ADVANCED TECHNIQUES FOR THE STUDIES OF STONES AND PAINTINGS ON WALLS: STATE OF THE ART AND OPEN PROBLEMS

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ABSTRACT:

Different imaging techniques are presented and applied to the study of historical and artistic objects and buildings, mainly belonging to Renaissance time, in the city of Bologna, where the *arenaria* (sandstone) of which they are constituted is largely degraded in the surfaces due to the effects of pollutants present in the atmosphere, since suitable 3D reconstruction algorithm may be very useful in panning restoration works. We based our investigation on multispectral techniques ranging from infrared reflectography, digital thermography and thermal diffusivity (mirage effect) and ultraviolet fluorescence. Possible contributions from ultrasound analysis as well as other non-destructive techniques are addressed. In addition, an original portable equipment based on the detection of Compton scattering photons and a further statistical analysis of the collected data has been utilized.

1. INTRODUCTION

1.1 General remarks

Investigation of materials, constituents and execution techniques in the field of cultural heritage plays a fundamental role in determining the preservation status of historical and artistic artefacts, in planning their best conservation conditions and possible future restorations and in the knowledge of their surface and bulk structures including defects, voids, water infiltrations, etc. These analyses need in most cases nondestructive methods avoiding sampling from the original work and portable equipments since measurements have often to be performed *in situ* because of fragility and consequent impossibility to move the artistic object (or instance, in the case of paintings on wood) or because it is not transportable (monuments, archaeological remains, frescoes, etc.).

Therefore, suitable physical techniques and advanced instruments are needed in addition to conventional chemical analyses which require sampling and even in best cases are clearly microdestructive. Moreover, traditional techniques generally provide local information about the considered structure, while innovative physical methods based on suitable radiation sources and interactions with matter provide a complete analysis of the whole structure (surface and/or bulk) by scanning procedures.

I present some results obtained by means of multispectral tools and X-ray spectrometry in addition to well-known thermographic and acoustic analyses of which they represent a natural complement, while in the second part of this article an application of remote sensing and reverse engineering is presented, always referring to cultural heritage.

Finally, I summarize the main results of an international research program for the development and application of multimedia tools to the investigation of the cultural heritage, in particular archaeological and medieval mosaics and monuments. A networking prototype computing system has been developed for the efficient storage and processing of multimedia data referring to these works of art and historical documents, including results of chemical and physical analyses and reports about past restorations. Innovative implemented tools for three-dimensional simulations of virtual museums of ancient mosaics, historical buildings and monuments are then introduced and discussed.

1.2 Compton spectrometry

A new imaging technique has been developed in the last years (Bonifazzi et al, 2000; Tartari et al, 2001a; Tartari et al, 2001b; Tartari et al, 1999) , based on the detection of Compton scattering photons and a further statistical analysis of the collected data. The photon detection has been performed by means of the Enhanced Compton Spectrometer (ECoSp), a recently devised instrument that allows to collect the backscattered photons by investigating the tested sample from one side only, as shown in Figure 1, as required for large structures such as walls, mural paintings,etc.
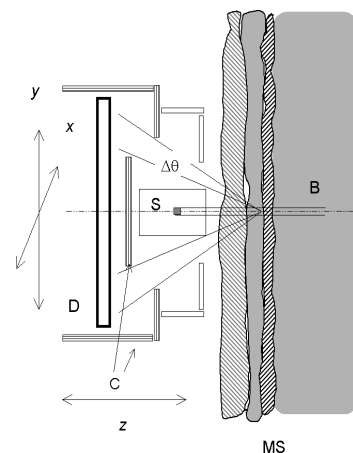

