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3D LASER SCANNER AIMED TO ARCHITECTURAL HERITAGE SURVEY: FROM THE POINT'S CLOUD TO THE GEOMETRICAL GENESIS DETERMINATION

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ABSTRACT:

The present essay is a result of a wider research we are conducting at the Laboratory of Architectural Photogrammetry and Survey of Catania directed by professor Luigi Andreozzi. The research concerns the experimentation on the scanner laser methodology applied to the study, the analysis and the documentation of the architectural heritage.
The use of this new technology needs a critical approach in data acquisition and processing for a possible intervention aimed to study, document and represent the intrinsic characteristics of architectonic monuments. This is done to evaluate both the capacities enclosed by this methodology (high density cloud of points which describes exhaustively the morphology of spaces and objects of various shape and geometry, in situ surveying times' reduction, consciousness of instruments' accuracy, surveying procedures' real time checking) and the integration of obtained results with the other surveying methods to be useful in the dialogue between information users and information providers.
The case here presented concerns the study of the vaulted system which covers the so-called Small Refectory of the Benedictine's monastery in Catania, designed in 1739 by a clever architect, G. B. Vaccarini. Because of its peculiar shape, for quite a time this room have been the centre of scholar diatribes in order to find out the geometrical genesis of its planimetric outline and arched ceiling.
Research work has been conducted starting from the raw data which outcome from each single scan and applying different sofwares to elaborate the cloud of points in order to recognize studied surfaces geometrical origin, to build possibile virtual models able to document and express the geometrical-morphological-materical essence of the vaulted room analyzed.

1. INTRODUCTION

The perception of a "built" space, as we can see when dealing with an architectural organism, is pointed out by its shape, structure, in a word by its geometry, so that a traditional two-dimension representation is inadequate to represent the spatiality of a certain room or of a single object.
In particular, this happens when studying the geometrical nature subtending particularly complex elements' structure, as when analyzing vaulted systems. In this case, the use of 3D laser scansion has proved to be the better strategy in comparison with the traditional surveying methods, because of these systems' remarkable geometrical complexity and inaccessibility. Indeed, thanks to the quickness of the survey, the instrument's high precision and the possibility of detailing the surveyed points' density, we managed to obtain, in the shortest time, a vault numerical model rich in metric information which was useful to understand the geometric genesis of its surfaces .
Moreover, thanks to a survey in which the acquired points appear as space co-ordinates and each point displayed on the monitor screen represents an actual point, we were capable, since the data acquisition stage, of interacting with the three-dimensionality of the numerical model obtained, by rotating it into the computer virtual space and by observing it from different points of view.
By using different kinds of software in data processing, we extrapolated from the 3d model all the information (cross-sections, profiles, contour lines, 3D views) suitable for the determination of the studied element's geometrical and morphological features, in order to reconstruct the former geometrical idea by critically and interactively analyzing the approach with reality.
Besides, in the case of vaulted systems, graphic tracing and building techniques are strictly interlaced; so it was essential to make reference to the handbooks of the period in order to carry out all the explanatory hypothesis fit to recognize the analyzed surfaces' geometrical genesis.

2. A CASE OF STUDY: THE BENEDETTINI'S MONASTERY REFETTORIO PICCOLO VAULTED SYSTEM

The aim of this study is to set out accurately the geometrical structure of the Benedettini's Monastery Refettorio Piccolo vaulted system, placed in Catania. For a long time, this structure has been the object of an inflamed discussion among eminent scholars expressing discordant opinions as regards the

Figure 1. Hyposcopic view of the vaulted system

geometrical nature of the plan, of the vaulted surface and lunettes intrados.

The Benedettini's Monastery was re-built by arch. Antonino Amato immediately after 1693 earthquake that razed to the ground most of the city's buildings. In 1739 arch. G. B. Vaccarini took the place of arch. F. Battaglia who had had some incomprehensions with the client monks. Vaccarini planned and realised the monastery north side that includes the Refettorio Piccolo, the Refettorio Grande and the Antirefettorio. Just for these refectories, he designed two oval plan rooms covered by a domed vault and lighted by lunettes which start from the vault's springer (Fichera 1934; Giarrizzo 1990).

We can enter the Refettorio Piccolo room through two entrances placed along the major axis whose dimension is of 15.80m (equal to 80 palmi, unit of measurement of the period), while the minor axis is of 13.50 m (60 palmi) and the maximum height referred to the keystone is about 13.10 m.

