LASER SCANNING SURVEY OF THE AQUILEIA BASILICA (ITALY) AND AUTOMATIC MODELING OF THE VOLUMETRIC PRIMITIVES

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ABSTRACT

The paper deals with the terrestrial laser scanning survey of the Aquileia basilica, one of the most significant monuments of the Italian Romanic architecture, the religious centre of a small town in North-East Italy famous for its roman archaeological ruins.
The laser data have been acquired with a Riegl LMS Z360i system integrated with a Nikon D100 metric camera, while the data processing has been carried out by the RiSCAN PRO software. The survey consists of 28 scans and 138 digital images for the internal aisles, and 14 scans and 55 digital images for the front external walls and the 73 m high bell tower. Thanks to 53 reflecting targets, surveyed from a GPS point network, the scans have been registered and geo-referenced in the Italian national cartographic system. An aerial laser survey of the whole Aquileia area, carried out with an Optech system, was yet available in the same datum.
In this way, a very detailed 3D model has been reached for such a very complex architectonic monument: by suitably exploiting the software tools, a large number of numerical products have been automatically obtained, as coloured point clouds, TIN surfaces, vector sections, image texturing and orthophoto, as well as very realistic virtual navigations among them.
For the automatic modeling of some main volumetric primitives, a three steps procedure, recently proposed by the authors, has been applied. By a nonparametric second order Taylor's expansion, the values of the 3D surface function, and the first and second order partial derivatives are locally estimated. From these, the elements of the so-called "Weingarten map" matrix are computed, and from the latter, the values of the gaussian and mean curvatures are finally evaluated. According to these values, the points are classified into four basic types (hyperbolic, parabolic, planar, and elliptic); after that, a region growing method allows a first raw segmentation. At last, a parametric regression for each raw cluster and a restricted surrounding buffer area is iteratively applied.
The automatic modeling procedure has been applied to the basilica main apse. The obtained results seem to be very promising: the procedure has correctly classified the bottom parabolic part, the planes close to the windows and the top elliptical part.

1. INTRODUCTION

Terrestrial laser scanning surveying is characterized by a level of automation that is day by day becoming always more astonishing: the data acquisition is practically automatic, while the data processing is efficiently accomplished by the nowadays available software. Throughout this paper, such a level of automation is investigated for an inside and outside surveying of a very complex building (chapter 2). The attention is mainly focused onto the very important steps of the point clouds registration and geo-referencing and the modeling of the main volumetric primitives. Commercial software is employed for all the traditional steps (chapter 3), including the registration and geo-referencing, while for the automatic modeling an original method is at first analytically introduced (chapter 4) and then numerically tested (chapter 5).

2. THE AQUILEIA BASILICA

The small and quiet village of Aquileia lies in the plain of Friuli (North-East Italy) not far from the lagoon of Grado. On the western bank the river Natissa, in the II century AD, the Romans built the town-fortress that became one of the most famous towns of the Empire, not only for its military, prowess and its economic wealth, but also for its cultural and spiritual magnificence. In the south eastern area of the Roman town, the Romanesque-Gothic lines of the basilica rise stately and solemnly; in truth, its origins date back to the beginning of the IV century. According to the tradition, St. Mark brought the message of the Gospel to these lands being sent here by St. Peter. As an Evangelist, during his mission in Aquileia, he met and converted Ermacora who became the first priest of the small Christian community. He was martyred with his Deacon Fortunato, and they are, together with the Virgin Mary, the patron Saints of the basilica. The persecution ended in the 313 as a result of the Edict of Costantine and Licio. The Christian community of Aquileia, ruled by Archbishop Theodore, was then finally able to build its first church. From that time, in about 1.000 years, many complex architectural changes took place, so turning the Theodorian church into the today basilica.
The first church was made up of two large rectangular halls: they were parallel to each other and connected by a third hall, that was later flanked by smaller rooms (Figure 1 at left). The Theodorian building was radically changed in the IV century: the north hall was hugely enlarged, in order to contain a more and more great number of faithful (Figure 1 at right).

