GEOMETRIC AND RADIOMETRIC ANALYSIS OF PAINTINGS

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ABSTRACT: The paper reports an overview of some experiences carried out by some Italian research groups (Politecnico di Milano, University of Palermo, Bruno Kessler Foundation in Trento) aimed to assess the conservation's state of some analysed paintings and provide useful information for further diagnostic applications. The activities were accomplished in interdisciplinary teams composed of photogrammetrists, surveyors, restorers and experts of non-destructive diagnostic techniques for Cultural Heritage. Two main aspects are considered: (i) the analysis of the radiometric contents using multispectral images and (ii) the 3D surveying for geometric deformation analysis by means of photogrammetry and laser scanning.

1. INTRODUCTION

Digital image and range data captures are fundamental in the Cultural Heritage domain, since they allow faithfully documentation, analysis, restoration interventions (computer-aided restoration), and digital preservation of artworks at different scales. In case of painting, multispectral image digitisation and 3D modelling are used for pigment identification, precise colour measurement, characterisation and rendering, highly detailed visualisation of the brush strokes but also for the measurement of the shape of the (wooden) support and the paint-layer roughness (Lahanier et al., 2008). Painting studies and analyses for material identification and restoration are based on non-invasive methods such as X-ray fluorescence (XRF), laser-induced breakdown spectroscopy (LIBS), reflectance and Raman spectroscopy, multispectral imaging (visible, IR reflectography and UV-induce visible fluorescence) (Pelagotti et al., 2008). These non-invasive analyses infer (image) data exploiting the fact that each material reflects, absorbs and emits electromagnetic radiations according to its molecular composition and shape. Thanks to the different energy, for each wavelength it is possible to infer specific information about the painting. Fluorescence imaging highlights the different varnishes and over-paintings. IR reflectography allows to inspect and reveal the hidden drawings laying underneath the first paint layers (visualizing e.g. artist's pentimenti). X-rays are able to deliver information regarding the internal structures. All these imaging techniques examine the paintings as two-dimensional objects ignoring the depth information. The planar nature of a painting justifies this approach, however, in some cases the deviation from the planarity either of the support and of the surface is a significant factor for conservators. For these reasons and thanks to the new developments of digital 3D surveying methods, stability of the support and deformation analyses are also performed nowadays as very informative inspections in particular when wood is used as support and for those artworks undergoing conservation treatments with possible changes of the environmental conditions, in particular humidity and temperature (Guidi et al., 2004; Robson et al., 2004). Indeed quantitative data about the deformations is particularly relevant for a correct evaluation of the restoration process that should be carried out. Furthermore, 3D data can provide crucial information for an early detection of the movements to prevent irreversible damages. 3D information can also be integrated with 2D data to create a complete package of information about an opera (Fontana et al., 2005).

The accuracy required by restorers for a proper modelling of process involved in painting maintenance is that typical of close-range metrology (0.01-0.1 mm precision), than that needed in architectural surveying (1-10 mm). The surveying techniques which could fulfil these requirements are photogrammetry and short-range active sensors. Photogrammetry has been giving an important support to the documentation and monitoring of painting deformations for decades but nowadays short-range laser scanners are also getting very popular for the recording of 3D details or movement surveying (Akca et al., 2007; Blais et al., 2007).

The paper reports a review of experiences carried out by some Italian research groups (Politecnico di Milano, University of Palermo, FBK Trento) aimed to assess the conservation state of paintings. Activities were accomplished in different teams made up of photogrammetrists, restorers and experts of non-destructive diagnostic techniques for Cultural Heritage. Two main aspects are considered: (i) the analysis of radiometric contents using multispectral images and (ii) the 3D surveying of a painting for its geometric deformation analysis along time. These aspects, often coupled with 3D images for documentation, conservation and visualization purposes, are the most often investigated and required for art diagnostics. The analysis of a set of multispectral images represents an effective tool to understand problems in conservation and restoration of paintings. We have developed an automated procedure, based on image features, able to quickly register at sub-pixel level precision an entire set of multispectral images. The work on geometric deformation analysis instead consists of experiences carried on with photogrammetry and laser scanners to evaluate the deformations of some important paintings as well as surveying the entire 3D shape of the masterpieces.

2. MULTISPECTRAL IMAGE ANALYSIS

In the Cultural Heritage domain, multispectral acquisition systems are mainly focused on acquiring and processing images in the UV, visible and IR part of the light spectrum. The first goal of multispectral systems was to achieve high colour fidelity of an artwork while nowadays the trend is to use multispectral images to identify materials. A series of monochromatic images are generally acquired, one for each transmission bandwidth of the employed filters. Obviously, the larger is the transmission bandwidth, the far we are from the ideal sampling and the signal reconstruction becomes very hard. As the employed optical system produces often small misalignments of the data due to the different length of the optical path, the acquired monochromatic images need to be perfectly registered for further diagnostic applications (e.g. spectra comparison). Indeed, multispectral images contain different but often complementary contents that thanks to the registration phase can allow an integrated visualization and analysis of the information originated from the same point on the art work.

