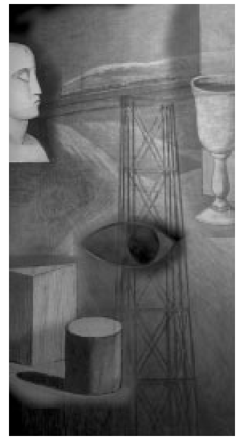
ArtShop: an art-oriented image-processing tool for cultural heritage applications



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Advances in electronic imaging over recent years have encouraged the development of new tools for cultural heritage applications. In this paper a software application called ArtShop is described, containing some tools for artwork image restoration, developed during several years of research at the Image and Communications Laboratory of the University of Florence. Copyright © 2003 John Wiley & Sons, Ltd.

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Introduction

Driven by the diffusion of multimedia systems and by the availability of increasingly effective digital imaging tools, image-processing techniques have been successfully applied to the analysis, restoration, archiving and preservation of artwork. Among recent developments, it is worth mentioning advanced virtual restoration techniques of artwork (offering users reproductions of artwork as they would have appeared when originally created or at least close to that),[1,2] generation of very high-resolution images of paintings for dissemination or study–research purposes,[3–6] evaluation of the perceptual quality of digital reproductions of artwork in printed or displayed form,[7–10] protection of artwork digital reproductions through digital watermarking,[11] and extended use of 3D digital techniques for the representation and processing of cultural heritages.[12–17] In this paper, we present ArtShop, a software application which collects many image-processing tools for artwork restoration. These tools can be used both to improve the quality of the displayed images and to make a virtual restoration of the work. It is interesting to underline that ArtShop's tools are specific for artwork restoration. In fact, a lot of commercial image-processing software could be used for similar purposes (e.g. PhotoShop), but these applications were conceived for generic image retouching and are not specific for artwork restoration, so that to obtain a result in this direction requires much more work for a lower final quality. For example, one of the tools of ArtShop is the vector median filter, which produces a median filtered image of high quality (without defocusing effects). Another tool involves scanner colour calibration. In fact, great attention must be paid to the acquisition and digital reproduction of paintings: even if a high-quality scanner is used, the colours of the resulting digital images can be different from the original ones. In these cases scanner colour calibration can improve the aspect of the artwork. On the other side some tools are proposed to be used as a guide to the actual restoration of the artwork (computer-guided restoration), or to produce a virtual restored version of the work (virtual restoration). Thanks to the computer-guided and virtual restoration tools the restorer can obtain a preview of the impact of his work on the painting or fresco before actually restoring it and evaluate every aspect of the possible work in a short time, thus improving the final result of the restoration.

ArtShop's Tools

As briefly described in the introduction, ArtShop operates in two different directions: quality improvement and virtual restoration.

Quality Improvement

Concerning image quality improvement ArtShop offers two tools: vector median filtering and scanner

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calibration. The vector median filter produces a median filtered image without introducing defocusing side effects. Usually, classical noise reduction techniques smooth the original image and change its colour span. Conversely, the median filters implemented by ArtShop do not produce this effect. As a general rule vector median filtering is a powerful tool for processing colour images and other vector signals. Vector median filters perform well in reducing noise by preserving contours. Given a set $S = \{\vec{v}_1, \vec{v}_2, \ldots, \vec{v}_N\}$ of N vectors in R^n, the vector median of the set is the vector $\vec{v}_{vm} \in S$ which minimizes the sum of the distances to the other points of the set, i.e.

$$\sum_{i=1}^{N} ||\vec{v}_{vm} - \vec{v}_i|| \leq \sum_{i=1}^{N} ||\vec{v}_j - \vec{v}_i|| \; j = 1, 2, 3, \ldots, N \qquad (1)$$

where $|| \cdot ||$ is a suitable R^n norm. Depending on the given norm, different behaviours are observed for the filter; the best performances are obtained by using the classical Euclidean norm (L_2) and the 1-norm (L_1). In particular the L_2 filter is sometimes preferred due to its isotropic behaviour. From the point of view of computational complexity, however, the vector median filter based on the Euclidean norm is outperformed by vector median filters based on the 1-norm and the squared 2-norm (L_2^2). This is due to the computation of the square root the Euclidean norm calls for, and to the unavailability of fast algorithms for minimizing the sum of the distances (which are, on the contrary, available for the L_2^2 and L_1 filters[18,19]). ArtShop allows users to choose between filters based on all these types of norms by always using the fastest algorithm available; moreover, it allows one to set different dimensions of the squared window, so users can apply the most suitable filters for the application at hand.[20]