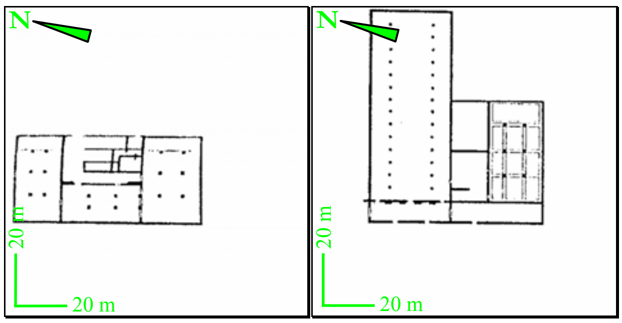


Figure 1. The basilica in the III (left) and IV (right) century.

After that, also the Theodorian south hall was transformed in a three aisles building (Post-Theodorian south hall) with a new great baptistery in front of its main entrance (Figure 2 at left).

The Post-Theodorian north hall was destroyed during the siege by Attila, King of Hun, in the 452 and never more rebuilt.
In the IX century the patriarch Massenzio took a definitive restoration which changed the entire aspect of the building (Figure 2 at right). The transept which gave the basilica a cross shaped plan for the first time, and the crypt under the presbytery were the main examples of the patriarch's work. Then he adjusted the basilica facade building the porch, and he linked it to the basilica through the so-called "Pagan's Church".

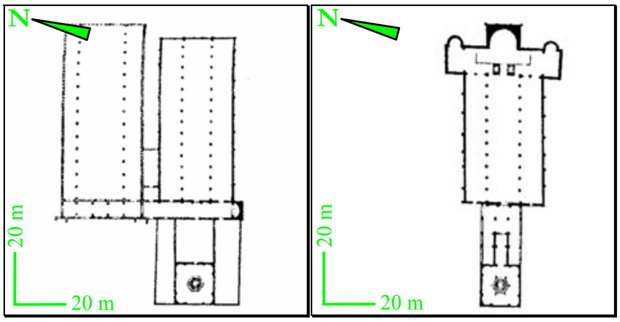


Figure 2. The basilica in the V (left) and IX (right) century.

After more or less two centuries, in the XI century, the Patriarch Poppone thought to carry out further restoration (Figure 3 at left). He raised the perimeter walls, made a new root, and the main apse was completely frescoed with images of great monumentality of Roman inspiration. Poppone also raised the 73 m high bell tower which dominates the plain of Friuli. The nowadays basilica aspect (Figure 3 at right) appear to the tourist practically as Poppone consecrated in 1031 July 13th.

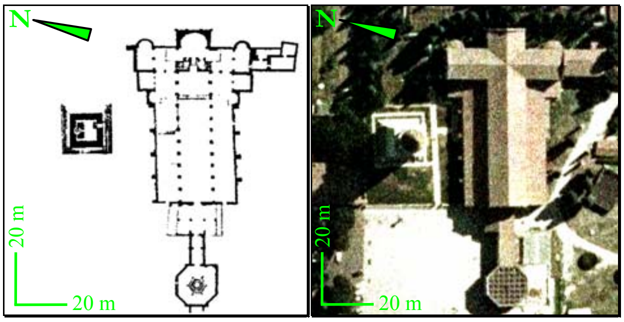


Figure 3. The basilica in the XI century (left) and today (right).

In the XII century, the Patriarch Voldorico of Treffen embellished the Massential crypt with a series of frescoes, one of the most important Romanic paintings in Northern Italy. Afterwards, from the Middle Age to the XIX century the basilica had more additions of lesser importance.
Last but not least, the treasure both of art and faith and the most precious of the basilica: the mosaic floor (Figure 9). It is the widest and oldest floor in the Christian western world, a magnificent example of Constantine Art. It is quite impressive that this masterpiece was discovered only in the 1909 from Austrian archaeologists under the pavement built by Poppone! The mosaic 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 which, in the 313, could finally be proclaimed in public.

3. LASER SURVEY OF THE BASILICA

For a so important, complex, and extended monument, the use of a terrestrial laser scanning system integrated with a photogrammetric camera surely represents the ideal surveying technique. These systems are currently largely applied not only for civil engineering surveying, but also for architectural, archaeological and cultural heritage sites, where their geometric irregularity can be well detailed and exhaustively 3D measured.
For the surveying of the Aquileia basilica, a Riegl LMS Z360i laser system (www.riegl.com) integrated with a Nikon D100 metric digital camera (www.nikonimaging.com) has been employed. This laser sensor exploits the distancemeter method, i.e. the *time-of-flight* principle, allowing measuring the distance laser-point, and computes the 3D point coordinates thanks to the instantaneous angles imposed to the mirrors. Furthermore, also the signal return intensity is acquired, mapping in this way the surface material. The global scanning effect is achieved changing the deflection angles of small user-defined increments, up to accomplish 90° in zenith and complete panoramic scans in azimuth. To obtain a precise positioning a high accuracy angular values recording is mandatory.
The main steps of the surveying, managed with the RiSCAN PRO® (Riegl) software, are briefly described in the following.

