LASER SCANNER INTEGRATED BY PHOTOGRAMMETRY FOR REVERSE ENGINEERING TO SUPPORT ARCHITECTURAL SITE AND RESTORATION OF THE MOSAIC FLOOR INSIDE ST. MARK'S BASILICA IN VENICE

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ABSTRACT

The research[1] here reported on illustrates an experimental case of Reverse Engineering in the architectural site of the St. Mark's Basilica in Venice to support the activity of the mosaic floor conservation and restoration. The paper, beginning with realization of a 3D digital orthophoto map of the floor at the scale of the 'tesserae' in order to support an advanced GIS for the documentation, maintenance and restoration of the mosaic surfaces of the Basilica, continues the guideline which link new LS technologies to Reverse Engineering. It has developed a 3D GIS data management for the conservative restoration of the floor, in order to identify and replace damaged parts, to aid ordinary maintenance and plan future interventions, as well as to re-install the damaged parts while maintaining the characteristic altimetric irregularities.
Reverse Engineering (RE) for multi-scale prototyping is used in research of the automatic extraction of altimetric profiles to build templates along the 80cmx 80cm block of mosaic to be restored on site, until real time extraction of block templates (1:1 scale), only when it occur. RE methodologies are studied to support the conservation of the natural altimetric undulation of the rough floor, distinguishing the morphological anomalies caused by incompatible concrete used in the past restoration from the typical dynamic-elastic structure of the Basilica based on pilings, characterized by tide flooding: the result is developing a mortar to replace in the origin position and 3D shape the tesserae, detached and cut off one by one, and finally 'turned over' from reverse model. Methodologies of surface interpolation can be related to the model of deformations controlled in these years and in the future to support simulation process of reversing degree, the control of decline process in the future beginning from the knowledge of the altimetric movements of the floor surveyed by LS and topographic ground control points, related to paste floor levelling and to the annual altimetric check of Basilica controlled by high precision levelling network.

1. INTRODUCTION

In this paper, we illustrate the phases completed to date in the research in progress to generate a high-resolution 3D model of the mosaic floor of St. Mark's Basilica.
The model most faithful to the original is theoretically a detailed representation. But all architecture, in time, undergoes changes due to deterioration and other factors and the survey and detailed representation capture the current conditions, not the original state at execution. *Reverse engineering* is a buzzword today but it has been used since antiquity and is the reproduction of the current and no longer the original. However, *reverse engineering* in its tautological meeting, considering the substantial changes between the origin or the original and the subsequent, leads to an apparently unacceptable conclusion that derives from apparently acceptable conclusions drawn from apparently acceptable reasoning. It represents the paradox of the heap, with a new twist: "If a set of 10,000 tesserae is a heap, a mosaic in our case is achieved for every number *n* plus *1*, if a group of n tesserae is a heap, then a group of *n-1* tesserae is also, therefore, even one tessera is a mosaic." Both of the premises seem acceptable but the conclusion that follows is clearly misleading. In terms of etymology, paradoxical means what is contrary (*para*) to common belief (*doxa*), i.e. that a tessera is a mosaic is paradoxical. As an explanation, we might paraphrase Mark Sainsbury that the conclusion of the argument would be what is contrary to the belief received or we might reject the second premise or deny that the conclusion follows the premise or again, demonstrate that the conclusion is acceptable and at the same time, accept its paradoxical nature.
In truth, the terms of the problem are objectively vague and this would authorize anybody to refuse to pose the problem.
In our case, *reverse engineering* means a partial re-appropriation of the original wherein the more it realizes the more it is faithful to the current and the current is faithful to the past. We do not ignore the problem; we ignore any "one size fits all" solution, limiting our scope to resolving the problem in the best way with theoretical and experimental integrity.

