Surveying, Modeling and Navigating the Theodorian Mosaic Floor of the Aquileia Basilica

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Abstract. The paper deals with the laserscanning and photogrammetric surveying, the 3D photorealistic modeling, and the virtual navigation of the Thodorian mosaic floor the Basilica of Aquileia, the widest and oldest mosaic pavement in the Christian western world. From the acquired data, 18 clouds of 3D point and 158 digital images, a detailed model of such non-planar surface has been obtained and the images have been projected onto it as 3D textures. Finally, some thematic routes have been defined so creating navigation virtual tours to well understand and enjoy the various parts of the mosaic floor.

Keywords: Laserscanning, Photogrammetry, 3D-modeling, Virtual navigation.

1 A brief overview on the Theodorian mosaic floor in Aquileia

The origin of the Basilica of Aquileia dates back to the beginning of the IV century when, after the edict of Constantine of 313, the Christian community of Aquileia, ruled by Archbishop Theodore, was finally able to build its first Church. From that time, many architectural changes took place, so turning the Theodorian church into the nowadays Basilica: the chronological evolution of the Basilica plan is reported in [2]. The first Church was made up of two large rectangular halls (South and North), parallel to each other and connected by a third hall, that was later flanked by smaller rooms; in the IV century the N-hall was hugely enlarged. The floor of the two main halls was constituted by millions of mosaic tiles, a treasure of both Art and Faith (e.g., [1]), the widest and oldest mosaic floor in the Christian Western world. In particular, the mosaic of the S-hall is made up of ten carpets separated by strips with *girali* (wreaths) of shoots and leaves of acanthus. It can be defined as a “Catechism through images”, as each image has relevance, liveliness, imagination and the truth of faith, those truths that, in the year 313, could finally be publically proclaimed.

Successively, the Theodorian S-hall was also transformed in a three-aisle building with a new great baptistery in front of its main entrance. Attila destroyed the N-hall during the siege in 452 and it was never rebuilt: therefore, since then, the Basilica was developed only around the Theodorian S-hall.

In the IX century, the Patriarch Massenzio took a huge restoration by constructing the transept which gave a cross-shaped plan for the first time, and by adjusting the façade, building the porch linking it to the Basilica through the so-called "Pagan Church".

In the XI century, the Patriarch Poppone carried out further restorations by ordering to raise the perimeter walls and to paint the main apse by frescoes. Most of all, he wanted a new pavement by completely covering the Theodorian mosaics: in some way, this has protected the mosaics for centuries, apart from eight areas where new columns were erected to share yhe central and right naves. At a glance, the today Romanesque-Gothic aspect of the Basilica is very similar to the one Poppone consecrated on July 13th , 1031, obviously except for the mosaic that was discovered only in the 1909 from the Austrian archaeologists under the over-built floor. The mosaic has strong height variations, due to the ground subsidence: geometrically, it is a non-planar surface.

2 Surveying of the floor by laser scanning and photogrammetry

In May 2010, for the surveying and the above described mosaic floor, a Terrestrial Laser Scanner (TLS) integrated with a photogrammetric camera has been exploited. A first survey of the Basilica was already carried out in December 2005 (see [2]): in this new occasion, the work has been explicitly realized for the mosaic floor.

The principle of measurements of the TLS surveying is simple: let consider a laser beam emitted from a TLS system in a certain spatial direction and a coordinate reference frame X^S, Y^S, Z^S with origin in the TLS centre, called "Scanner' Own Coordinate System" (SOCS). The three coordinates of the hit point are computed by:

$$X^S = D sin\varphi sin\vartheta \;\; ; \;\; Y^S = D sin\varphi cos\vartheta \;\; ; \;\; Z^S = D cos\varphi \tag{1}$$

where:

- D is the distance from the TLS centre to the point: it is computed by the *time-of-flight* or *phase difference* method, knowing the form of the emitted-returned wave;
- φ is the "vertical" angle of the ray direction: it is known since imposed by the rotation of a suitable mirror around the "horizontal" axis;
- ϑ is the "horizontal" angle of the ray direction: this is known also, since imposed by the rotation of the mirror around the "vertical" Z^S -axis.

The *scanning* effect is achieved quickly (up to 100.000 times per second!) sending the laser beam in different directions, by changing of small values the mirror angle.

TLS systems measure still the intensity I of each returned beam, mostly depending from the material of the scanned surface, but generally they do not work in the color spectrum. To overcome this, firmly mounting over the TLS head a metric camera, the system becomes a "laser scanner and photogrammetric integrated system", giving as output *clouds* of millions of X^S, Y^S, Z^S, I points and lots of digital metric images.