In our analyses we used a scientific cooled digital CCD camera (3072x2048 px, 9 μm pixel size) coupled with a 50 mm lens and 15 interferential filters, spaced at 50 nm from 400 nm to 1100 nm. The system (property of Art-Test snc, Florence, Italy) is associated with the appropriate lamps in order to acquire images in three modalities: visible reflectance (400-750 nm), UV-induced fluorescence (400-750), and near IR reflectography (800-1100 nm).

2.1 Overview on data registration

Similarly to what happens in the medical field, also for art diagnostics and visual Cultural Heritage it is often needed to compare and integrate different sets of information, coming from different sources and stored in different datasets. In order to successfully integrate these data, features corresponding to the same areas need to be registered. Registration is therefore the determination of a geometrical transformation that aligns features in one dataset with the corresponding features in another dataset. Data registration is often performed manually, iteratively setting the parameters of the geometrical transformation or interactively seeking the corresponding features. However, these approaches are time consuming and can give subjective results. Data registration is necessary as the information might come from:

• Different imaging sensors (multi-modal data): data related to the same object or scene are acquired by different sensors e.g. working in different parts of the light spectrum (multi-spectral data). These data need afterwards to be aligned and overlapped for information fusion, multi-spectral analysis or other diagnostic applications.

• Different viewpoints (multi-view data): data of the same object or scene are acquired from different standpoints for 3D reconstruction purposes or to generate high-resolution views or panoramas.

• Different acquisition times (multi-temporal data): data of the same object or scene are acquired at different times e.g. to evaluate changes or movements.

Registration can be performed between 2D-2D data (e.g. images), 2D-3D data (e.g. an image mapped onto a 3D model) or 3D-3D (e.g. range maps).

In case of 2D data (e.g. images or maps), the registration is needed for mosaicking, 3D geometry extraction, art diagnostic, change detection, etc. Registration methods are generally based on area-based and feature-based matching procedures. Area-based methods mainly use squared, rectangular or circular windows around an interest point or even on the entire images. If small windows are used, a match is established using cross-correlation or least squares matching methods while Fourier (Reddy and Chatterji, 1996) or the Maximization of the Mutual Information (MMI) (Viola and Wells, 1997; Cappellini et al., 2005) methods are generally applied to the entire images. On the other hand feature-based methods combine features like regions or edges with descriptor information matching them using spatial relations (Vosselman, 1992), relaxation methods (Zhang et al., 2000), wavelets (Stone et al., 1999) or descriptor similarities (Mikolajczyk et al., 2005).

2.2 Automated registration of multispectral images

The developed methodology for the registration of multispectral images was originally designed for the alignment of multi-view images acquired with frame CCD/CMOS cameras for typical photogrammetric applications (Barazzetti et al., 2009). The automated registration procedure consists of two steps: (i) feature matching and (ii) image transformation. Firstly all images are sorted with respect to their wavelength. Following the progressive order, the algorithm matches each image *i* with the adjacent one *i*+1 by using the SIFT (Lowe, 2004) or SURF (Bay et al., 2008) operators. To remove possible wrong correspondences, a preliminary analysis of the derived descriptors is carried out by using the ratio test and a prefixed threshold. This means that the Euclidean distance of the descriptors of the two possible correspondences must be less than a predefined threshold. Afterwards a more robust outlier rejection is performed with a robust estimator (RANSAC) to compute a planar homography between the two images. It is based on the random extraction of a minimal dataset and, iteratively, on the identification of a dataset which does not contain outliers. A planar homography allows the analysis of flat objects (like most paintings) but can work even in the case of strong 3D deformations of the painting. In fact, if the perspective centre of the camera is fixed, the images are still connected by an homography. Higher order transformations were also tested, but the accuracy of alignment results did not improved. Once that the transformation between adjacent images is computed, each image is resampled in order to derive a new image correctly registered with the other one.