2. SURVEY OF THE MOSAIC LAYER

The brickwork structure of the St. Mark's Basilica is nearly wholly faced with marble on the columns and walls of the naves while mosaic faces the remainder of the Basilica. Over time, movements and warping have occurred, demonstrated by fissures, detachments of the wall mosaics, movements in the floor, and unevenness in the marble facings. In many places, the decorative facing conceals structural problems which were discovered in an advanced state. The less than excellent construction quality was noted by Viollet-le-Duc in one of his

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many visits to the city from 1837 onward; attentive observation of the monument, favoured by the possibility of accessing the site during renovation works (executed by Giovanbattista Meduna, Proto della Basilica) caused him to define the church, in the original version, as a building in poor conditions, whose structural impoverishment contrasted with the wealth and quality of the decorative apparatus. The thousand years of history of St. Mark's mirrors the history of the city of Venice, a city that stands on water, which explains the problems it faces every so often. Composition of the land is typical of the lagoon areas and is constituted, as shown in surveys made along the northern side, by a 2-meter surface layer of fill material topped by a 5-meter layer of lime clay, atop this is a 5 to 10-meter-layer of lime sand with higher mechanical characteristics and finally by lime clay. At a depth of 70-90 cm from the pavement level, there is a 2-meter foundation in stone, composed of large blocks of sandstone and trachyte. Under the stone foundation is a wooden platform 10 cm thick, which supports 1-1.50 meter long wooden poles. The Basilica stands on a low-resistance surface whose geometric layering varies from place to place and is subject to subsidence and tide surges. Add to this the numerous interventions, among which the raising of the lead-coated domes and it is easy to see why the structure and floor has endured so many movements. During past interventions, restorers frequently changed the conformation and material qualities of the mosaic floor, considering that mosaic was not a respected art form at the end of the 1800s.

The parts deteriorated due to wear or excess moisture and chemical reactions caused by the salt contained in the mortar of the underlayer were readily replaced with new materials and new techniques, maintaining only the original design. As a result, the rippling of the floor, due to subsidence and movement, was also eliminated and the even level restored. The irregular surface was considered an intrinsic characteristic to the mosaic only in recent times. It is now protected and must be carefully considered in protection and conservation projects. In the 1980s and the following decade, high precision monitoring was made of the altimetric changes of the structure on seventy or so points, with uncertainty of 0.1 mm and movements of the floor on about one thousand points with uncertainty of 1 mm. In the last case, periodic levelling was done on the distinctive elements of the mosaic layer, easily retraced due to detailed monographs, identified on the planimetries obtained from the photogrammetric layout at a 1:50 scale, executed halfway through the 1980s. A 3D model was created using a TIN. This was the first axonometric document which is now compared with new surveys that use the technological developments of software and hardware products.

3. 3D DIGITAL ORTHOPHOTO

The ability to associate a 3D model of the floor with the wealth of information provided by photogrammetric rectification provides a representation of the object on several levels: quantitative metric data are associated with semantic data. To date, mosaicists have used high-quality, albeit amateur, photographic cameras taking images from above, usually from the galleries, converted them to actual scale and rectified them using the usual photographic techniques. The resulting quality is good, but does not reflect the exact disposition of the tesserae due to undulation in the floor and due to lens distortions in the image. An approximate plane photo of the floor is realized and printed on non-warping woven paper which is the layer on which to bond the recovered and new tesserae. The procedure is limited by an impossibility to represent the historic and natural 3D progression of the floor and potential incorrect disposition of the tesserae due to errors on the image, due in the central project to the non-plane object or the distortion of the lens.

Figure 1. The orthophoto of narthex

These limits cause a positioning error of around 1-2 cm at the time the mosaic tesserae are installed, although it is difficult to precisely establish what remains of the original mosaicists' designs and the geometries of the floor of the Basilica. Over the centuries and especially during 19th-century restorations, portions of the mosaic were removed to do work on the foundations or to remedy deterioration of the floor. The mosaic was lifted and later repositioned, without having prepared drawings or tracings of the mosaic surface; therefore, the tesserae weren't always replaced in their original position and frequently, the restorer would introduce new materials or new techniques into the historic work.