Figure 1. Planar sketch showing the ECoSp at work. (S) Shielded source, (B) collimated beam, (MS) Mural Structure, (C) collimator rings, (D) detector, (Δθ) scattering angle set by the annular collimator. The coordinates X, Y and Z indicate the allowed movement directions.
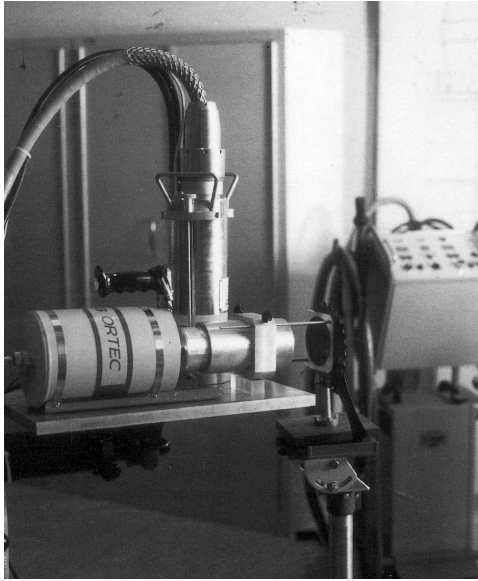
Figure 2. The ECoSp apparatus in the laboratory.

Photons collected during the planar scanning of a given area are used to describe the electronic density of the sample as a density image; afterwards, the Principal Component Analysis (PCA) is applied to the image (Jackson, 1991; Krozanoski, 1987). As a case study, a non-destructive testing of plaster substrates supporting mural paintings has been performed using this technique, searching for flaws, defects, fractures, and so on (see Figure 2 for a picture of ECoSp at work).
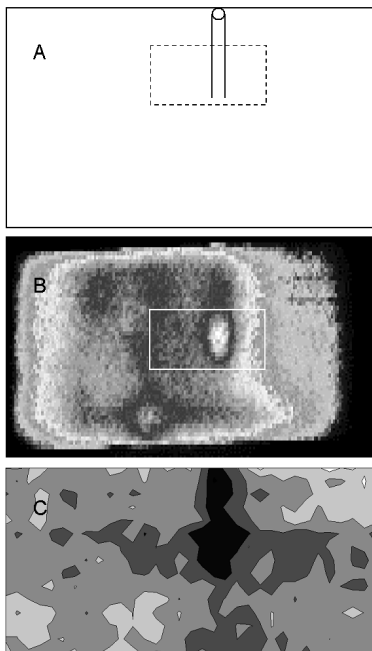

Figure 3. (A) Row figures showing the brick profile with the drill-made empty inclusion: the dashed rectangle delimits the tested area. (B) Thermography of all the mural structure revealing the empty inclusion. (C) Image pixel density of the same tested area reconstructed by ECoSp measurements.

The rationale behind this procedure is that the presence of such gaps into the otherwise uniform material can be revealed because the existing correlation between the back scattering radiation detected by ECoSp from each adjacent Volume of Interest (VOI) during the scanning. The Principal Component correlation analysis performed over the resulting data from all VOIs then reveals each gap in his size, shape and position.

In fact, the Principal Component Analysis (PCA) performed on the total back scattered photons coming from all the tested VOIs allows to identify the presence of fractures and empty inclusions as local variations of the image pixel density as separated images.

One main feature of ECoSp is the possibility to obtain the density image of hidden layers, by a two-dimensional scanning where a gamma-ray source (^{241}Am in the present cases) is coaxially arranged with a large area detector and moved in front of the area to be studied. This allows to completely control the amount of radiation incoming to each VOI (irradiation) of the area under test, and to choose the optimal spatial resolution for imaging. Both the resolution and irradiation strongly influence the detection of flaws and defects, and some test on a phantom model was preliminary made to verify the proposed technique.

A mural structure simulating a fresco painting made of a wall brick and three strata of plaster was then prepared, and to create a substrate degradation a drill-made cylindrical hole has been carried out in the plaster layers. The area containing the plaster defects was roughly delimited by firstly performing a thermography of the whole mural structure; afterwards, the VOI-by-VOI scanning of the area of interest was performed by ECoSp, and the number of collected photons from each of the tested VOIs has been used as pixel value of the resulting density image. The PCA performed on this image clearly shows the presence of a cylindrical defect with a variable depth, superimposed to a large and thin fracture distributed over the whole area tested that resembles a plaster lamination.