The shot centre of the photogrammetric camera defines a new coordinate reference frame, called "Camera Coordinate System" (CMCS) but, since the camera is mounted on the TLS system, the rotation and translation from SOCS origin are known: this allows a fully automatic integration between laser scanning and imaging data.

The data acquisition is performed by setting the integrated system over a tripod in opportune fixed positions (stations) and it is automatically carried out in few minutes. Afterwards, the digital images are acquired by rotating the camera around the Z^S-axis by a suitable angle ϑ, so each CMCS position and attitude is easily computable.

The data acquisition of the Aquileia Basilica floor has been carried out with the Riegl Z390i system integrated with a Nikon D200 camera of the International Centre for the Mountain Research (www.cirmont.it) of Amaro (Italy). The instrument has been placed in five positions “Central nave”, “Presbytery”, “Entrance”, “Central nave from right”, and “Right nave”, the last two over the glass walkway built around the columns sharing central and right nave. In four positions, TLS has been also turned to better survey the floor: at the end, 18 point clouds have been acquired with various Z^S-axis orientation and angular scanning step, for a total of 30 millions of points.
The following Figs. 1 ÷ 4 show, colored by intensity in grey-values, the four tilted scans acquired with the maximum resolution (0,05°) in 2D views with ϑ-abscissa and φ-ordinate in the same scale. In these representations, horizontal objects (e.g. mosaic borders) and vertical ones (e.g. columns) appear even more curved for angles growing from the centre. The number of the acquired points is proportional to the figure area.

Fig. 1. Scan “Central nave –30°”: 3,1 M points, 110° ≤ ϑ ≤ 250°, 60° ≤ φ ≤ 114°.

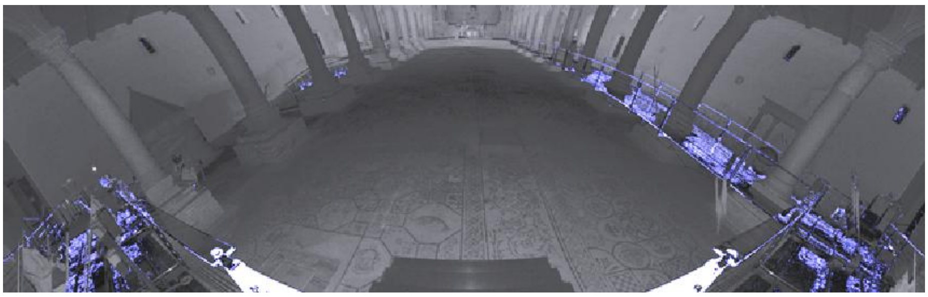

Fig. 2. Scan “Entrance –35°”: 6,2 M points, 70° ≤ ϑ ≤ 290°, 50° ≤ φ ≤ 120°.

Fig. 3. Scan “Central nave from right –40°”: 4,7 M points, 90° ≤ ϑ ≤ 280°, 60° ≤ φ ≤ 120°.

Fig. 4. Scan “Right nave –70°” (at right): 5,9 M points, 50° ≤ ϑ ≤ 260°, 50° ≤ φ ≤ 120°.

From the same scan stations, 94 metric images (3.872x2.592 pixel, 20mm focal length) have been acquired by rotating the TLS and so the digital camera fixed onto it. Figs. 5÷8 report the images corresponding to the scans of Figs. 1÷4: the image “vertical” angular field is 60° and so it can result lower to the scan “vertical” field.

Fig. 5. Scan “Central nave –30°”: 4 images.

Fig. 6. Scan “Entrance –35°”: 6 images.

Fig. 7. Scan "Central nave from right –40°": 6 images.

Fig. 8. Scan "Right nave –70°": 6 images.

Images have different mean scales and light discontinuities: for such a reason, other 64 *ad hoc* images were acquired, very close to the mosaic, by the same camera alone, then with unknown CMCS positions and attitudes. Four of the images are shown in Figs. 9,10 with a higher scale than those of Figs. 5 ÷ 8.

Fig. 9. Two of the images acquired by the camera alone in the Story of Jonah area.

Fig. 10. Two of the images acquired by the camera alone in the Medallion of Theodore area.

3 Modeling of the Theodorian mosaic floor

Acquiring TLS data from different points of scanning, namely from different SOCS, originates the problem to merge together such clouds of points by rotating and translating each one: this essential problem is known as "registration" of the scans.

For such aim, various *reflecting targets* are suitably put in the scanning area. Thanks to their high reflectivity (they can be detected in Fig. 1 ÷ 4 colored by intensity), these targets are automatically found within the scans and exploited as *tie points* with same coordinates; analytical details can be found in [3]. By applying the estimated transformations, each cloud "moves" from its own SOCS frame to a common "Project Coordinate System" (PRCS): in this way, an overall unique cloud of points is finally obtained, generally constituted by tens of millions of points.