Regarding scanner calibration, it is known that when a digital image is acquired by a scanner the colours of the final image can differ from the original one; obviously the higher the quality of the scanner the higher the chromatic fidelity of the acquired image. For this reason, it is useful to develop a transformation which inverts, to the largest possible extent, these colour degradations. This transformation can be evaluated for each different scanner using a reference colour table. Usually these tables are standardized (one of the most used standards is called IT8[21]) and provided with the scanner. Thus, the colour remapping function is constructed by acquiring the reference table with the scanner and by minimizing the differences between the colours obtained and the expected ones. The expected colours are provided in a separated data file by the manufacturer of the IT8 table used to calibrate the scanner. If we assume that the changes between colours acquired and expected ones can be modelled by an affine linear transformation we can obtain the remapping function by estimating the matrix W of the following linear system:

$$\vec{c'} = A\vec{c} + B = (A \quad B)\begin{pmatrix} \vec{c} \\ 1 \end{pmatrix} = W\begin{pmatrix} \vec{c} \\ 1 \end{pmatrix} \qquad (2)$$

where $\vec{c} = (c_R, c_G, c_B)^T$ represents the vector of the RGB component of the acquired colour, $\vec{c'} = (c'_R, c'_G, c'_B)^T$ is its true value and W is the matrix modelling the affine linear transformation. The calibration of the scanner is equivalent to determine the coefficients of W in such a way to minimize the mean square error between the acquired colours and the true ones:

$$e_m = E[||\vec{c} - \vec{c'}||^2]. \qquad (3)$$

The algorithm proposed by ArtShop produces an estimation of W by using a *pseudo-RANSAC* scheme to avoid numeric problems (e.g. ill-conditioning) that could affect the direct estimation of W. Following the RANSAC philosophy,[22] we randomly choose the minimum subset of colours from those represented in the IT8 tables to build and solve the system (2). Each colour gives us three equations; we have 12 unknown parameters so the minimum number of colours to solve the system (2) is four. We solve it by singular value decomposition (SVD), obtaining a mean square error estimation of W. Obviously we solve a rewritten version of (2) taking into account that the unknowns are the elements of W. This process is iterated a predefined number of times, obtaining a set of transformation. We take as final W the one which best maps the acquired colours with the true ones according to

$$\hat{e}_m = \frac{1}{n} \sum_{s \in S} \Delta D_{RGB}(s) \qquad (4)$$

where S is the entire set of colours represented by the IT8 table minus the ones used to compute the estimation and D_{RGB} is the following metric:

$$\Delta D_{RGB} = \sqrt{(c_R - c'_R)^2 + (c_G - c'_G)^2 + (c_B - c'_B)^2} \qquad (5)$$

Thanks to calibration, the colours of an image acquired by a given scanner and displayed by means of ArtShop looks more similar to the original ones (see the section on Experimental Results).

Virtual Restoration

Thanks to the diffusion of multimedia technology more and more image-processing techniques are applied to the analysis and restoration of artwork. When seen as tools for art work restoration, image-processing techniques can be used as a guide to the actual restoration of the artwork (computer-guided restoration), or they can produce a digital restored version of the work, which itself is valuable, although the restoration is only virtual and cannot be reproduced on the real piece of work (virtual restoration). In this framework ArtShop provides two aids for virtual restoration of art images: crack removal and lacuna filling. It is well known, in fact, that in many cases the presence of cracks and lacunas deteriorates the aspect of paintings and frescos because of their number and their heaviness. Hence, a system capable of restoring them is of great interest, even if restoration is only virtual.