3.1. Laser and imaging data acquisition

First of all, 53 cylindrical or adhesive flat reflecting targets were placed inside and outside the basilica as "tie points" for the step of registration and geo-referencing of the laser scans (3.2). Therefore, the data were acquired by setting the laser instrument over a tripod at 13 suitable scan positions inside the basilica. From these stations, 28 point clouds, with different angular steps and ranges, were collected. Anyway, from each instrument position, a scan with the maximum angular sensor resolution (0,100°) was accomplished, so acquiring clouds up to 3.240.000 points. In particular, for the quasi-vertical scan "AbsideV" of the basilica main apse acquired from a station about in its centre, up to a 5x5 mm grid, namely 40.000 points/m^2, on the frescoed wall surface were carried out!
As regards the reflecting targets, they were automatically detected thanks to their very high reflectivity yet in-situ: for any one, also a fine scan of meanly 12.000 laser beams was thus performed, so to accurately measure their barycentre position.
Finally, from the same scan stations a total number of 138 high-resolution digital images (3.008x2.000 pixels, 20 mm focal length) were acquired, by rotating the camera around the laser Z-axis with a 40% carefulness overlap. Shortly, for the inside basilica, more than one Gb of data were acquired in two days!
The external survey of the basilica frontal part and of the 73 meters high bell tower was carried out from 5 stations, making possible 14 different scans (from panoramic of the surrounds to very narrow of the bell tower only) and 55 digital images.
The 3D coordinates of each scanned point were practically computed in real-time into different arbitrary local datum (scanner frame), with origin in the instrumental centre and Z-axis as the instrument one. These values have been later registered and geo-referenced, so obtaining a unique point cloud defined with respect to a global system.

3.2. Registration and geo-referencing of the laser scans

This step is analogous to the well-known photogrammetric problem of the relative and absolute orientation. From the analytical point of view, both the scan registration and geo-referencing involve the estimation of rotation and translation parameters: for such reason, they can be solved simultaneously.
The registration of terrestrial scans differs from the aerial case (alignment) since the rotation and translation required for each scan are not small, but can assume a finite value.

The geo-referencing into a cartographic reference frame can be solved by means of direct or indirect methods (e.g. Schuhmacher and Böhm, 2005). In the first case, the laser system is integrated with GPS or topographic devices. In the second one, a cartographic database matching is carried out or a topographic survey of some scanned point is performed from some vertexes defined into a global datum; this last, classically exploiting “control points”, is the widely employed method.
Following this approach, the 53 reflecting targets have been suitably surveyed with a Leica TCRA 1103 EDM station from the vertexes of a topographic network (Figure 4).

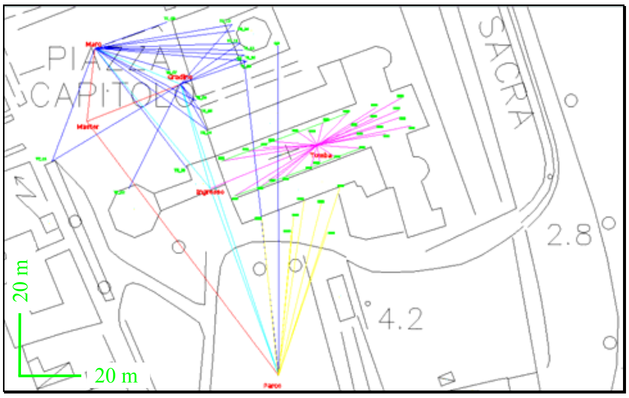


Figure 4. GPS and EDM network and reflecting target points.