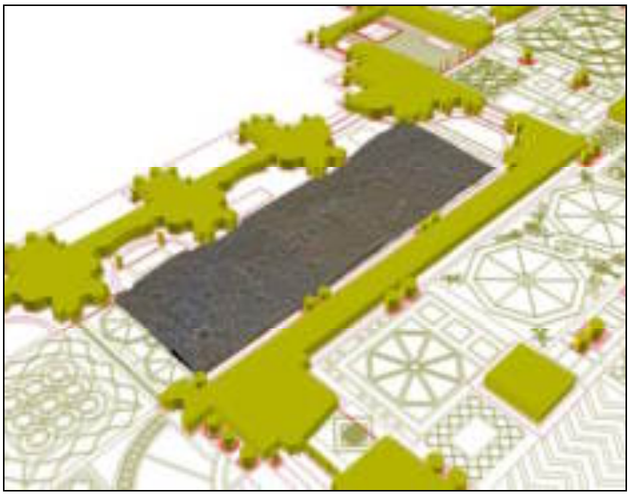

Figure 2. 3D view with 3D digital orthophoto of narthex

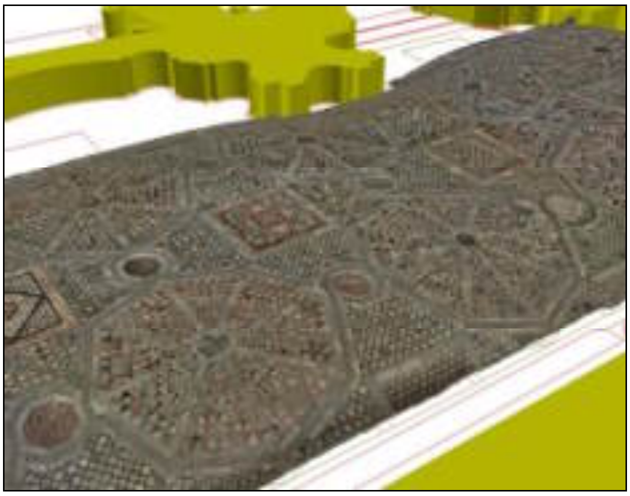

Figure 3. View with 3D digital orthophoto of narthex (particular)

In compatible environmental situations, the 3D orthophoto, obtained with a high resolution photogrammetric camera can provide a ground resolution of the pixels of 0.5 mm and support standard enlargements on a 1:1 scale without losing definition. It can read all the necessary quality information, obtain altimetric information and limit the error in planimetric and altimetric positioning to one millimetre. Setting the need for a 1:1 scale of representation, after experimenting with hardware and software on a test area of 40 m2 and after verifying the ability to achieve the objectives, the entire floor was blanketed by nearly 2,000 photograms at a scale of 1:50, supported on 9 control points per photogram for a total of 2,240 points, each with a longitudinal coverage between the photograms (more than 60%) along the axis of the strips and with transversal coverage between the strips (more than 20%). The DB44 Rollei camera with calibrated f/40 Zeiss lens and fully motorized Leica stations and Leica digital levels were the topographic instruments used.

The software used for the test area was APEX PCI 7.0 for rectification of the DTM and the 3D orthophoto and ArcGIS 8.1 and ArcINFO 8.0.2 for viewing. For the rest of the Basilica (for at this point only the north narthex) Socet Set 5.2.0 by BAE System and Bingo for rectification in addition to the visualization software mentioned. (fig. 1-3).

To correctly and extensively assess the system with which the final result was obtained in the test area, the intermediate steps of the processing were analyzed in order to associate the error with each step. In the aerial triangulation phase, the software can compare the topographical coordinates of each point that belongs to calculation of the parameters of orientation (support points and transition points) and the respective coordinates calculated in the T.A. (all the variables are expressed in millimetres).

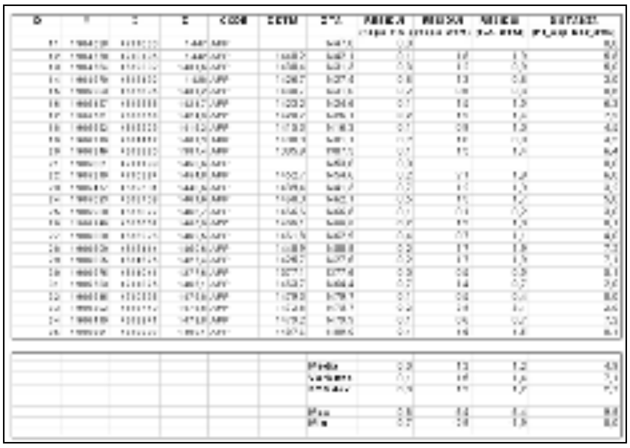

Figure 4. Report of aerial triangulation

After extracting the DTM and the orthophoto, an additional comparison was made, considering the remainders (fig. 4):

- between the topographical quotas of the support points and the quotas of the same points recalculated in the estimate of the T.A. ;
- between the topographical quotas of the support points and the points after creating the DTM, obtained directly from the 3D model at the centres of the pixels (15x15mm) closest to the topographic vertices;
- between the quotas deriving from the support points, recalculated with the TA and the quotas of the DTM.