Figure 3 summarize the obtained results in comparison with usual thermographic remote measurements (Bonifazzi et al, 2004a), and clearly indicates the validity of the advanced approach which confirms the previous findings but allows a better spatial resolution than thermographic data and the possibility to determine the constituent materials by analyzing the detailed spectra in each VOI. This result demonstrates that the PCs image analysis allows to detect the presence of gaps into the fresco substrate in its size, shape and position simply by the visual inspection of the single PCs reconstructed images (Bonifazzi et al, 2004b).

Therefore, the possibility to access large samples from one side only makes the Compton scattering based technique suitable for density inspection of stone materials, in particular degraded layers and mural supports of frescoes. This imaging approach based on a combination of an experimental set-up and a multivariate analysis of data is then introduced in order to describe the density variation and elemental composition in hidden layers of large dimensions.

It has been shown – for instance - that ECoSp instrumentation, which acts in a quasi-backscattering modality, is able to supply reflection images of barium K X-ray fluorescence distribution in hidden layers even when low resolution of detectors is considered. The capability of the ECoSp proposal to identify false positives is also outlined with examples in previous papers (Tartari et al, 2005).

2. INVESTIGATION OF MARBLE SCULPTURES

Laser scanner and reverse engineering techniques have been applied together with ECSP spectrometry to the investigation of a Renaissance Hebraic gravestone which has been severely damaged in the past and partly cut to remove the original inscription for a new dedication to a Catholic family (Maino, 2007). By means of these methods it has been possible to recover the initial form of the stone and reproduce it in its integrity thanks to a high-resolution digital model then produced in scale in plastic material.

Figure 4. The two parts of the Hebraic gravestone with fracture lines possibly produced when it has been cut. The re-sculpted part (on the right) is walled out of the Certosa church in Bologna (see following Figure 5).

2.1 Methods and validation

The ECoSp device basically consists of a cylindrical collimated Am-241 γ-ray source (59.54 keV), as previously outlined, coaxially associated with an annular collimator device and a large-area NaI(Tl) detector, that allows to detect the Compton backscattered radiation coming form a cylindrical volume 3-mm wide and about as deep as the overall thickness of the tested sample. Before entering into the NaI(Tl) detector the scattered rays are collimated by two parallel rings in a angle range of 10 degrees centered around the Compton scattering angle (θ=160˚) (Tartari et al, 1999). As depicted in Figure 1, the collimated beam entering the sample and the vertexes of the cone-shaped profiles set by the parallel collimator rings ideally define the Volume-of-Interest (VOI), and the photons collected within the angle amplitude are assumed to highlight the local electronic density of the sample within the VOI as well as the pixel value. Because ECoSp takes one pixel at a time, the whole image is obtained by moving the coaxially joined source and detector in an two-dimensional fixed reference frame at a fixed step: those in the vertical direction will be named "scans" and those in the horizontal direction as "pixels", as shown in Figure 6.

An important ECoSp experimental feature is that an optimal, completely uniform illumination of each VOI is assured, so removing any further necessity to account for any systematic error on the resulting pixel density image. Basically, PCA relies upon an eigenvector decomposition of the covariance matrix of the X^{mxn} data matrix containing the pixel values, $Cov(X)=X^{T}X/(n-1)$ (Jackson, 1991), where the m rows are pixels and the n columns are the scans. Providing that the matrix X is suitable scaled the PCA decomposes the data matrix X into the sum of the *outer products* of vectors z_i and u_i plus a *residual* matrix E,

$$X = z_1 u_1^T + z_2 u_2^T + \ldots + z_k u_k^T + E \ . \qquad (1)$$

Here, the z_i vectors are known as *scores* and the *loads* u_i vectors are the *eigenvectors* of the *covariance* matrix; the eigenvectors u_i contain information on how the original variables (the scans) connect to the new independent variables; i.e., the *score vectors* z_i. The pairs in eq.(1) are arranged in descending order accordingly with the associated eigenvalue, where z coefficients are a measure of the amount of variance described by each (u_i, z_i) pair. The most important feature of PCA is that the k value in eq.(1) is less or equal to the smaller dimension of X. It is also generally found that the number of factors $z_i u_i^T$ describing the correlation between the original variable in data matrix X can be adequately determined by a statistical test (Jackson, 1991; Krozanoski, 1987).