As to crack restoration, the system first asks the user to manually select a point of the crack; then, it automatically tracks the crack. The user must manually select a point of the crack because it is impossible for the system to distinguish between cracks and lines belonging to the drawing. Once the system has detected the crack, the user can decide to erase it by applying an interpolation algorithm. The system waits for confirmation by the user before filling the crack, and thus allows the user to manually recover possible tracking errors.

Concerning crack identification,[1] after the user has selected a starting point (say A), at each step all the pixels (say B_j) in a proper neighbourhood of the crack (the part of the crack already identified by the algorithm) are tested for possible inclusion within the crack. Inclusion is accomplished if the following relations are satisfied:

$$\begin{aligned} |f(A) - f(B_j)| &\leq T, \\ f(B_j) &\in [T_1, T_2] \end{aligned} \tag{6}$$

where $f(A)$ and $f(B_j)$ are the grey levels at corresponding pixels positions, while T, T_1 and T_2 are adaptive thresholds. The first condition means that the crack has to be uniform, while the second means that the grey level of the crack pixels must be included in a given range. The advantage of this strategy is that it describes the crack as a sequence of fronts which are roughly perpendicular to the crack direction; this helps in passing over gaps. Crack points are searched for along the direction perpendicular to the last front. Referring to interpolation, ArtShop uses the Shepard interpolation technique as proposed by Franke-Little.[1]

Regarding lacuna filling, the tool proposed by Artshop operates as follows: the user is asked to pick out manually a point of the lacuna to be filled (i.e. by means of a mouse click); then, the lacuna is automatically recovered by using a segmentation algorithm developed for this particular application; finally, the recovered lacuna is restored by applying different region-filling techniques, which simulate the actual techniques commonly used in the restoration laboratories. By comparing the images restored by different algorithms, it is possible to estimate which kind of restoration technique is more suitable for the considered painting.

In particular, the segmentation algorithm is used to locate all the pixels belonging to a lacuna. Since only the user is able to distinguish between lacunas and areas belonging to the drawing, a manual selection of a point inside the lacuna is needed. By referring to this selected single-pixel region, the neighbouring pixels are examined one at a time and added to the growing region if a given homogeneity criterion is satisfied. The procedure continues until regions cannot grow further. The homogeneity criterion used in ArtShop[2] takes into account colour features by using the HVS (hue, value, saturation) system, since this is the system that better simulates human eye perception. For each feature, the variance of the pixel values of the region is considered: a pixel P is added to the region only if the objective function γ increases:

$$\gamma = \frac{A_1}{\sigma_H^2} + \frac{A_2}{\sigma_V^2} + \frac{A_3}{\sigma_S^2} \tag{7}$$

where A_1, A_2, A_3 are heuristic constants, and σ_H^2, σ_V^2, σ_S^2 are the variances of hue, value, and saturation respectively, calculated on the region plus P. Furthermore, region boundaries information is incorporated within the proposed segmentation algorithm and used to stop the growing of the region. In particular, the gradient of the image is computed through the Sobel operator,[23] and the mean value of the magnitude of the gradient values of the region (G_m) is inserted in the γ function:

$$\gamma = \frac{A_1}{\sigma_H^2} + \frac{A_2}{\sigma_V^2} + \frac{A_3}{\sigma_S^2} + A_4 \cdot G_m \tag{8}$$

Generally, G_m takes low values everywhere but on region boundaries. Hence, at the beginning the value of γ increases since we consider pixels belonging to the lacuna with homogeneous characteristics; when we consider pixels belonging to region boundaries γ increases for the term G_m; finally, γ decreases beyond the region boundaries and region growing stops.

After they have been recovered lacunas must be filled. ArtShop gives the opportunity to simulate and compare different region-filling techniques actually applied in the restoration laboratories. In particular, some restoration methods have been implemented by basically referring to two different restoration schools: the *Scuola Romana* of Cesare Brandi[24] and the *Scuola Fiorentina* of Umberto Baldini.[25] According to these restoration schools a lacuna can be distinguished as *restorable* or *non-restorable*: in the former case, the lacuna still contains some original colours or a part of the original drawing (called 'sinopia'); in the latter, the lacuna consists of a large damaged area of a painting where it is not possible to recover the original drawing.