The last column provides the value of the planimetric distance between the vertices of support and the dead center position of the pixels of the DTM.

The figure 5 represents the values of the remainders between the three different sets of data:

- the points for identification are located in abscissa;
- the values of the remainders in millimetres are given in ordinate.

The specifications reached in a situation of extreme decay of the mosaic in the test area provide some comfort on the ability to extend the method to the entire floor.

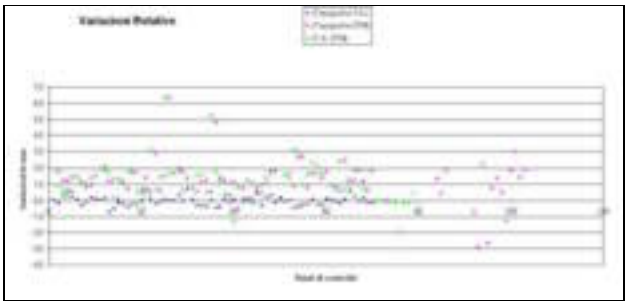

Figure 5. The remainders between the three different sets of data

Where the mosaic is cracked (fig. 6), it is necessary to introduce break-lines in order to achieve a concrete adherence of the model made up of the orthophoto to the real model.

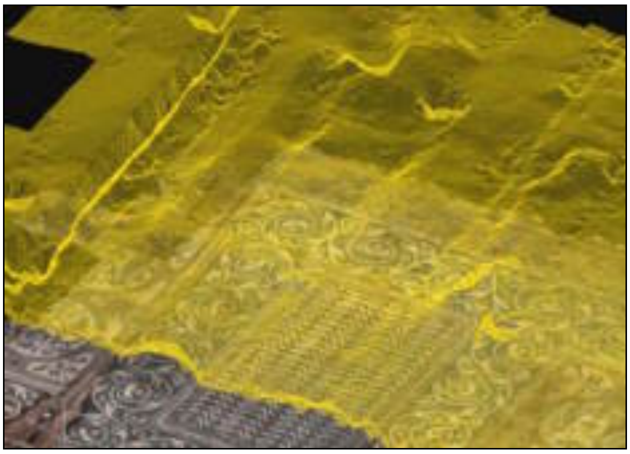

Figure 6. Test zone, the mosaic and the 3D mesh

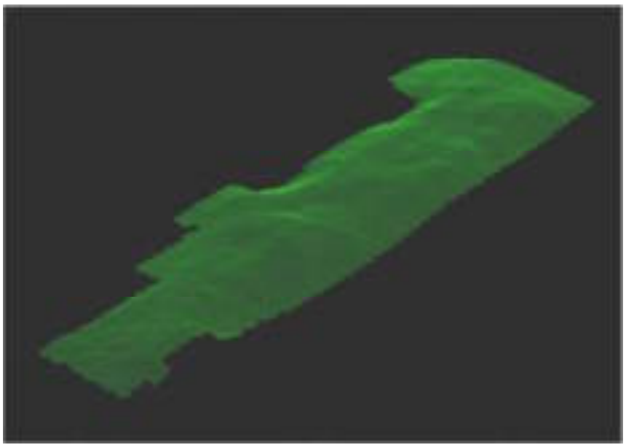

Figure 7. TIN lattice generate by laser scanner (12 million of points)

4. ORGANISATION OF A GIS OF THE SURVEY

The historic and artistic wealth of the St. Mark's Basilica call for tools suitable to comparing the information contained in them. All the iconographic documents, written records, studies and investigations made to expand the understanding of the Basilica represent an enormous body of information which leads to the need to analyze, interpret and correlate this data.

This information is difficult to manage unless it is organized into a GIS. A GIS is a virtual archive, easily accessible and referenced, where all the material available can be managed and used by restorers, structural engineers, historians, critics, chemists, etc.