The results obtained on phantoms as well as in realistic cases such as the Medieval Crucifix of St. Damiano in Assisi (Italy) exhibit some common features as for the percentage of variance explained by each eigenvalue: The first two latent radices (eigenvalues) retain about the 70% of the total variance, and the residual variance is distributed over the remaining eigenvalues in a linear decreasing order. The variance distribution indicates that – in general cases - the first two PCs reproduce the matrix X with a "sufficient accuracy", and this result is confirmed by Cross-Validation Tests (Krozanoski, 1987). The CVT(k) value measures the square difference between the pixel numbers $x_{i,j}$ and the corresponding estimated values $\hat{x}_{i,j}$ computed by the linear model (1) for an increasing k-number of factors $z_i u_i^T$: its minimum value indicates the number of PCs needed to "adequately describe" the data matrix X (Jackson, 1991; Krozanoski, 1987).

This result makes evident that the PCA strongly increases the ability in describing the size, shape and position of gaps and defects detected by the ECoSp device in the plaster substrate of a painting simulating fresco, as described in section 1.2. This fact is important in the field of cultural heritage preservation since it allows to carefully plan the relevant restoration. However, it is worth emphasizing that these improvements follow from a simple correlation analysis of the detected image and that this technique may be adopted to extract information from all images where the pixel value represents a given physical observable, such as photons counts, wavelength intensity, temperature, and so on.

2.2 The ECoSp results

Figures 5 and 6 show the experimental setup installed in the church of Certosa of the monumental cemetery of Bologna (Italy) during the campaign of measurements with the ECoSp instrument. The whole surface of the half Hebraic gravestone sculpted with Catholic inscriptions has been scanned with the Compton spectrometer and both density data (integral number of backscattered photons by the electrons) and single spectra have been archived on a PC hard disk for subsequent PCA analysis.

A typical result is depicted in Figure 7 where the electron density measured in the spatial region of the gravestone shown

in Figure 6 is reported. Clearly three different density patterns appear, arising – as deduced from a detailed investigation of spectra from backscattered photons - from chemical process acting on and below the surface on the bulk marble due to sulphur in airborne pollutants.
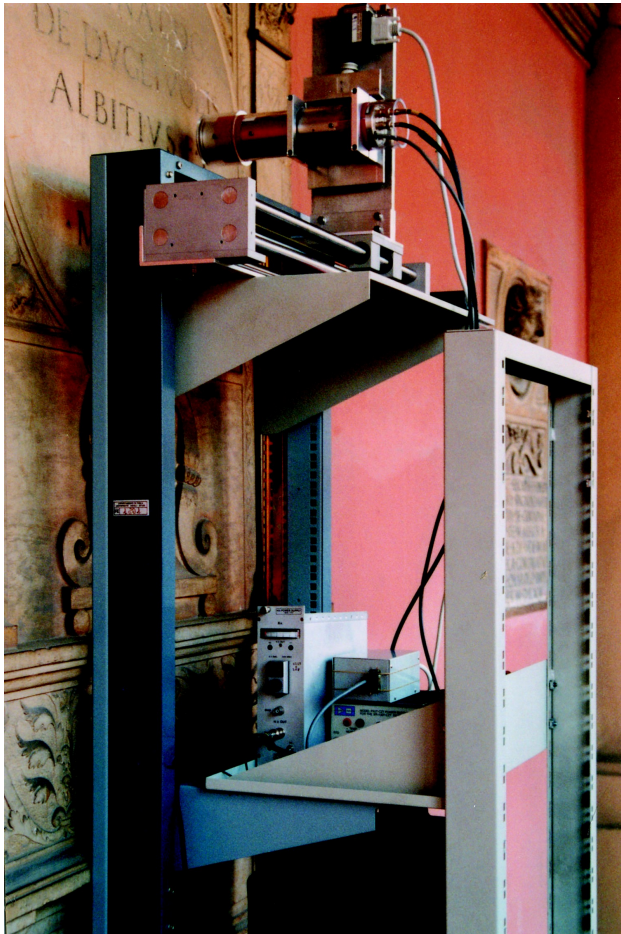