The *Scuola Romana* uses the techniques of *rigatino* and *puntino* for restorable lacunas. The technique of *rigatino* uses a short, vertical and polychromatic hatching that fills all the lacuna. The technique of *puntino* is very similar to the previous one, but small dots are used instead of hatching. Both methods attempt to recover the original colour of the lacuna, but they aim at making the restoration visible if observed closely and invisible when looked at by a distant observer.[24]

The *Scuola Fiorentina* uses the technique of *selezione cromatica* for restorable lacunas: this method is computed by using a short, tapering and polychromatic hatching. Unlike the hatching used in the technique of *rigatino*, in this case many kinds of inclination are adopted for the hatching, according to the shape of the lacuna; moreover, the tapering shape of the hatching gives a sort of vibration to the restored colour. Also in this case the restored colour must be similar to the neighbouring colours, but the lacuna must be recognizable if observed closely. In the case of non-restorable lacunas, the *Scuola Fiorentina* uses the technique of *astrazione cromatica*. According to this technique a neutral colour is achieved by using a polychromatic, diagonal and crossed hatching: the obtained colour gives a higher-quality result with respect to that achieved with a plain neutral colour.[25]

The previously described restoration techniques have been implemented in ArtShop: in particular the colour that must be restored in a given lacuna is determined by using the colours of neighbouring pixels. The user thus has the opportunity to test different lacuna

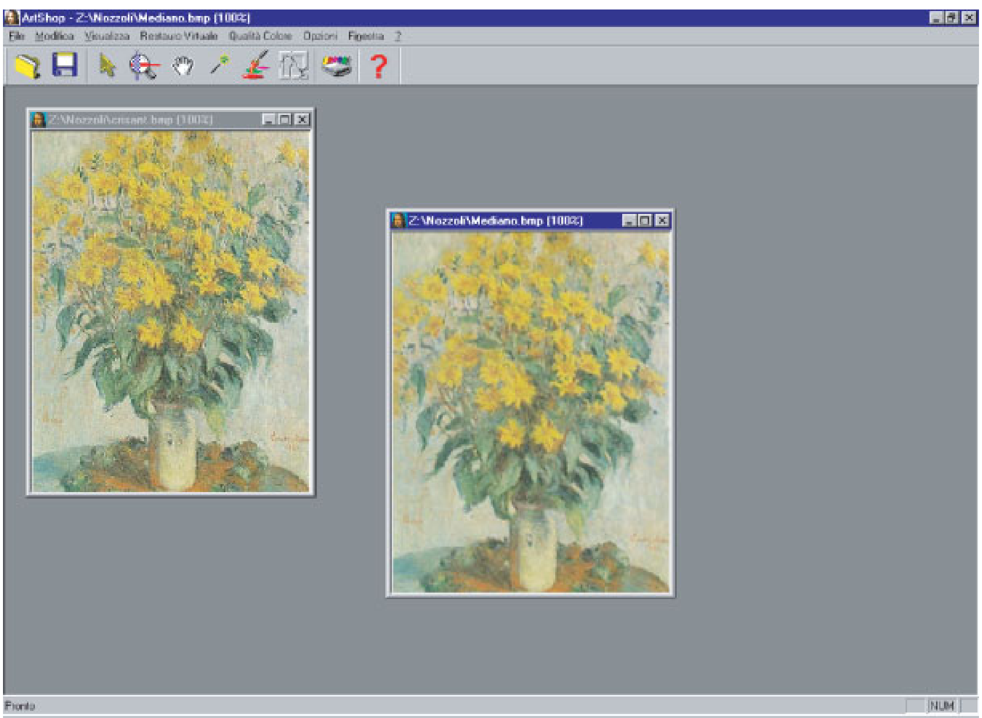
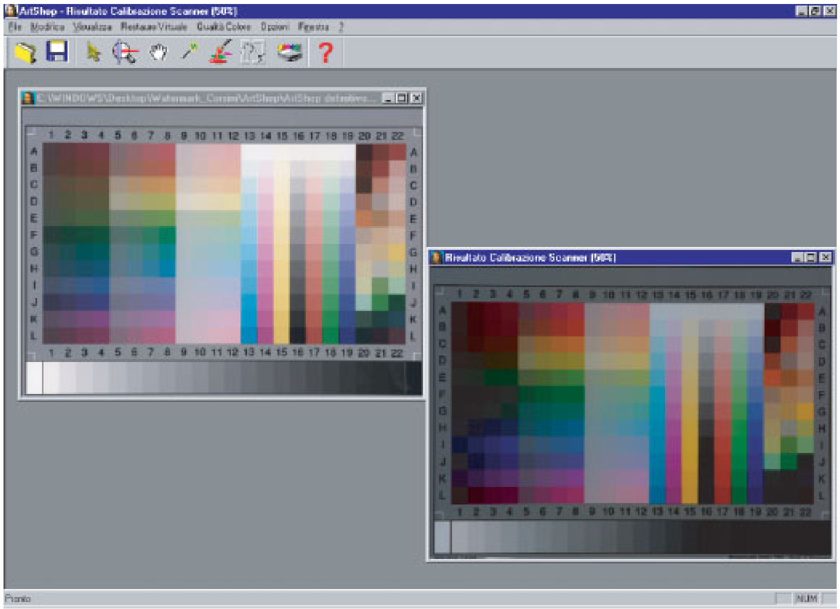
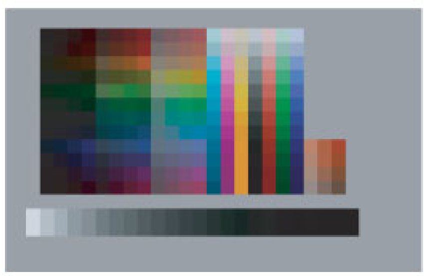