For the scans of the Basilica, the registration as well as the other processing steps has been done by RiSCAN PRO software: the medium residual after the registration was around 3 mm, thus the obtained global point cloud is reliable (Fig. 11).

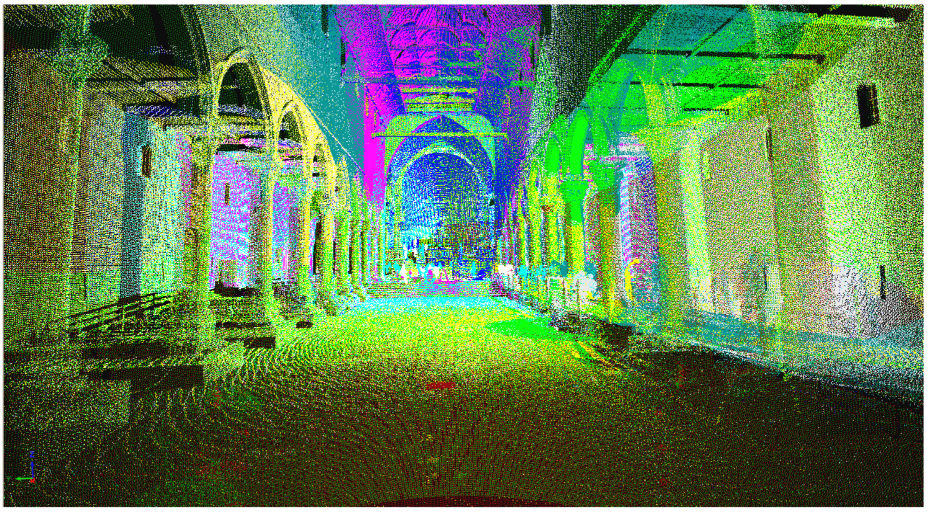

Fig. 11. View of the various scans, each one with a different color, after their registration.

Among the successive steps of TLS data processing, the conversion from the 3D-point cloud to one or more 3D-surfaces is the essential one. This phase is the *modeling* of the surface fitting the correct points and yields the so-called "Dense Digital Surface Model" (DDSM) for its general very high resolution, built by means of TIN 3D-meshes, best known as *Delaunay triangulations*, or by means of regular grids.

The modeling of the mosaic floor, a 2,5D surface for its irregularity, has regarded the pavement of the central and the right nave of the Basilica (38 x 20,5 ≅ 780 m^2). Starting from about 4,5 millions of points (5.770 points/m^2) acquired onto the floor, having deleted those of the eight column basements and a modern baptistery, the DDSM has been built over a grid of 2 x 2 cm. In this way, the Z^P values of about

1,3 millions of vertexes, forming about 2,6 millions of triangles (some very large under the deleted points) of the mosaic surface, have been automatically computed. The floor DDSM has been later optimized by means of a smoothing and decimation tool, so to assure a fine level of detail, but without too many triangles: a good compromise has been found reducing the triangles to about 400.000 (85% of decimation). Fig. 12 reports it colored by false colors (from red to blue) according to the elevation: it is surprising to observe a range of 31cm of the subsidence effects, often very localized.

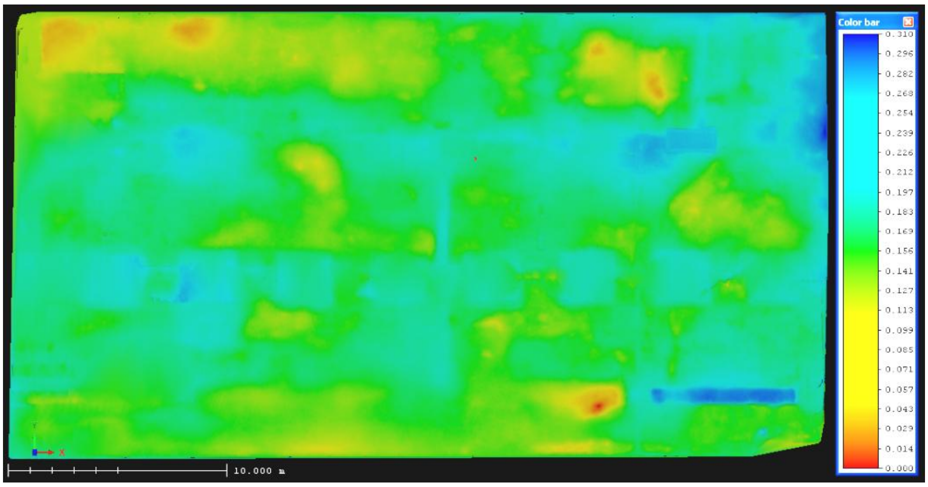

Fig. 12. DDSM of the mosaic floor colored by elevation varying in a 31 cm range.