This matching procedure is repeated for all consecutive image pairs in order to estimate several homographic transformations. A generic homography can be expressed in terms of a 3×3 matrix **H** with only 8 degrees of freedom. For a generic image pair this relation can be written in homogenous coordinates as:

$$\begin{bmatrix} x_1 \\ y_1 \\ 1 \end{bmatrix} = \mathbf{H}_2 \begin{bmatrix} x_2 \\ y_2 \\ 1 \end{bmatrix} \quad ; \quad \vec{x}_1 = \mathbf{H}_2 \vec{x}_2 \tag{1}$$

The advantage of this notation is related to the possibility to combine consecutive homographic transformations by multiplying only the matrices. Thus, the homography between a generic image *h* and another image *k* is given by:

$$\vec{x}_h = \mathbf{H}_{h+1}\mathbf{H}_{h+2}\cdots\mathbf{H}_k \vec{x}_k \tag{2}$$

According to this consideration, the central image of the sequence is generally assumed as the reference of the available dataset for the progressive concatenation of all the other images. Compared to other registration methods, our approach is very fast and does not require any initial approximation of the unknown transformation parameters. The procedure has a limited computational cost and demonstrated a good robustness even in case of low information content shared by consecutive images. Figure 1 shows a typical result for an image pair matched with the proposed procedure. Despite the large number of common points between consecutive images, the procedure is very fast and, for example, it takes approximately 20 mins to register 23 images (6 Mpx). After the image registration, the reflectance spectra can be calculated or RGB images can be generated starting from the single monochromatic multispectral images (Figure 1).

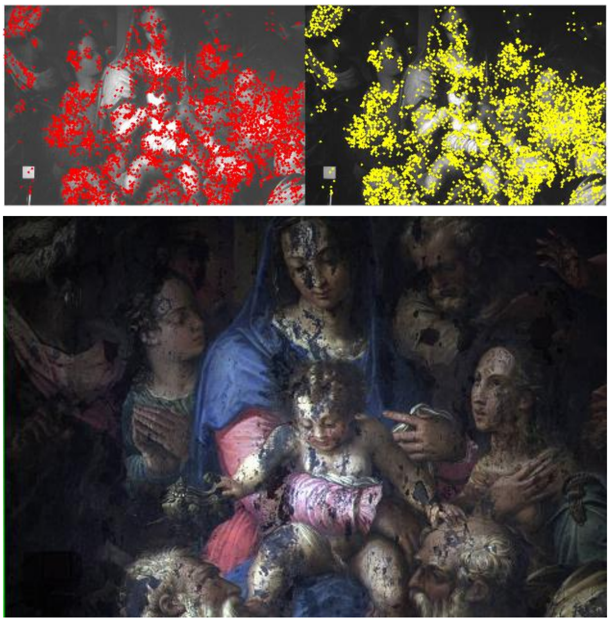

Figure 1: A multispectral image pairs with the related matched features extracted and matched with the proposed strategy (above). The reconstructed RGB image from 3 multispectral UV-induced fluorescence acquisitions (below).

3. 3D SURVEYING AND DEFORMATION MONITORING USING PHOTOGRAMMETRY

The use of photogrammetry as measuring technique to survey and determine the possible deformations of canvas can deliver:

- deformation analyses of single points, defined by artificial targets or natural features which can be identified and measured in different measuring sessions;
- 3D dense and detailed surface models;
- high-resolution orthoimages used as reference for the localization of all diagnostic data.

The first solution provides for point-based deformations and it is often not applicable as targets cannot be placed on ancient painting surfaces, unless simulations are done. The second approach is more appropriate to determine the global deformations of the entire object in a single epoch (comparing the derived surface model with a theoretical plane) or in multiple sessions (comparing the surface models between the sessions and deriving the relative movements). Unfortunately the texture information of paintings is often problematic for image matching algorithms resulting in noisy DSM.

3.1 A simulation of point-based deformation analysis

A study was conducted with the Centre for the Study of Materials for Restoration (CESMAR7, Italy) to verify whether a photogrammetric survey would be able to measure the geometric deformation of a canvas. An artificial painting model was created to reproduce the layering of 17^{th} century canvas paintings with typical Venetian red preparation. The used model is approximately 52x67 cm and was consolidated with the materials and dilutions most frequently used in the field of conservation (Figure 2). The main purpose of this study was to evaluate the relative accuracy and the potentialities of the photogrammetric survey (done by non-expert) in revealing deformations at sub-millimetre level without using any special network design concept. The photogrammetric survey was carried out using a calibrated Canon EOS 1Ds Mark II digital camera (16.7 Mpx) equipped with a 50 mm lens. The dataset contains 10 convergent images taken from an average object-camera distance of 1.2 m and an average photogrammetric scale of 1/23 (footprint equal to 0.16 mm). The images were acquired in two epochs (R1 and R2) within a reduced time interval and under the same environmental conditions to verify the repeatability of the photogrammetric approach.