Figure 1. ArtShop's interface: application of vector median filter to Vaso di crisantemi *by Claude Monet.*



(a)



(b)

Figure 2. (a) ArtShop's interface: the image of the acquired IT8 table before (left) and after (right) colour remapping; (b) a photo of the original IT8 reference colours table.

filling methods on the same artwork and to choose the most suitable restoration technique for the painting at hand.

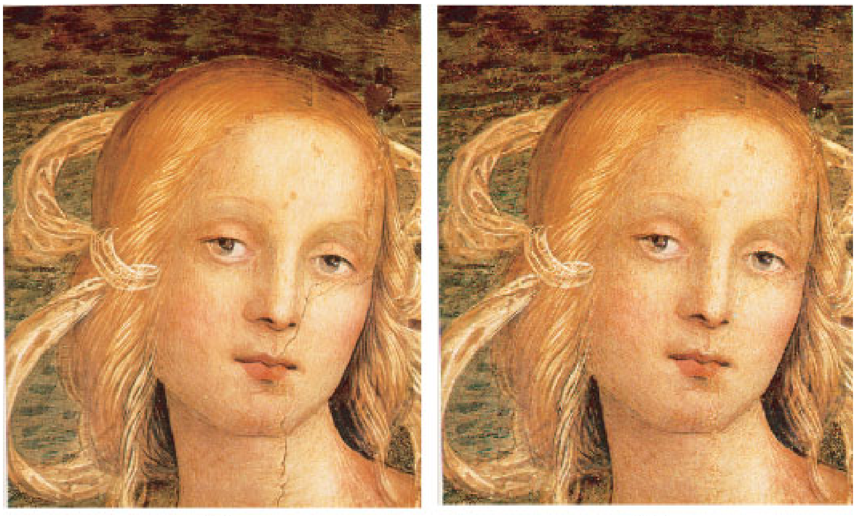
Experimental Results

We now present some experimental results achieved by applying some of the tools of ArtShop. In Figure 1 the ArtShop's interface is shown: in this case the vector median filter tool is applied to the reproduction of *Vaso di crisantemi* by Claude Monet. On the left the original image is displayed, while on the right the processed image is achieved.