Figure 5. ECoSp experimental apparatus in front of the church of Certosa (Bologna, Italy) during scanning measurements.

Figure 6. Same caption as for Figure 5 but from a different point of view and in more detail.

Sulphur dioxide, a major pollutant in the atmosphere, mostly comes from the burning of coal or oil in power plants. It also comes from factories that make chemicals, paper, or fuel. Like nitrogen dioxide, sulphur dioxide reacts in the atmosphere to form acid rain and particles. Consequently, it can harm trees and crops, damage buildings since sulphuric acid produced by sulphur dioxide in the presence of humidity strongly interacts with the calcium carbonate of which the marble is made, forming the so-called black crusts and transforming the rock in the friable gypsum.
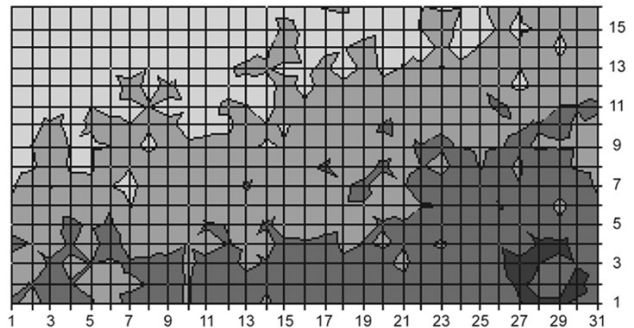

Figure 7. Map density of the marble gravestone in the region where the spectrometer is located in Figure 6.

Since sulphur (Z=16) has lower Z and mass numbers than calcium (Z=20), the signature of ita large presence is provided by the region of low density in Figure 7. This finding, further confirmed by the EDXRS analysis of a microsample at the scanning electron microscope (SEM), gives an essential information to provide a suitable environment for the preservation of the gravestone before the degradation process becomes evident at visual inspection.

2.3 3D laser scanning

A laser scanner Vivid 900 Minolta (see *htpp://www.minolta-3d.com/*) has been used to obtain a three-dimensional representation of the gravestone in the Certosa cemetery to recover – together with an analogous relief of the other half part conserved in the Museo Civico Medievale in Bologna – the original form of the marble sculpture by means of digital image algorithms and produce a material reproduction in scale. The Minolta instrument operates with three different autofocus optics, to be chosen depending on the size and distance of the object to be reproduced, namely f= 25.5 mm, 14.5 mm and 8.0 mm. The whole scanning area can be grabbed in 0.3 sec through the fast mode or in 0.25 sec in the fine mode, so assuring a higher resolution. This second option has been adopted, resulting in a data cloud of about 300,000 points, once a scanning area of 111 x 84 mm has been selected.

The Poygon Editing Tool software provided by Minolta has been used for the automatic storage of data, their processing and conversion on a PC equipped with Windows XP operating system.

Figure 8 shows the experimental setup and Figure 9 presents the final digital image of the gravestone together with two details of the relief.

As for the Hebraic gravestone in the Museo Civico Medievale an analogous relief has been carried out with a similar high resolution and accuracy less than 1.0 mm on the whole surfaces, as illustrated in Figure 10. In Figure 11 a detail of the scanning is shown and, finally, Figure 12 presents the numerical result concerning the two divided gravestones.