Four network vertexes were occupied with two Leica system 520 GPS receivers with static differential measurements, so to directly fix the laser data into the Italian national Gauss-Boaga cartographic system, as the regional technical map in Figure 4. In this way, considering for the target points the local X,Y,Z coordinate and the corresponding global E,N,H ones, the 13 high resolution internal scans (Figure 5) and the 5 external ones (Figure 6) have been simultaneously registered and geo-referenced. For each scan, 12 target points have been averagely exploited and the resulting mean residual is 2-3 cm: this is really satisfactory, above all considering the difficulty to topographically collimate the centre of the cylindrical targets.

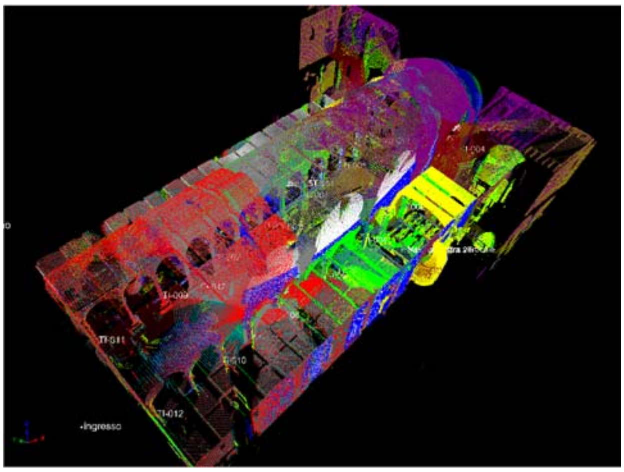


Figure 5. The 13 inner scans (in different colours) after their registration and geo-referencing.

Furthermore for the whole town of Aquileia, an aerial laser survey with an Optech ALTM 3033 system was available and referred to the same Gauss-Boaga datum, although acquired with a rather low resolution (1-2 points/m^2). A unique terrestrial and aerial point cloud of an area larger then the only basilica is thus obtained (Figure 7 & 10): a better survey completeness and also information about the surroundings are hence gained.

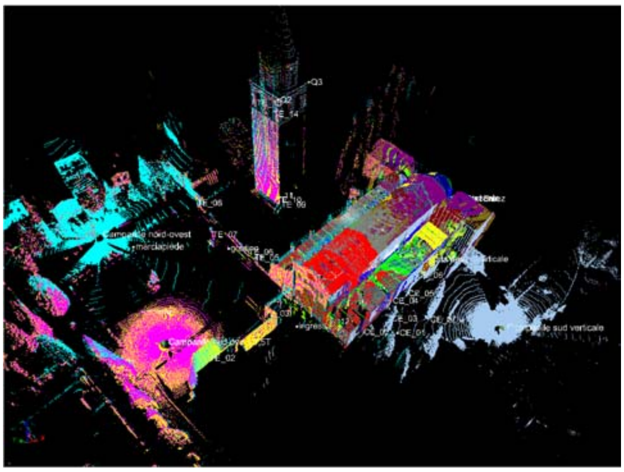


Figure 6. The 7 external scans after registration and geo-referencing joined to the internal scans.

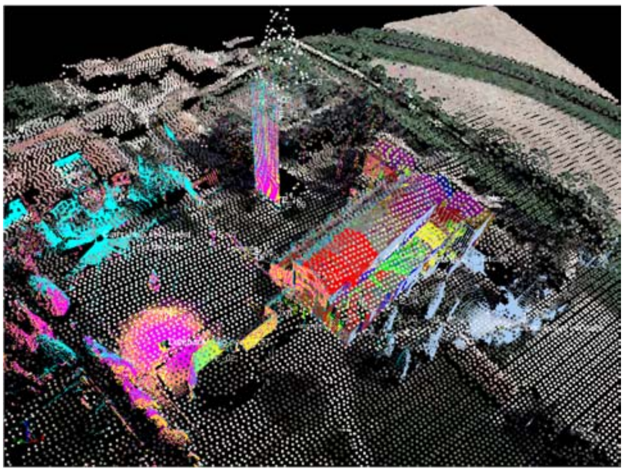


Figure 7. The aerial scan (in RGB) joined to the terrestrial ones.