Figure 2 shows the output of the calibration procedure. As we can see, the reproduction of the reference table after colour remapping (on the right in Figure 2a) is very similar to the original table (Figure 2b).

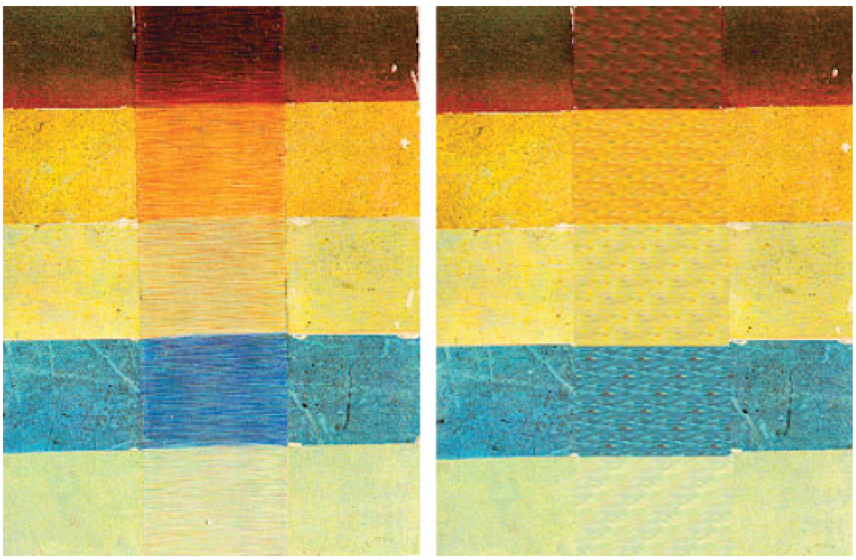
By referring to crack restoration, in Figure 3 an example of crack removing is presented: a detail of *L'Onnipotente con i profeti e le sibille* by Pietro Perugino is shown before (Figure 3a) and after (Figure 3b) the application of the crack restoration tool implemented by ArtShop.

Regarding lacuna restoration, firstly the validity of the virtual filling system is highlighted by comparing the technique of *selezione cromatica* actually realized in a restoration laboratory with the one achieved virtually by means of ArtShop, as described in Figure 4. Figures 5 and 6 show two examples of lacuna restoration by using different lacuna-filling techniques implemented in ArtShop. In particular, in Figure 5(a), a part of



(a) (b)

Figure 3. Example of crack removing: a detail of L'Onnipotente con i profeti e le sibille *by Pietro Perugino before (a) and after (b) the application of the cracks restoration tool proposed by ArtShop.*



(a) (b)

Figure 4. Example of restoration (central column), using the technique of selezione cromatica, *carried out in a restoration laboratory (a) and carried out virtually by applying the lacuna filling tool of ArtShop (b).*

(a) (b) (c)

Figure 5. Example of lacuna filling: a detail of the fresco San Pietro risana uno storpio *by Masolino da Panicale (a); the result of the segmentation algorithm (b); the result of lacuna filling by applying the* chromatic selection *technique implemented in ArtShop.*

San Pietro risana uno storpio, a fresco by Masolino da Panicale, is displayed; Figure 5(b) shows the output of the segmentation procedure, while Figure 5(c) presents the output of the system after restoration using the *chromatic selection* technique. In Figure 6 a detail of *Madonna dei Francescani* by Duccio da Buoninsegna is reported before (Figure 6a) and after (Figure 6b) lacuna restoration: in this case the technique of *puntino* has been chosen.

Conclusions

In this paper the software ArtShop is presented. This application allows the user to experiment with many tools for image processing, like filters for removing noise, colour calibration procedure, or virtual restoration tools. In particular, one of the virtual tools for painting restoration, lacuna filling, simulates the actual

(a) (b)

Figure 6. Example of lacuna filling: a detail of Madonna dei Francescani *by Duccio da Buoninsegna before (a) and after (b) lacuna restoration by using the* puntino *technique implemented in ArtShop.*

restoration carried out in the restoration laboratories. Thanks to this tool ArtShop allows a restorer to plan the restoration work, saving time and tests by trying different filling algorithms.