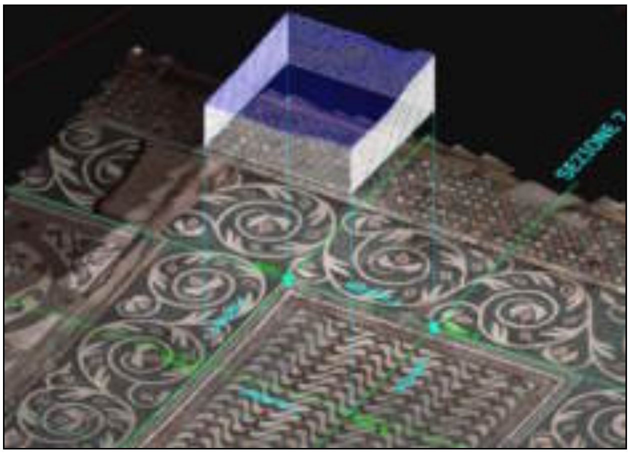

Figure 8. Test zone, reverse engineering of the mosaic. DTM generate by automatic image matching

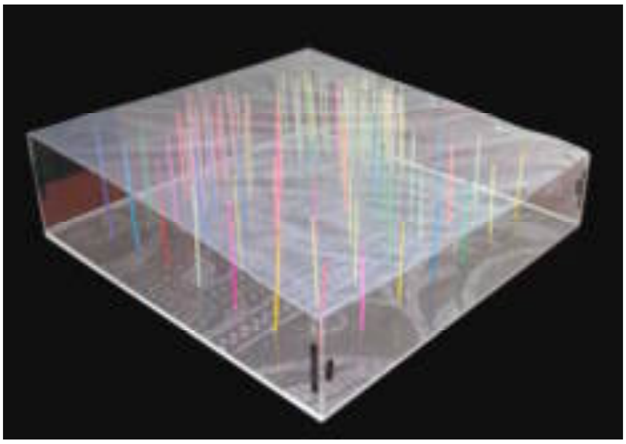

Figure 9. Test zone, 3D real model

This means, for example, visualizing the 3D orthophoto on the floor of the Basilica and, selecting a portion of it, laying out the numerous types of information in addition to the image of it conditions at actual scale, including a description of the historic iconography, material composition, any restoration interventions done, the description of the execution techniques used, and more. The system can also access interesting information for the history and life of St. Mark's by linking up with other archives through the web and expanding the boundaries of knowledge aimed mainly through various channels of communication.
For many years, the Procuratoria di San Marco has been gradually converting all of its documents and archives into a digital format in order to obtain a data base that would support and facilitate the work of scientists and scholars. Still, as the surveys have become available and technological progress has advanced hardware and software, computer models are being built that acquire and control the data and can flexibly and immediately incorporate, elaborate and represent the information required by the job.

Approximately 5,000 written documents and iconographs that make up the historic archives of the works in the Basilica have already been added to the computer archives. There are also photogrammetric surveys of the building rectified in numeric format, plan and altimetric sections, digital altimetric models of the floor (DTM) and control of its movements, obtained from high precision levelling. In recent years, the studies of mathematical models of the structural stresses with 3D graphic presentation were added to the altimetric progress of the mosaic floor and other architectonic elements, as one of the five main domes, elevations, layouts and sections in numeric form to the nominal scale of 1:50 and for the most 3D digital orthophoto.

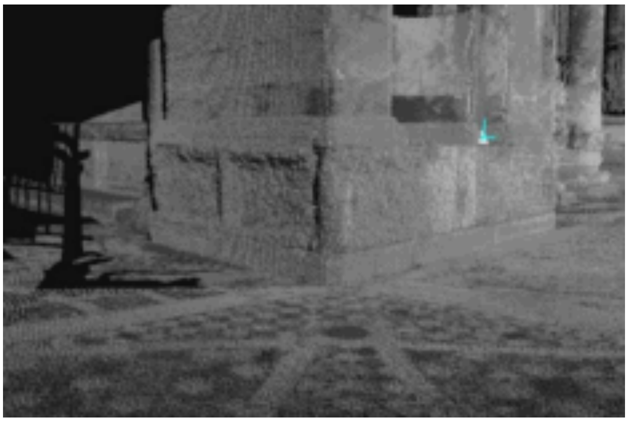

Figure 10. Registration of clouds laser scanner

The GIS is useful for protecting, engineering and job site management through several phases developed according to the knowledge acquired and which lead to simulation models for prevention and "scheduled" maintenance.
The phases can have several levels, such as geographic cataloguing and storing the document sources relating to the area object of study from an historic perspective and a chemical and physical perspective; to provide support to the restoration project by extracting information linked to quality aspects (radiometric knowledge of the surface object of restoration, identification of surface deterioration phenomena, etc) and metric aspects. In particular, this form automatically extracts the templates of the altimetric profiles to use in the subsequent phase of repositioning the tesserae on the recomposed floor in its actual progression to represent the basis for processing provisional models relating to the states of risk and future interventions.
The state of development of the GIS is considered an open system, namely, the hypothesized structure must be applied to real during the concrete restoration work in progress, in addition to representing the information archives of the knowledge on the parts and whole of the Basilica, including their relation to the surroundings.