3.3. Editing of the points and TIN surface generation

Once all the laser points are geo-referenced, the successive step involves the removing of blunders and useless points and the conversion from a 3D point cloud to a 2D surface. The available softwares make use of several commands/tools, implementing statistical analysis and/or geometrical criteria to remove gross errors, outliers, isolated points, duplicated points, and so on. RiSCAN PRO allows to automatically *clean* and *filter* the points, and in addition to *resample* the scans with a less resolution angular grid. Furthermore, the classical CAD tools for manual 3D selection (and deletion) are also available.
The surface, fitting the correct points, called Dense Digital Surface Model (DDSM) for its high resolution, can be modelled by means of TIN (Triangulated Irregular Network) meshes or regular grids. The first method is generally preferable since it can better follow the discontinuities and the concave/convex surfaces, typical for architectural surveys. With RiSCAN PRO various meshes have been generated in form of Delaunay triangulation. Lastly, the DDSMs have been improved by the commands *smooth* (averaging the small irregularities) and *decimate* (deleting the too much small triangles).

3.4. Integration with photogrammetric images

Last processing step is the use of a high-resolution digital camera to obtain a texture data with a resolution still better than the laser data. Many of the available software provide tools for texturing the DDSM with images: the analytical problem is to know the image orientation parameters. Using images of a camera without prior knowledge of its internal and external orientations, requires the manual definition of control points both in the scan data and in the image data. Integrating instead a high-resolution calibrated camera into a laser scanning system provides a very efficient, convenient, and powerful system to automatically and accurately generate high-resolution textured 3D models. In this sense, the Riegl&Nikon system employed is a *hybrid sensor* composed of a laser scanner and a calibrated digital camera firmly mounted to the laser scanning head. For each acquired image, its position and attitude was so directly measured with high accuracy in the scanner frame: the 3D scan data and the 2D image data were so combined in an automatic way. In our case, the RGB pixels have been projected:

- in correspondence of each laser point, colouring thus a cloud of more than 70 millions of points; for each one the East, North, Height, Intensity, Red, Green, and Blue values are obtained, proving the extraordinary completeness and detail of this architectonic surveying;
- over the laser DDSM, as intermediate step to generate the digital orthophotos of the various plans of interest.

3.5 Numerical products of the survey

By suitably exploiting the RiSCAN PRO tools, a large number of 2D/3D numerical products have been automatically obtained, further to the previous coloured clouds and TIN surfaces, as sections, profiles and mixed raster/vector representations.
A transversal section showing the well congruence among internal and external scans is reported in Figure 8: by assigning a certain size to the points and using the smoothing option in the visualization, this point cloud already seems an orthophoto.

Figure 8. Transversal section of the basilica towards the apse.

Figure 9 reports an orthophoto with contour lines of the mosaic floor showing its irregularity due to the ground subsidence.

Figure 9. Orthophoto and 1 cm contour lines of the mosaic floor.

Furthermore, all these 3D products have been made available to the users in form of very realistic virtual navigations, either interactively in VRML environment or along predefined outside (Figure 10) or inside tours (Figure 11) by AVI multimedia files.

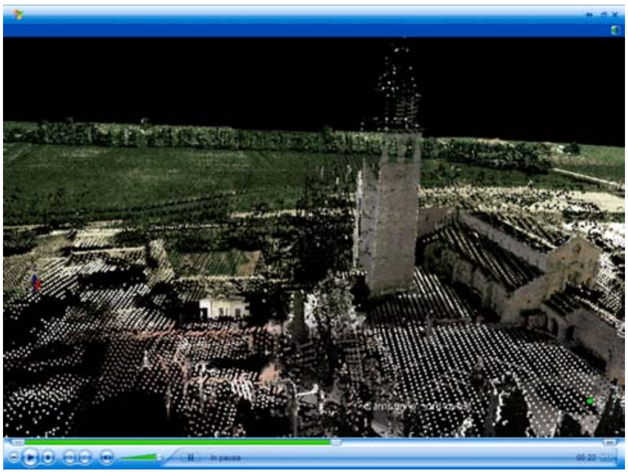


Figure 10. Frame of the virtual navigation outside the basilica.