For each image acquired with a TLS/photogrammetric system, the CMCS position and attitude is practically known. Laser scan and imaging data can be thus integrated in a straightforward way, exploiting the *equations of collinearity*, the fundamental analytical model of the photogrammetry, as explained e.g. in [3]. The RGB values relating to each image pixel are then used to automatically "color" the corresponding TLS point, so the point cloud becomes a *colored point cloud*, as in Fig. 13.

Fig. 13. View of Fig. 11 scan, with RGB colors from the photogrammetric images acquired.

Furthermore, making use of the same equations, the images are automatically *wrapped* onto the DDSM, hence obtaining a *mosaicked (!) texture* which, in turn, can be projected onto a representation plane as an *orthophoto*, as that in Fig. 14.

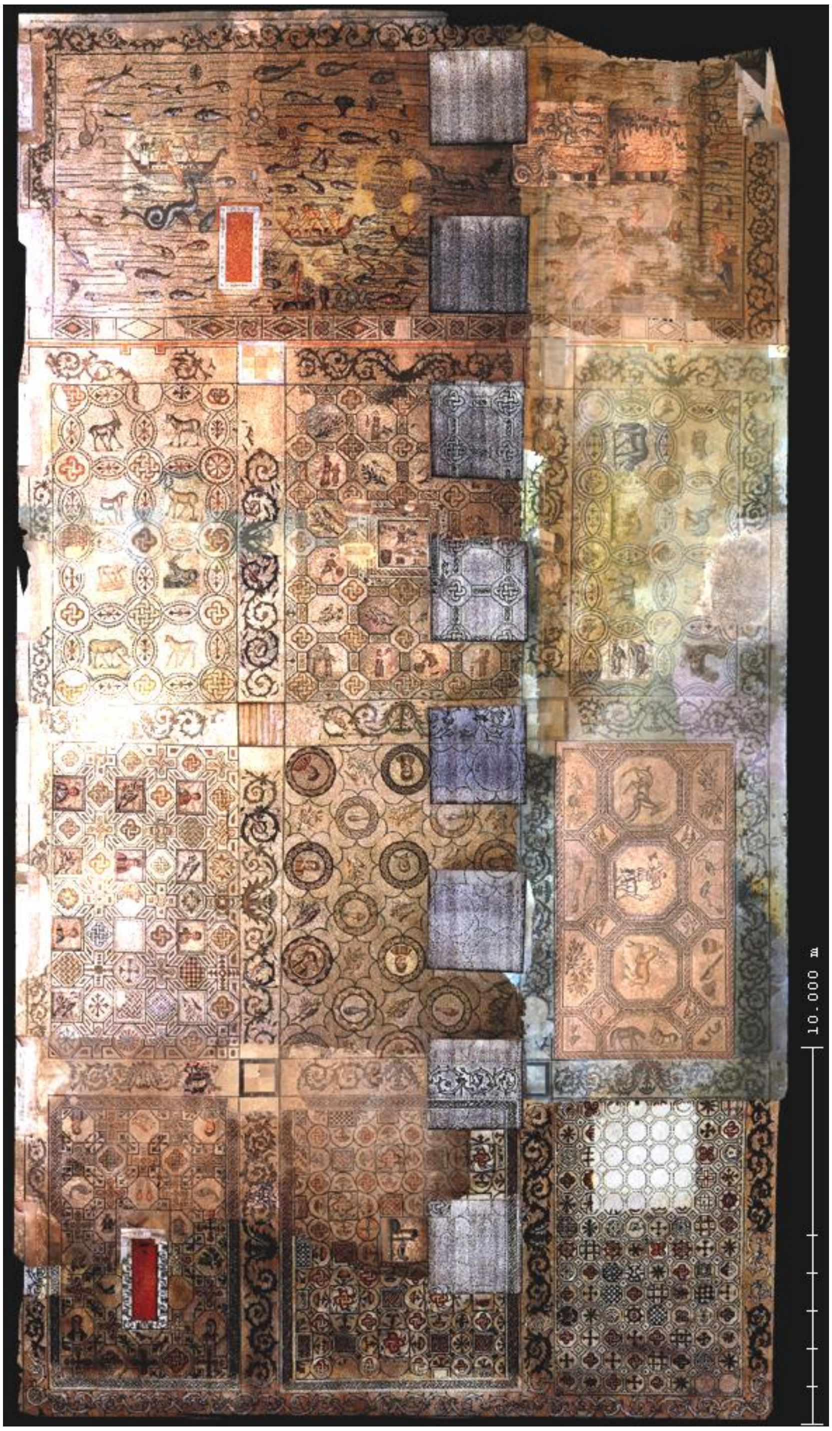

Fig. 14. Mosaic floor orthophoto: areas under the columns and the baptistery are reconstructed by gray scale drawings of experts.