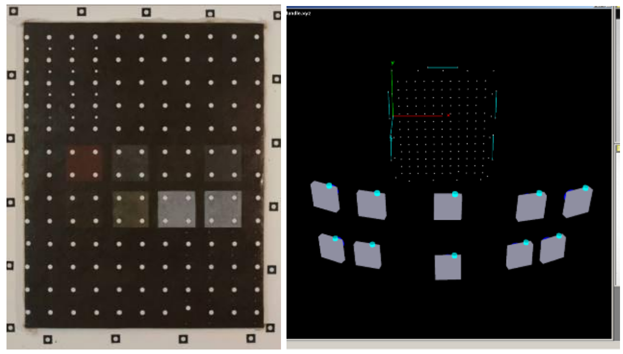

Figure 2: The model of an ancient painting with the targets used in the deformation analysis study (left). The camera poses of the first image network (right).

The external orientation of the images was calculated using all the targets on the painting (143) and some targets placed on the out-of-plane wall outside the painting. Five calibrated bars, measured with a laboratory microscope with a precision of ±10 μm, were used to determine the scale of the photogrammetric model and to check the final accuracy of the adjustment. The orientation procedures were conducted using the commercial software Australis v6.06 (Photometrix) and the adjustment results are reported in Table 1. Comparing the values of the coordinates computed in two epochs (R1 and R2), the relative accuracy of the photogrammetric survey could be derived. The RMS of the differences in XYZ is ±0.026 mm and can be attributed only to the intrinsic precision of the measurement and not to the deformation of the canvas surface. These results are within the requirements of the restoration centre and show the possibility of evaluating deformations in the order of ±0.1 mm by non-experts and multi-image close range photogrammetry.

	RMS X [mm]	RMSY [mm]	RMS Z [mm]	RMS XYZ [mm]
R1	0.009	0.009	0.023	0.026
R2	0.011	0.010	0.026	0.030

Table 1: RMSE of the computed object coordinates in the two measuring epochs.

4. 3D SURVEYING AND DEFORMATION MONITORING USING ACTIVE SENSORS

Active sensors, in particular interferometric techniques (e.g. micro-profilometer based on conoscopic homography) (Fontana et al., 2003), short-range laser scanners (Blais et al., 2007) and stripe projection systems (Akca et al., 2007), are all good methods for the 3D surveying and deformation monitoring of paintings. Indeed range sensors, although still expensive, are able to survey large surfaces in detail and deliver dense 3D data useful for:

- 3D reconstruction of the surface details at very high geometric resolution (Blais et al., 2005);
- instant evaluations of the entire shape of the painting;
- multi-temporal analysis and measurement of the movement of the (wooden) shape of the support.

For large paintings (some meters), Time of Flight (ToF) sensors could be employed to determine the gross shape of the painting and check its deviation from a theoretical planarity. Triangulation-based sensors or conoscopic micro-profilometer are instead more suited to study the small features of the surface, analyse craquelure patterns, highlight and document colour raisings, detachments or engraving as well as deliver high-resolution 3D models

4.1 Detailed 3D surveying and deformation analysis

Different studies were conducted on some paintings attributed to Giorgio Vasari (1511-1574) and located in the church of Bosco Marengo (Alessandria, Italy).

For two of them ('Giudizio Universale' and 'Martirio di S. Pietro'), the goal was to derive the current shape of the entire wooden painting, to immediately see, at macro scale, if significant deformation were present. A Leica Scanstation2 laser scanner was used to survey the entire artworks at 3 mm geometric resolution, and retrieve the possible deformation from the ideal flat plane. The surveying results, shown in Figure 3, identified, respectively, a uniform bending towards the borders of the artwork up to 2.3 cm and no significant deformation.

For a third painting (Adorazione dei Magi) a more detailed surveying was required and carried out using a ShapeGrabber laser scanner (Table 2). The entire painting was firstly surveyed with the SG1002 head at 0.3 mm geometric resolution. 84 scans were acquired and then aligned in a unique point cloud of ca 200M points (Figure 4). For a photo-realistic visualization, 8 images acquired with a Nikon D3X (24.5 Mpx) were mosaicked to produce a final texture of ca 141 Mpx. Those huge images can also be visualized and shared in remote using interactive viewing technologies on the web (e.g. Zoomify or Microsoft HD View).