5. THE CAUSE OF THE DETERIORATION CONSERVATION AND RESTORATION OF THE MOSAIC LAYER

The Procuratoria di San Marco has always been steadfast in defining a diagnostic picture that is broad and extensive enough to formulate concrete hypotheses on the main causes and mechanisms of deterioration of the components, the Basilica, and therefore, provide useful information in order to optimize the conservation and use of the building, which demonstrates and has always demonstrated very complex conservation problems. For example, the conditions of decay of the mosaic floor is clear even from a completely superficial observation, despite the constant and recurring maintenance works (restoration and partial rehabilitation) by specialized experts of the Procuratoria and who attempt to preserve vast portions from the wear and tear of tourist traffic by putting up physical barriers (metal rails, mandatory routes, floor coverings).
These factors are augmented by "contingent" factors which are added to the aspects related to the specific environmental conditions caused by the lagoon setting, namely, flooding, salts, nitrogen oxide, and nitrogen dioxide (due to vehicle traffic in the canals), hydrogen sulphide (which is formed by fermentation of the algae), which contribute to aggravating and making the problem of protection more complex.
One example is the part of the mosaic in the test zone (fig. 8-9). In this area, there are several swollen areas on the mosaic surface caused by insertion of Chioggia cement in the mortar mixture used to bind the tesserae. In nearly the entirety of the pavement, the first supporting sublayer is made up of aerated lime, sand and pottery shards that represents the mortar historically used in the Basilica, slightly different due to the brick dust and frequently used as a binder. Only the areas subjected to 19th-century restoration displayed a cement subfloor or the use of Portland cement, which was added to give better hold to the mortar. The proto of the Basilica, Pietro Saccardo, introduced the practice of conservational restoration in the Basilica in the late 1800s and opposed replacements made during traditional restorations, arguing the importance of using cement as an important technological advancement. He used it several times and considered it a real revolution in the field of building materials, since it worked well in the lagoon setting because it is essentially free of salt and compatible with other mortar compounds.
The Chioggia cement used in restorations done in the 1960s/1970s in the right transept contains a salt, stringite, that reacts with the damp rising up from the foundations and in a few months, after several years of implementing the works, it led to noticeable swelling of the surface. These swellings were caused by a strong tensile state that was caused between the elements making up the supporting layer of the tesserae, together with a disintegration of the binding, caused by the presence of marine salts rising to the surface in large quantities and acting in the presence of damp environments, debilitating the mortar and tesserae. The impoverishment of the binder on the sublayer, together with the action of the salt, led to deterioration so serious that urgent restoration work was required and the zone was closed to the public. The same problems occurred in other parts of the floor, but this area was much graver, probably due to the internal microclimate generated by its distance from the entrance doors and little moving air currents. The chemical debilitation is directly linked to the damp from spread and absorption that promote the soluble salt to crystallize and the humidity produced when there is the maximum flow of visitors in the Basilica, especially in the summer, which leaves condensation and carbon dioxide.
Impoverishment of the binder disintegrates the pebble fragments and leads to subsidence of the mosaic tesserae that it supported. The subsidence, of varying degree, can take the form of hollows with or without surface fractures, depending on the elasticity and dimensions of the tesserae of the floor.
The general undulation of the floor is presented as a series of bumps and depressions caused by settling of the land: partly natural (subsidence) and partly due to structural modifications which have altered the loads (domes and similar) on the sandy clay of the subsurface, which subsided in a differentiated way.
Particular care is taken in restoration of the floor: the concept of "replacement" characterizing the total rehabilitation of the floor

mosaic in the left nave in 1867, executed with modern materials and installation techniques and with comprehensive levelling of the subfloor, is replaced with "maintenance" based on conservation of the original parts and integrating in areas where gaps are found. Integrations attempted to camouflage the new works with historic and original pieces, even in stone material, making the new difficult to recognize.