In truth, to obtain best textures and orthophotos, the *ad hoc* acquired images have been used: their own CMCS position and attitude (exterior orientation parameters) are estimated finding detail points in the mosaic as *control points*, with $X^P, Y^P, f(X^P, Y^P)$ PRCS coordinates from a DDSM textured with the original oriented images. Since more than one image depict the same part of mosaic, is it essential to suitably choose the one with best mean scale and color quality. Nevertheless, in their mosaicking, a great care has to be devoted in clipping the images as much as possible onto the figure edges of the mosaic. Last consideration is on the number and the size of such textures: in our case, 42 textures have been created, stored in a total of 581 sub-images in JPG format which, together with the DDSM in OBJ format, occupy 412 MB.

4 Navigating onto the Theodorian mosaic floor

A 3D digital model textured with 2D-color images, as the above described DDSM, is the best photorealistic representation of an object of interest, since it allows us to create an unlimited number of *shots* in virtual reality environments, by iteratively explore it and/or following certain navigation routes. For the Aquileia case, both possibilities are carried out, because this work is thought for different kinds of users. Indeed, it is part of a Regional interdisciplinary project involving scientific and humanistic departments of the University of Udine, called *Computer Sciences and Web for the Cultural Heritage: innovative portable and 3D-services for Cultural Tourism* (www.infobc.uniud.it). Leaving an expert user to explore the mosaic model by him/herself, virtual navigations along philologically correct routes can well guide a "non-expert" tourist among the lots of subjects enclosed into the Theodorian mosaic and not easily readable, since sometimes mixed together or repeated.

Fig. 15. Frame from the movie "The Story of Jonah" onto the mosaic floor.

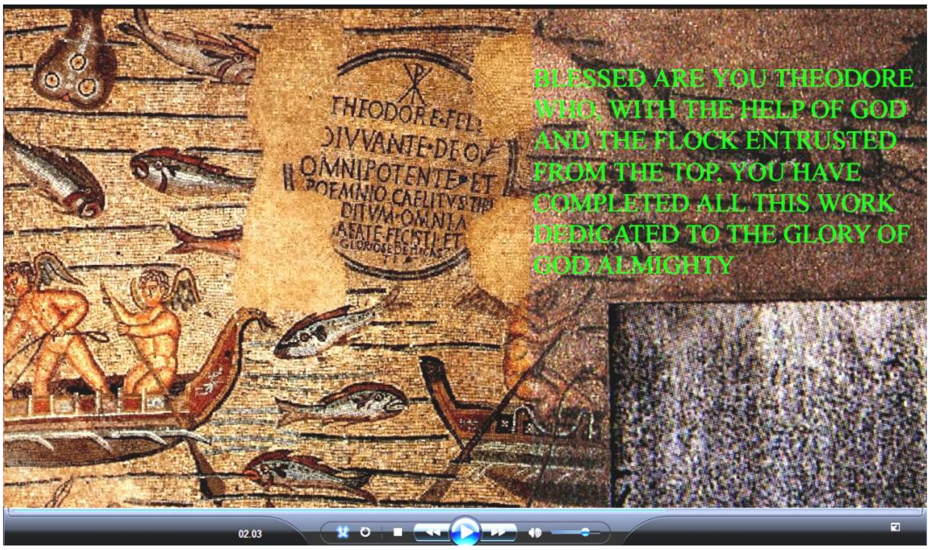

Fig. 16. Another frame from the movie "The Story of Jonah" onto the mosaic floor.

Figs. 15 and 16 show two frames of the "The Story of Jonah" tour, for which the glass walkway (see Fig. 8 and 10) has been virtually removed, and, from a certain frame on, the column basements are substituted by drawings of the covered mosaics.

5 Conclusions

The paper briefly describes the 3D-modeling of the precious Theodorian mosaic floor of the Aquileia Basilica surveyed by a TLS and photogrammetric integrated system. The modeling of the 4,5 millions of acquired points has allowed to accurately reconstruct the mosaic surface and to texture it with the images. This has led to produce virtual navigation tours to better know and appreciate this work of art.

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