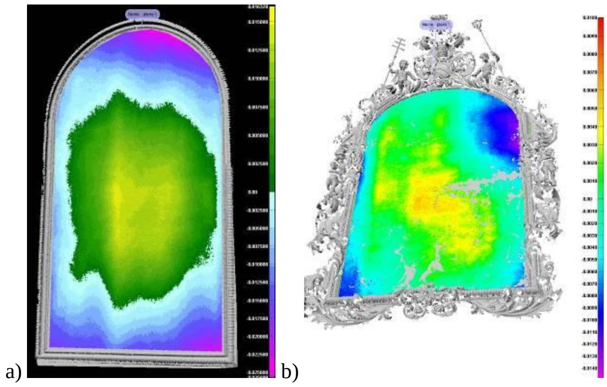

Figure 3: a) The 'Martirio di S.Pietro' (ca 4.5x2.45 m) and its actual state of deformation, showing a uniform bending towards the borders. B) The 'Giudizio Universale' (ca 6x3 m) with no significant deformation (less than 1 cm) but with some gaps in the acquired 3D data due to the dark colours of the painting (no laser response).

	SG1002	*SG102*
Working range (Z)	300-900 mm	120-170 mm
Lateral resolution (XY)	300 μm	100 μm
Range resolution (Z)	30 μm	5 μm
Noise (1σ)	150 μm	25 μm

Table 2: Specifications for the ShapeGrabber laser scanner (head SG1002 and SG102) employed for the surveying of the "Adorazione".

Afterwards, following the instructions of the restorators, some specific areas where digitized at 0.1 mm resolution (SG102). This enabled to accurately document some brush strokes (Figure 5b), some significant paint detachments (Figure 5c) and highlight the roughness of the painting.

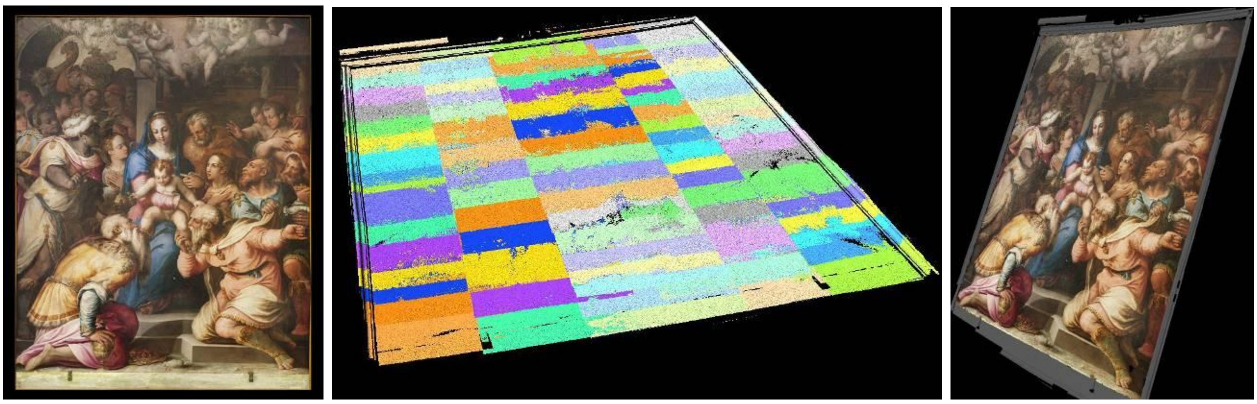

Figure 4: The 'Adorazione dei Magi' (2.6x2 m), surveyed with 84 acquisitions at 0.3 mm. The final textured 3D model contains ca 55Mil. polygons.

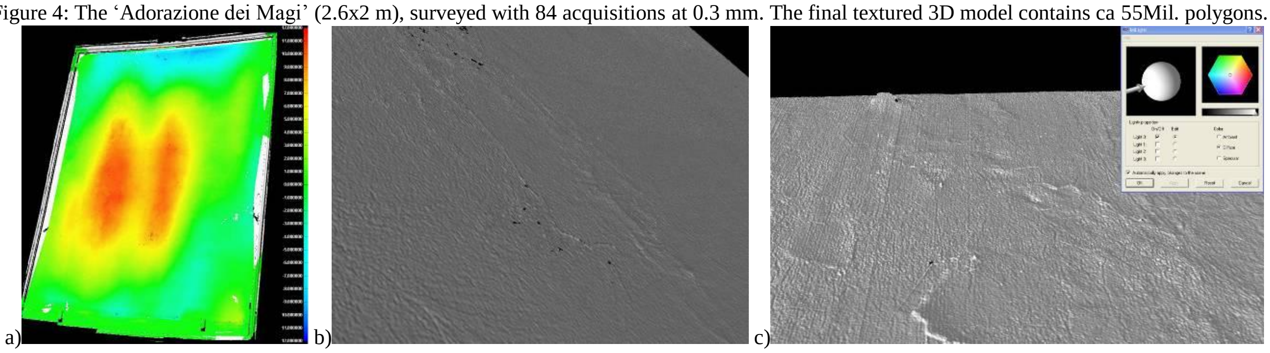

Figure 5: a) Deformation map of the 'Adorazione dei Magi' (red areas are ca 1.1 cm above the medium plane); b) Brush strokes on the painting; c) paint detachments easily visible changing the light direction during the rendering of the 3D data.