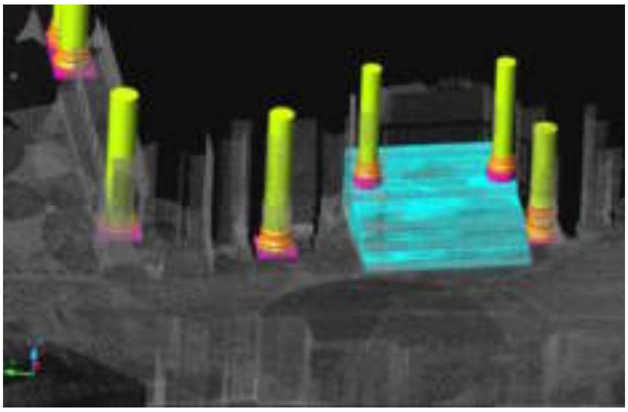

Figure 11. Construction of the model 3D, generated by the data laser

Only in more recent times has there been a use of "recognizable" imitation, for the use in the restored parts of materials with similar colours but with a more subdued tone with respect to the original. In the same way, new installation techniques were gradually being experimented on: from the use of modern cement to mounting prefabricated portions laid onto sheets of marble to installation execution according to the traditional technique, using only mortar and pebble fragment paste. The fact that mosaic has been recognized as art (previously attributed only to painting and copied cartoons used to execute mosaics since the 16^{th} century) has traditionally allowed them to be completely reworked, in the belief that the design contained could be repeated and improved upon.
Coloured cartoons or tracings were rarely realized on deteriorated mosaics due to the difficulty of realization and because the compositions no longer met the aesthetic tastes of subsequent periods; therefore they were replaced with arbitrary rehabilitations or adaptations which on several occasions have compromised the historic memory of the object.

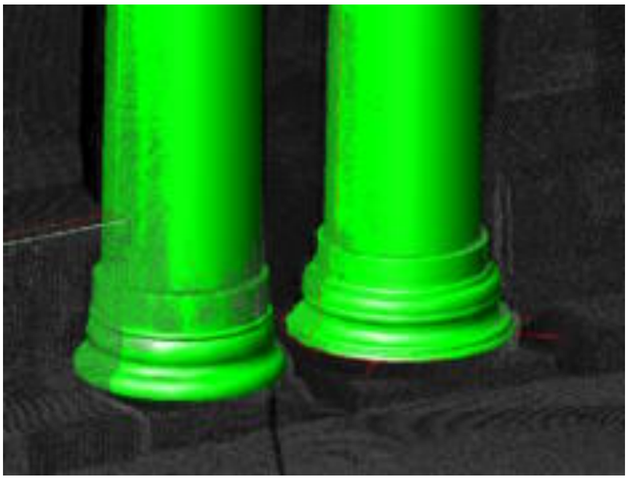

Figure 12. Construction of the model 3D, generated by the data laser, particular

The "reverse" procedure in use for some time involves laying the tesserae of the composition of the figures on top of movable supports and works with fairly small portions of mosaic, easier to transport and handle. Once the work of cleaning and restoration of the mosaic is concluded, the pieces are gathered together to lay them on the ground. The method consists of bonding the mosaic on sheets of paper with a reverse coloured image of the portion involved so that the faces of tesserae are bonded to the support with a vegetable glue and the other side, a truncated pyramid, faces upward. Subsequently, the composition is transferred onto the mortar spread out in an area to decorate and it is left to dry. After the glue sets, paper is removed and the surface of the tesserae is cleaned of any glue residue.
The original design is taken with a photograph of which the negative is used, printed on special material. The procedure used by the engineers of the Basilica to rectify the photograph of the floor at actual scale is not suitable for representing the characteristic undulation of the floor, while the 3D orthophoto is. A level of detail never reached previously and a cognitive instrument are achieved that can be immediately used in protection, engineering and site management. In the test area, a 3D orthophoto was used for restoration of the mosaics as direct support of the work of the mosaicists, which work daily on maintenance and conservation of the mosaic heritage.
The digital orthophoto at a 1:1 scale establishes the disposition of the tesserae starting with photographic images in which the metric information is associated with the visual information and all is inserted into a GIS.
The immediate application of the orthophoto results from its digital format, thanks to which all the portions of the floor in which it was divided in the design phase of the restoration up until definition of the mosaic tesserae. As mentioned, once there is a 3D model (fig. 10-12), it is also possible to automatically extract the sections that are representative of the undulating progression of the floor and which can be used to make the templates for the mosaicists to take note of the quotas in restoring the subfloor.

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