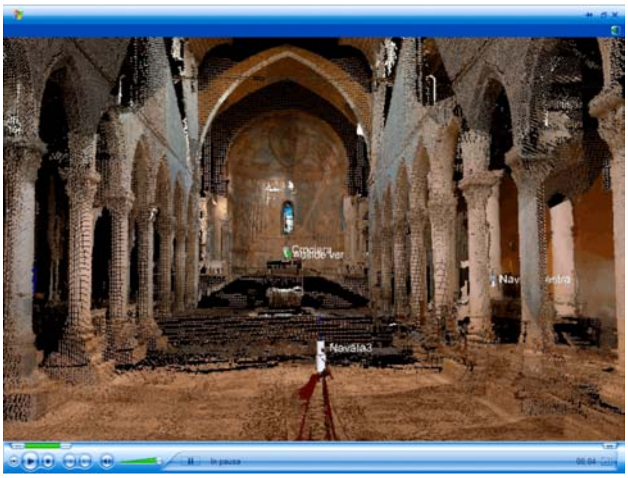


Figure 11. Frame of the virtual navigation inside the basilica.

Concluding, the different levels of automation in the software solution of these steps can be quoted as "fully-automatic" for 3.1, 3.3, 3.4 and 3.5. For the key-point (from the analytical point of view) step 3.2, the data processing is carried out in "quasi-automatic" way: the crucial phase is the correct pairing of each target point among the different scans and the control points. In our case, renaming the target points exactly as the control points skips this trouble, otherwise, permutation algorithms find well enough the coupling. Hence, we can state that the available softwares solve automatically also this step.

4. MODELING OF THE VOLUMETRIC PRIMITIVES

The last processing step concerns the automatic modeling of the main volumetric primitives i.e., for architectural data, the recognition of the main constructive elements. This is not an easy task and, in truth, not any softwares have tools to solve it. For such aim, we recently introduced a three steps fully automatic analytical procedure (Crosilla, Visintini and Sepic, 2006), implemented in a C language software tool. Analytical details can also be found in Beinat, Crosilla and Sepic (2006) in these proceedings: herewith the procedure is only summarized.

4.1. Computing of local surface parameters exploiting a nonparametric model

Let us consider the following polynomial model of second order terms (Cazals and Pouget, 2003):

$$Z_j = a_0 + a_1 u + a_2 v + a_3 u^2 + a_4 uv + a_5 v^2 + \varepsilon_j \tag{1}$$

where the coefficients and the unknown parameters are locally related to a measured value Z_j by a Taylor's expansion of the height function $Z = \mu + \varepsilon$ in a neighbour point *i* of *j*, as:

$$a_0 = Z_{0_i}\ ;\ \ a_1 = \left(\frac{\partial Z}{\partial X}\right)_{X_i,Y_i}\ ;\ \ a_2 = \left(\frac{\partial Z}{\partial Y}\right)_{X_i,Y_i}\ ;\ \ a_3 = \frac{1}{2}\left(\frac{\partial^2 Z}{\partial X^2}\right)_{X_i,Y_i}\ ;$$

$$a_4 = \left(\frac{\partial^2 Z}{\partial X \partial Y}\right)_{X_i,Y_i}\ ;\ \ a_5 = \frac{1}{2}\left(\frac{\partial^2 Z}{\partial Y^2}\right)_{X_i,Y_i}\ ;\ \ u = (X_j - X_i)\ ;\ \ v = (Y_j - Y_i)$$

with X_i, Y_i and X_j, Y_j plane coordinates of points *i* and *j*.
The weighted least squares estimate of the unknown parameters vector $\boldsymbol{\beta}$ from a limited number of *p* neighbour points result as:

$$\hat{\boldsymbol{\beta}} = (\mathbf{X}^T \mathbf{Q} \mathbf{X})^{-1} \mathbf{X}^T \mathbf{Q} \mathbf{z} \tag{2}$$

where (for j = 1, …, p):

$$\boldsymbol{\beta} = [a_0 \ \ a_1 \ \ a_2 \ \ a_3 \ \ a_4 \ \ a_5]^T$$

X is the coefficient matrix, with *p* rows as:

$$\mathbf{X}_j = [1 \ \ u \ \ v \ \ u^2 \ \ uv \ \ v^2]$$

Q is a diagonal weight matrix defined by a symmetric kernel function, centred at the *i*-th point, whose diagonal elements are:

$$w_{ij} = \left[1 - (d_{ij}/b)^3\right]^3 \ \text{for} \ d_{ij}/b < 1 \quad w_{ij} = 0 \ \text{for} \ d_{ij}/b \geq 1$$

where d_{ij} is the distance between the points *i,j* and *b* is the half radius of the window encompassing the *p* closest points to *i*.
To locally determine the values of the *gaussian, mean* and *principal curvatures*, it is necessary to compute for each point the so-called "*Weingarten map"* matrix **A** of the surface *S* (e.g. Do Carmo, 1976), that is given by:

$$\mathbf{A} = -\begin{bmatrix} e & f \\ f & g \end{bmatrix} \begin{bmatrix} E & F \\ F & G \end{bmatrix}^{-1} \tag{3}$$

where E, F, and G are the coefficients of the so-called "*first fundamental form*", obtained from the estimation (2) as follows:

$$E = 1 + {a_1}^2\ ;\quad F = a_1 a_2\ ;\quad G = 1 + {a_3}^2$$

e, f, and g are the "*second fundamental form*" coefficients, as:

$$e = 2a_3 \Big/ \sqrt{{a_1}^2 + 1 + {a_2}^2}\ ;\quad f = a_4 \Big/ \sqrt{{a_1}^2 + 1 + {a_2}^2}\ ;$$
$$g = 2a_5 \Big/ \sqrt{{a_1}^2 + 1 + {a_2}^2}$$

The *gaussian* curvature K corresponds to the determinant of **A**:

$$K = \frac{eg - f^2}{EG - F^2} \tag{4}$$

The *mean* curvature H can be instead obtained from:

$$H = \frac{eG - 2fF + gE}{2(EG - F^2)} \tag{5}$$

while the *principal* curvatures k_{max} and k_{min}, corresponding to the eigenvalues of **A**, are given from the solution of the system $k^2 - 2Hk + K = 0$, i.e. from $k_{min,max} = H \pm \sqrt{H^2 - K}$.

4.2. Raw segmentation by a region-growing method

The analysis of the sign and of the values of K and H allows the clustering of the whole geometric surface into the following basic types (see Table 12): hyperbolic (K < 0), parabolic (K = 0 but H ≠ 0), planar (K = H = 0), and elliptic (K > 0).

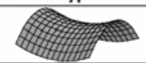
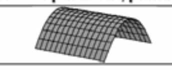
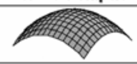
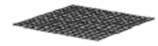
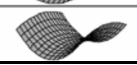
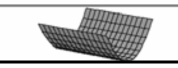
	K < 0 : **hyperbolic**	K = 0 : **parabolic/planar**	K > 0 : **elliptic**
H < 0			
H = 0			not possible
H > 0			

Table 12. Classification of surfaces according to the values of *gaussian* K and *mean* H curvatures (from Haala et al., 2004).

This makes possible to classify the various volumetric primitives and to define a priori the kind of polynomial of the subsequent parametric model (4.3) for the refined segmentation.
To classify and segment the dataset, a region growing method is applied, starting from a random point not yet belonging to any subset. The surrounding points having a distance less than the bandwidth are analysed, by evaluating the values of the estimated height Z_{0_i} and the values of the *gaussian* and *mean* curvatures. If the neighbour points present difference values within a threshold, fixed according to the laser noise, than they are labelled as belonging to the same class and putted into a list. The same algorithm is repeated for each list element, till this is fully completed. Afterwards, the procedure restarts again from a new random point, ending when every point has been analysed. Summarising, in this way a first raw segmentation of the whole dataset is carried out: hence, each cluster represents an initial subset to submit to the next refining segmentation step.

4.3. Refined segmentation by a parametric model

Previous authors paper describe in detail this step (Crosilla, Visintini and Prearo, 2004; Crosilla, Visintini and Sepic, 2005): it is based on the application of a Simultaneous AutoRegressive (SAR) model to describe the trend surface of each point cluster, and on an iterative Forward Search (FS) algorithm (Cerioli and Riani, 2003) to find out outliers. Starting from a point cluster detected by the region growing method (4.2), the FS approach allows to perform a robust estimation of the SAR unknown parameters, this for every object-cluster. At each iteration, one or more points are joined according to their agreement with the surface model. If some statistical diagnostics reveal an outlier incoming, the enlarging process is interrupted: the object-cluster is so bounded, hence a refined segmentation is achieved.

5. MODELING OF THE BASILICA MAIN APSE

First results of the modeling procedure applied to the points of the Aquileia basilica main apse are now shown. For such part, about 4,4 millions of points were acquired: they have been suitably resampled by the RiSCAN PRO tool so obtaining a dataset of 90.257 points, shown by RGB and by Z values in Figure 13. The Z coordinates represent the horizontal depth, modelized by (1). Other figures illustrate the local surface parameters after each step: Figure 14 shows the values of the *gaussian* K curvature by (4) and *mean* H curvature by (5), while Figure 15 the values of the *principal* curvature k_{min} and k_{max}.