5. 3D SURVEYING AND DEFORMATION MONITORING USING INTEGRATED TECHNIQUES

As shown in many surveying projects (El-Hakim et al., 2008; Guidi et al., 2009), nowadays the best surveying and 3D modelling results are generally achieved by integrating different surveying techniques.

A representative example on technique integration for painting surveying and deformation monitoring was performed on the artwork by Andrea Mantegna (1431-1506) known as 'Pala Trivulzio' (1497), currently hosted at Castello Sforzesco in Milan, Italy. Besides 3D surveying, the state of health of the painting was investigated with different diagnostic techniques, including VIS, UV, IR and X-rays images and scan spettro-photometry (Pesci and Toniolo, 2008). Laser scanning was employed to survey at multiple epochs (4) the macro off-plane deformation of the canvas along the period when it was under restoration. Photogrammetry was instead used to derive a high-resolution orthoimage to be used as reference for the visualization of all the diagnostic data. The presence of vibrations due to the underground line just below the room where the canvas is conserved prevented from using highly precise range sensors (like phase-shift or triangulation-based scanners). A Leica HDS-3000 was therefore employed to survey the artwork and derive a total amount of 1.7M points. Georeferencing was carried out by using retro-reflective targets placed on the canvas frame. The first laser scanning acquisition dated back to March 2005, before starting the restoration of the canvas. A second survey (May 2006) was performed at the end of the substitution of the frame, which resulted in flattening the whole canvas and eliminating macroscopic waves on its shape (amplitude up to 3 mm). The third 3D survey was done in July 2006 and the last one (March 2007) was repeated to check any possible change of the canvas at the end of the restoration period. Amazingly, the last DSM showed that the canvas was no longer flattened as supposed to be, but assumed again a bended and ondulated shape similar to the one present before the restoration start (Figure 7).

The photogrammetric survey was performed using a block containing 40 images divided in 5 strips (Figure 6). A calibrated digital camera Rollei DB44 with a Phaseone CCD sensor (4080x4076 px, 9 μm pixel size) and a 40 mm lens was used. A baseline of ca. 35 cm allowed an overlap of ca 60% along strip and ca 20% across strip. To establish the reference system, some targets were placed on the canvas frame, while further natural points were identified inside the texture of the painting.

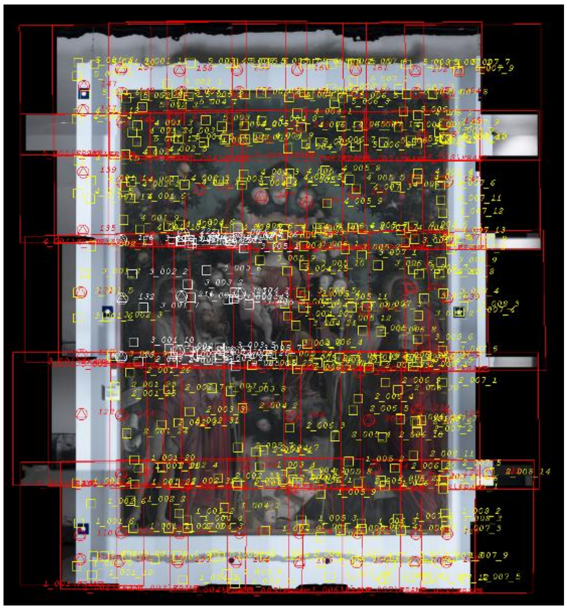

Figure 6: Layout of the photogrammetric block adopted for the generation of the DSM of the Pala Trivulzio' surface; triangles in circles represent GCPs, while squares are the extracted tie points for the bundle adjustment.

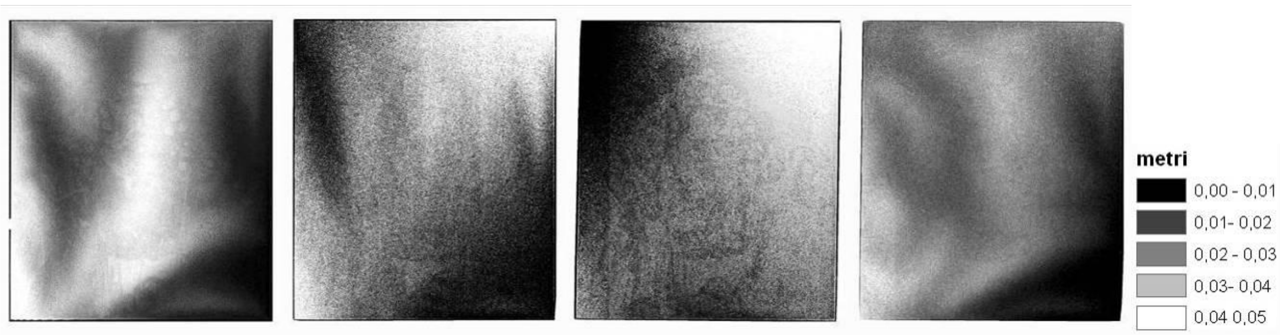

Figure 7: Raster visualization of the DSMs acquired at four epochs (from left to right: mar 05, may 06, jul 06, mar 07).