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Mauro Barni graduated in electronic engineering at the University of Florence in 1991. He received the Ph.D. in informatics and telecommunications in October 1995. From 1991 through 1998 he was with the Department of Electronic Engineering, University of Florence, Italy, where he worked as a post-doc researcher. Since September 1998, he has been with the Department of Information Engineering of the University of Siena, Italy, where he works as associate professor. His main interests are in the field of digital image processing and computer vision. His research activity is focused on the application of image processing techniques to copyright protection and authentication of multimedia data (digital watermarking), and to the transmission of image and video signals in error-prone, wireless environments. He is author/co-author of more than 120 papers published in international journals and conference proceedings, and holds three European patents in this field. He guest-edited three special issues on watermarking-related topics of Elsevier Signal Processing, of the IEEE Communication Magazine and of the Journal of Applied Signal Processing (Eurasip). He also organized several special sessions on watermarking-related topics in important conferences and workshops including ICIP, Eusipco and MMSP. He serves as associate editor of the IEEE Transactions on Multimedia, the IEEE Signal Processing Magazine and is in the editorial board of the Eurasip Journal of Applied Signal Processing. Prof. Barni is a member of the IEEE Multimedia Signal Processing Technical Committee (MMSP-TC) and the Signal Processing Conference Board.

Vito Cappellini obtained the degree in Electronic Engineering from the Politecnico of Torino in 1961. After some activities in the industry and research activity at National Research Council Insitute in Florence, in 1975 he obtained the Full Professor degree in Electrical Communications at Florence University, where he was director of the Department of Electronic Engineering and Dean of the Faculty. He was also Director of the CNR Research Centre Nello Carrara in Florence. His main research interests are: digital signal-image processing, digital communications, remote sensing, biomedicine, IPR protection (watermarking), multimedia systems and art-work analysis-restoration. He has published over 300 papers in the above fields and contributed to several books. He is in the Committee of the Italian Telecommunications Group (TTI). He received in 1984 the "IEEE Centennial Medal". He is "fellow" of the IEEE, member of EURASIP, AEI, and AIT.

Massimiliano Corsini was born in San Marcello (PT), Italy, in 1974. In 2000 he obtained the degree in Information Engineering at the Florence University. After a period as free-lance programmer and multimedia technology consultant he joined, in January 2002, the Department of Electronics and Telecommunications of the University of Florence as PhD student where he is working on novel 3D watermarking technology. His research interests are related to Computer Graphic field and include multiresolution modeling, parameterization of surfaces, subdivision, and more generally, the so-called framework for digital geometry processing.

Alessia De Rosa was born in Florence, Italy, in 1972. In 1998, she graduated in Electronic Engineering at the University of Florence, Italy. In February 2002, she received the PhD degree in informatics and telecommunications from the University of Florence. At present she is involved in the research activities of the Image Processing and Communications Laboratory of the Department of Electronic and Telecommunications of the University of Florence, where she works as a postdoc researcher. Her main research interests are in the field of digital watermarking, human perception models for digital image watermarking and quality assessment, image processing for Cultural Heritage applications. She holds an Italian patent in the field of digital watermarking.

Alessandro Piva was born in Florence, Italy, in 1968. In 1995, he graduated (cum laude) in electronic engineering from the University of Florence, Florence, Italy. In February 1999, he received the Ph.D degree in informatics and telecommunications from the University of Florence. He is now with the National Inter-university Consortium for Telecommunications (CNIT), where he works as Research Scientist. His research activity is focused on multimedia systems, digital image sequence processing, video and image protection and authentication (watermarking), image processing techniques for cultural heritage applications and secure communication protocols. He has published more than 50 papers on these topics in international journals and conferences. He holds two Italian patents in the field of digital watermarking. He is Co Guest Editor for a Special Issue of IEEE Transactions on Image Processing on Image Processing for Cultural Heritage, to appear on October 2003.