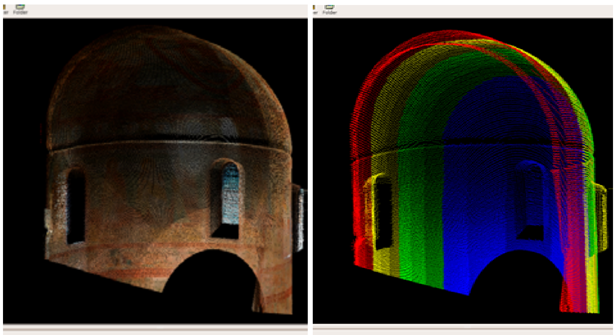


Figure 13: Apse points coloured by RGB (left) and by Z (right).

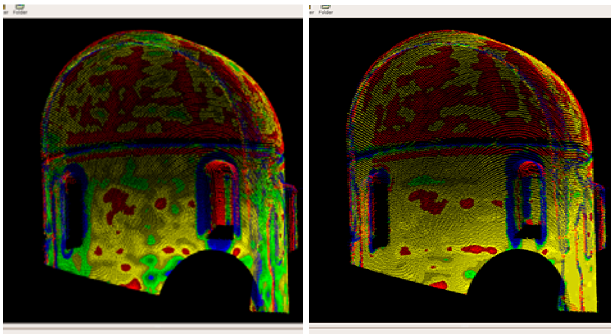


Figure 14: Apse points coloured by K (left) and by H (right).

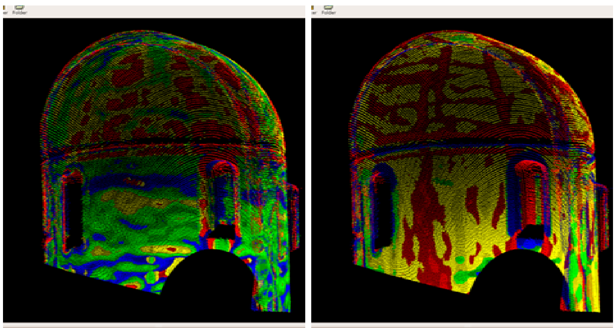


Figure 15: Apse points coloured by k_{min} (left) and by k_{max} (right).

By suitably considering altogether the previous values, the region growing method (4.2) yields a first raw segmentation, reported in Figure 16 at left: the bottom (orange) parabolic part, the planes (green) close to the window and the top elliptical (magenta) part have been exactly distinguished and classified.

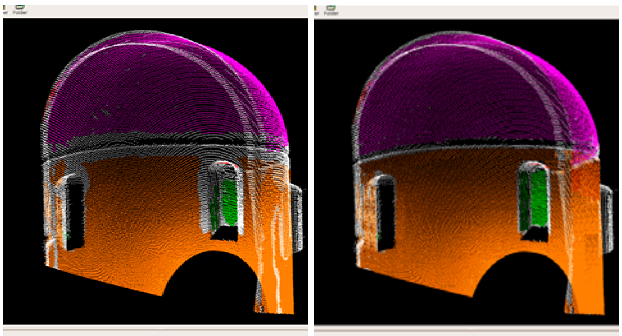


Figure 16: Apse points coloured by the clusters after the raw segmentation (left) and the refined segmentation (right).

At last, Figure 16 at right shows the clusters after the refined segmentation by means of the parametric model (4.3): the clustering is well improved just in the borders, where the values estimated by (2) can not be correct for the interpolating effect.

6. CONCLUSIONS

The challenge embedded in the modern laser scanning surveying technique is to bring the astonishing level of automation of the data acquisition into the data processing. Throughout this work, this automation has been evaluated for the survey of a very complex building as the Aquileia basilica, obtaining positive responses. The step of registration and geo-referencing of 20 different point clouds has been correctly and reliably solved in automatic way by the commercial software employed for. Concerning the fully automatic modeling of the main volumetric primitives, our original method has been briefly described and then numerically tested for the basilica main apse, with correct classification and segmentation results.

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