Figure 8. The experimental setup for 3D laser scanning of the gravestone in the front of Certosa church.
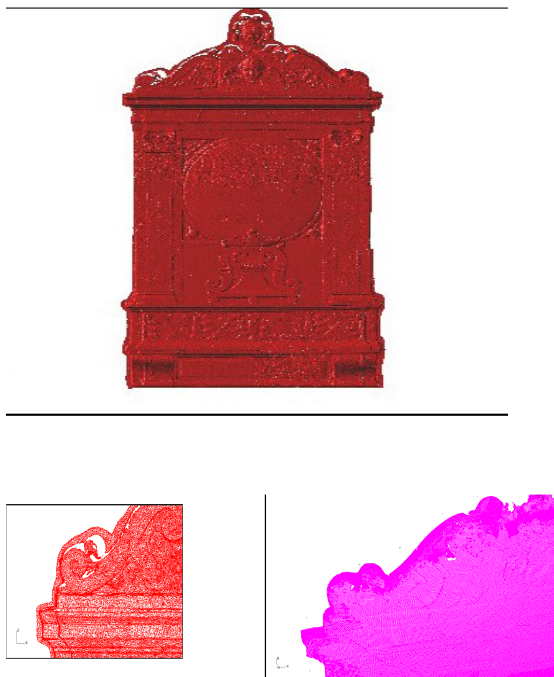

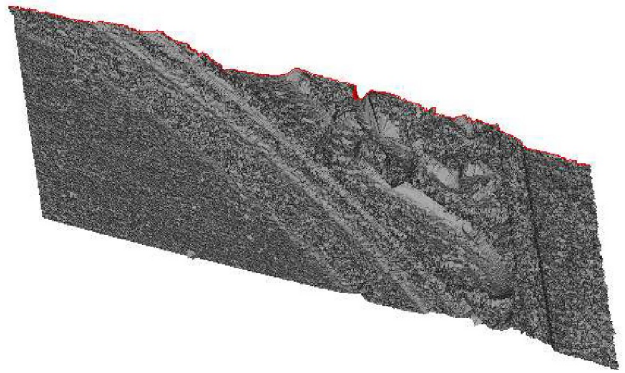Figure 9. 3D image of the Certosa gravestone.

Figure 10. Particular of the high-resolution scanning.

Figure 11- Another detail of the digital images of the gravestone.

2.4 Reverse engineering and prototyping

By means of usual reverse engineering (RE) and rapid prototyping (RP) techniques a material duplicate of the two grave stones has been obtained putting together the two separated parts and presenting the object as a whole as it was originally. The manufacturing arises from three phases in RP (Gatto and Iuliano, 1998):

- determination of a given number of cross-sections of finite thickness from the CAD (computer aided design) 3D model;
- realization of the first cross-section;
- manufacturing of the following sections which must stick to the first one.

Figure 12. The final result of the 3D reproduction and reconstruction of the Renaissance tombstones.

The cycle thus produces the planned structure by means of successive additions of strata, but introduces two sources of error. First of all, some cutting is present in the surface of the final model due to the approximation produced by the finite size of the triangles used in the CAD model. By decreasing the triangle sizes and increasing, therefore, the amount of data in graphic standard STL. The second error, the scale effect, depends on the roughness from the building of finite cross-sections and the effect is magnified by curve surfaces. Therefore, usually the artefact requires a final handworking.

2.5 3D laser scanning of mosaics

Mosaics have an intrinsic three-dimensional structure due to finite size, shape, position and orientation of tesserae in order to produce particular effects by light reflection, formation of shadows, etc, as well as an extrinsic one since they are often located on curve surfaces such as vaults, domes, pillars and so on. Unfortunately, the usual photographic documentation does not account for these peculiar characteristics and propose a necessarily planar image of mosaics, thus neglecting important information that, in the case of surveys preliminary to restorations, for instance, is rendered in graphics by means of conventional notations.