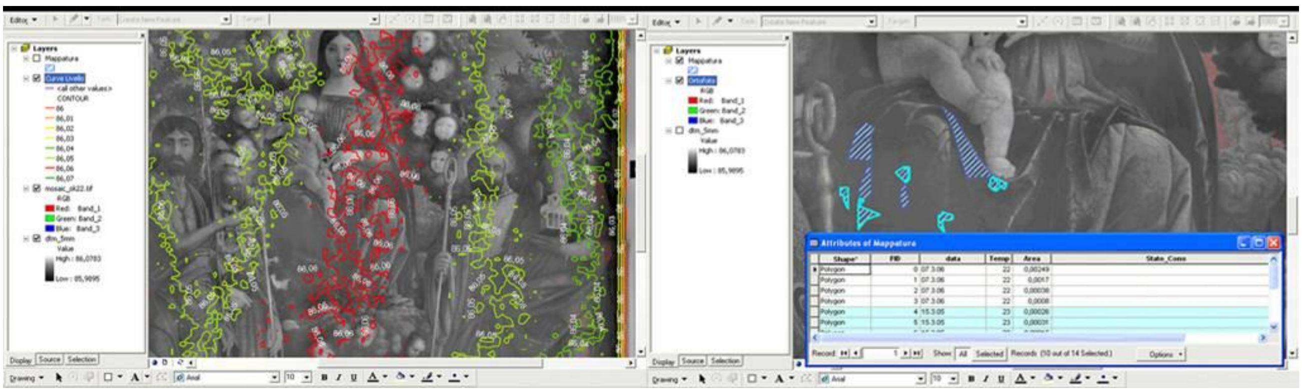

Figure 8: The high-resolution orthoimage of the 'Pala Trivulzio' was used inside GIS environments for archiving, comparing and understanding results obtained from different investigation techniques.

All these points (99) were measured with theodolite obtaining an average accuracy of ±0.4 mm on their 3D coordinates. Images were then oriented by means of a bundle adjustment. Accuracy of 3D point determination resulted as ±0.35 mm in the canvas plane, and ±0.6 mm in orthogonal direction. A dense point cloud was then extracted using Socet Set 5.2 (Bae System). A TIN model was afterwards generated for the successive generation of a high-resolution orthoimage (pixel size 0.2 mm on the canvas). Finally all the data (diagnostic, photogrammetry and scanning) were collected and used in a GIS environment (Figure 8) to: (i) link other geo-referenced information to the canvas (in both raster/vector format); (ii) visually explore canvas details; (iii) assess the off-plane deformation of the canvas shape by overlapping the DSMs generated at different epochs. The results obtained from the integrated survey helped the managers of the restoration process to visually and geometrically document the painting and pushed them to analyse unconsidered dynamics of the static behaviour of the 'Pala Trivulzio' and modify the initial project.

6. CONCLUSIONS

Non-invasive surveying techniques and evaluation methods for Cultural Heritage objects are nowadays fundamental. The paper gave an overview of 3D surveying and multispectral imaging applied to painting monitoring and studying. Multispectral images can be quickly and accurately registered for material identification and spectra computation. 3D models are instead useful for archiving, comparing and understanding results obtained using different techniques as well as to derive deviation maps from planarity due to the curving and warping of the wood, leading to the possibility of planning interventions in order to prevent further deterioration. The heritage and museum community would benefit from adopting these common technologies and techniques for their daily work and for interventions policies.