Therefore, use of 3D laser scanner has been proposed to overcome these difficulties and provides archaeologists, art historians and museums keepers with suitable tools for a better knowledge and representation of mosaics. The instrumentation described in the previous sections has been utilized on samples and large mosaics such as those in the Basilica of St. Apollinare Nuovo in Ravenna (Italy).
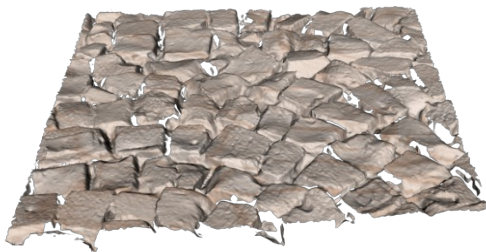

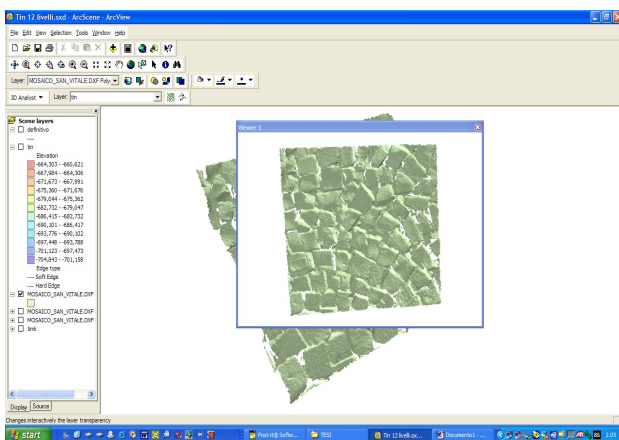Figure 13. Three-dimensional rendering of a mosaic sample.

Figure 14. Screen view of a GIS for mosaics.

A main difficulty arises from lack of data in some regions in correspondence with tesserae borders and dark colour elements – in particular for black tesserae where the laser light is completely absorbed and dark green ones – resulting from the dominant glass material in mosaics composition since its lucid and compact surface reflects the light in such a way that it is only partly detected by the optical sensors of the instrument.

This disturbing phenomenon is often generated in scanning bronze works, which - to overcome this limitation - were, in some cases, treated with powder or spray opacifiers provided their removability. It was considered necessary, in our case, sprinkle the mosaic surface of powder, thus making possible the acquisition of a sufficient amount of points from all the tiles.

In the attempt to compensate for any gap in the data cloud configured in the first scan tests, it was thought to capture the same portion of the surface several times, by inclining the laser emitter at different degrees. For these operations, the manufactured support which allows a shift (50 cm. x 35 cm.) was fixed to a rotatable mechanical base, connected to the computer and operated directly by the software processing of the clouds of points, in order to define precisely the angle of inclination of the surface to be collected with respect to the scanner.

After completing the acquisition of the mosaic, taken to an inclination of 0°, 15°, 30°, 45° and 70°, respectively, it was made the realignment of the five resulting clouds of points. By means of the Poygon Editing Software Tool , supplied as a standard accessory to the scanner by Minolta, one has identified counterparts of the points in each cloud, to be aligned through suitable roto-translations. A subsequent merging feature has produced a single mesh of points, where the lack of information derived from the cloud at 0 ° scan is partially compensated by the superimposition of the other clouds. The final result is shown in Figure 13.

This work, even still in progress, already allows one to outline a few useful remarks on the benefits granted by these investigations to the study of mosaic works. As for the scheduling of a real campaign of three-dimensional relief for mosaics of large dimensions, a few issues that could be solved thanks to the rapid evolution of these technologies have to be carefully planned as previously shown, resulting laser scanning a useful tool for documentation of mosaics. Moreover, reverse engineering methods are interesting for several reasons.

The creation of virtual models of small portions, representing compositions where they belong, would permit to carry out comparative investigations of mosaic cycles, leading to quantify similarities and differences in terms of processing and surface rendering of the mosaics themselves. From the virtual model one can perform accurate measurements on the size of the tesserae, their distance, position and orientation, even their projection with respect to the support. An example of these operations, shown in Figure 14, proceeding on the basis of a particular acquired surface, clearly shows the precision and the interesting perspectives offered by the mathematical treatment of data in this form.