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REFERENCES

References from Journals

Bay, H., Ess, A., Tuytelaars, T., Van Gool, L., 2008. SURF: Speeded up Robust Features. CVIU, 110(3): 346-359

Guidi, G. Atzeni, C., Seracini, M., Lazzari, S., 2004: Painting survey by 3D optical scanning: The case of "Adoration of the Magi" by Leonardo da Vinci. Studies in Conservation, Vol.49: 1-12

Guidi, G., Remondino, F., Russo, M., Menna, F., Rizzi, A., Ercoli, S., 2009: A multi-resolution methodology for the 3D modeling of large and complex archaeological areas. IJAC, 7(1): 40-55

Lowe, D., 2004. Distinctive image features from scale-invariant keypoints. IJCV, 60(2): 91-110

Mikolajczyk, K. Tuytelaars, T., Schmid, C., Zisserman, A., Matas, J., Schaffalitzky, F., Kadir, T. and Van Gool, L., 2005: A comparison of affine region detectors. Int. Journal of Computer Vision, Vol. 65(1/2): 43-72

Pelagotti, A., Del Mastio A., De Rosa, A., Piva, A., 2008: Multispectral imaging of paintings – A way to material identification. IEEE Signal Processing Magazine, 25(4): 27-36

Reddy, B.S., Chatterji, B.N., 1996: An FFT-based technique for translation, rotation and scale-invariant image registration. IEEE Transactions on Image Processing, Vol. 5: 1266–1271

Stone, H.S., le Moigne, J., McGuire, M., 1999: The translation sensitivity of wavelet-based registration, IEEE Trans. PAMI, Vol.21: 1074-1081

Viola, P., Wells, W.M., 1997: Alignment by maximization of mutual information. IJCV, Vol. 24: 137–154

Vosselman, G., 1992: Relational matching. Lecture Notes in Computer Science, No. 628, Springer Berlin, 190 pages

Zhang, Z., Zhang, J., Mingsheng, L., Zhang, L., 2000: Automatic registration of multisource imagery based on global image matching. PE&RS, Vol. 66(5): 625-629

References from Other Literature

Akca, D., Gruen, A., Breukmann, B., Lahanier, C., 2007: High definition 3D-scanning of art objects and painting. Proc. Optical 3D Measurement Techniques Conference, Vol.2, pp. 50-58

Barazzetti, L., Remondino, F., Scaioni, M., 2009: Combined use of photogrammetric and computer vision techniques for fully automated and accurate 3D modeling of terrestrial objects. Videometrics, Range Imaging and Applications X, Proc. of SPIE Optics+Photonics, Vol. 7447, 2-3 August, San Diego, CA, USA

Blais, F., Taylor, J., Cournoyer, L., Picard, M., Borgeat, L., Dicaire, L.-G., Rioux, M., Beraldin, J.-A., Godin, G., Lahnanier, C., Aitken, G., 2005: Ultra-High Resolution Imaging at 50µm using a Portable XYZ-RGB Color Laser Scanner. Int. Workshop on "Recording, Modeling and Visualization of Cultural Heritage", Ascona, Switzerland

Blais, F., Taylor, J., Godin, G., Cournoyer, L., Beraldin, J.-A., Picard, M., Borgeat, L., Rioux, M., Lahanier, C., 2007: Ultra High-Resolution 3D Laser Color Imaging of Paintings: The Mona Lisa by Leonardo Da Vinci. Proc. of 7th Int. Conference on Lasers in the conservation of Artworks (Lacona VII), pp. 435-440

Cappellini, V., Del Mastio, A., De Rosa, A., Piva, A., Pelagotti, A., 2005: An automatic registration algorithm for cultural heritage images. Proc. IEEE Int. Conf. Image Processing, Vol.2, pp. 566-569

El-Hakim, S., Beraldin, J.-A., Remondino, F., Picard, M., Cournoyer, L., Baltsavias, M., 2008: Using terrestrial laser scanning and digital images for the 3D modelling of the Erechteion, Acropolis of Athens. Proc. of DMACH Conference, pp. 3-16, Amman, Jordan

Fontana, R., Gambino, M.C., Greco M., Marras, L., Materazzi, M., Pampaloni, E., Pelagotti, A., Pezzati, L. Poggi, P., 2005: 2D imaging and 3D sensing data acquisition and mutual registration for painting conservation. Proc. SPIE Videometrics VIII, pp. 51-58

Lahanier, C., Aitken, G., Pillay, R., Beraldin, J.-A., Blais, F., Borgeat, L., Cournoyer, L., Picard, M., Rioux, M., Taylor, J., Breuckmann, B., Colantoni, P., de Deyne, C., 2008: Two-dimensional multi-spectral digitization and three-dimensional modelling of easel paintings. Report, NRC Publication Archive

Pesci, F., Toniolo, L., 2008: Andrea Mantegna. La Pala di San Zeno. La Pala Trivulzio. Conoscenza conservazione monitoraggio. Marsilio Editor (in Italian)

Robson, S., Bucklow, S., Woodhouse, N. and Papadaki, H., 2004: Periodic photogrammetric monitoring and surface reconstruction of a historical wood panel painting for restoration purposes. IAPRS&SIS, Vol 35(5), pp. 395-400