2.6 GIS and virtual museums for mosaics

Figure 14 represents the screen view of a geographical information system (GIS) – namely, ArcGis – where the three-dimensional relief of the mosaic has been implemented. Therefore, one can exploit all the features of a GIS software to

perform numerical analyses of the whole surface, the position, shape and orientation of single tiles, average values and so on, and create a valuable geo-referenced database documenting in great details the investigated mosaics. A an example, Figure 14 shows a precise measurement of the orientation of a single tessera with respect to the plane of the support.
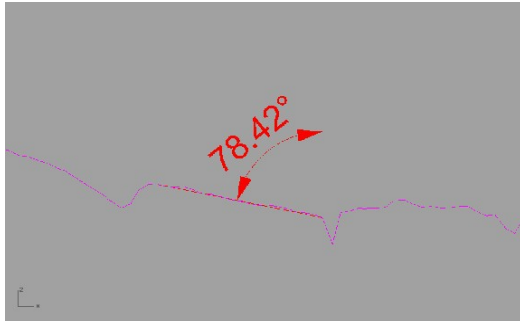

Figure 15. Schematic profile of a single tessera and its orientation.

Figure 16. View of a query of the multimedia database of mosaics.

Figure 17. Image of the tab with information relevant to mosaics.

The application of GIS in a mosaic has been then tested by the integration of data from three-dimensional laser scanning, using software such as Rhinoceros 3.0 and ArcGis 8.01. The first program is a model of land and is used mainly to handle

the file format. Stl directly derived from scanning laser data. It has been necessary to convert this format in order to be able to import data into the GIS system, which is not configured to manage the files of this type. The file format .Stl was then converted into a file .Dxf (drawning exchange file), a standard for CAD vector systems. By this way, it was possible to import the model of the mosaic inside ArcGis. The file can then be configured as a set of lines and polygons that describe the geometry of the object and its morphological characteristics.

With these data it has been feasible to build a TIN based on the elevations of geometric primitives. Represented graphically by means of chromatic intervals, the file provides clear and immediate information in the performance of the quantitative measurements of 'tessellato'. The GIS also includes the possibility of statistical analysis on which one can draw in real time characteristics such as maximum and minimum value of the selected fields (height in this case) and the standard deviation, so these precise calculations and immediate morphological study on the surface are easier and quicker than in traditional mappings, thus allowing archaeologist and art historian to have objective data on which to base their thoughts and assumptions on the interpretation of mosaics.

Finally, Figures 16 and 17 illustrate the multimedia database developed in collaboration with the International Centre for Documentation of Mosaics (CIDM, Ravenna, Italy) and described by Kniffitz et al (2006). The virtual three-dimensional environment where mosaics can be displayed including every relevant textual and visual information and the user can freely move walking or flying, etc., is shown in Figure 18 (Maino et al, 2002).

3. CONCLUSIONS

Advanced techniques for nondestructive diagnostics one combined with laser scanning methods can provide reliable information about many kinds of artistic and historic objects as well as archaeological sites and monuments or buildings.

Figure 18. Images of the virtual museum of mosaics.

These innovative instruments and procedures therefore complement traditional physical analyses (thermography, radar and acoustic inspections) which do not require to take samples as in chemical analyses, but generally provide more precise and (semi)quantitative data on presence of defects, voids, water infiltrations, etc. and on the material constituents.

However, also usual methods are knowing major developments and improvements, by introduction, for instance, of acoustic microimaging and the so-called mirage effect (Lucia, 2004), and the multispectral analyses in a large range of radiation wavelengths supplemented by suitable algorithms for the relevant image processing (Maino, 2004), To sum up, the recent progresses in diagnostics techniques coupled to the implementation of efficient methods of storage, processing and query through internet browsers for the produced data allow a very effective way for the best knowledge and preservation of the cultural heritage.

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