2.1 Data acquisition and processing

In order to study this object geometrical complexity it was necessary to use specific procedures of surveying, highly accurate instrumental methodologies which result in a set of points made of known spatial co-ordinates: they make real the inquired surfaces' three-dimensionality thus giving data for a global evaluation.

On the other hand, by analyzing the existing survey graphics (dated 1979), we found out that they were not adequate to describe exactly the vaulted system's geometry.

In this case Laser Scanner LPM-25HA, made by Riegl, has been used; it is based upon the time-of-flight (TOF) measurement of a short laser pulse which is optimized in order to perform short distance measurements (from 2 to 80 m) with the highest accuracy (0.009 degrees).

Considering the surveying room characteristics and the available instruments specifications, we managed to shoot the whole vaulted system from a single scanning point, placing the scanner in a barycentric position in comparison with the span to be surveyed. So that it was possible to carry out different scanning sessions with a differentiated points' density related to the kind of surveying surfaces, all that in order to obtain a better data management during the following processing step.

Indeed, by using this instrument and setting a single scanning position, the point clouds captured from the same scanning position were automatically and accurately aligned to a common co-ordinate system. This way, it was possible to process the data "piece by piece" in order not to overload and reduce workstation calculus and display power.

In particular, we carried out one scanning session of the upper vaulted room applying a medium resolution (step width equal to 1,3 cm along the horizontal plane and fluctuating along y and z axis in relation to the vault bending ray) in order to extrapolate, from the surveyed points' cloud the geometrical elements necessary to quickly accomplish the subsequent processing. A different scanning high resolution session (step width equal to 1 cm) was performed to acquire the decorative motif details (friezes, volutes, windows' and doors' timpani).

We weren't able to acquire the whole room ambient, from floor to ceiling, because of the presence of tall shelves leaning against the wall (the Refettorio Piccolo being included in Ursino Recupero Civic Library).

The gained raw data (cloud of points) provided a first representation of the surveyed room rather suggestive and realistic because they re-established, in the computer virtual space, the three-dimensionality of the real object: each point displayed on the monitor screen represented an actual point, surveyed and saved into the file.
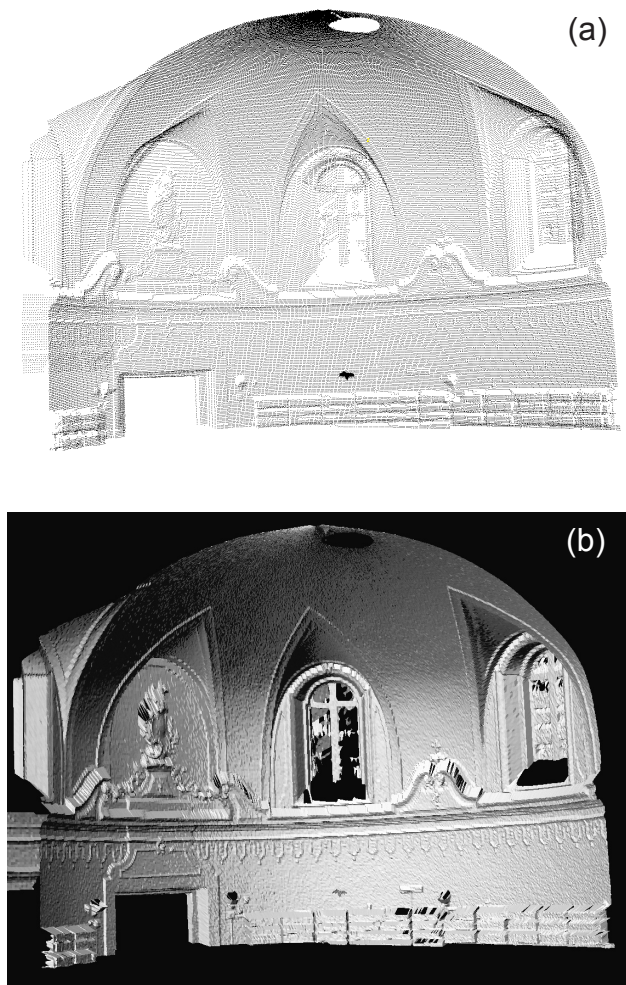

Figure 2. Data acquiring step

Figure 3. Different kind of the 3D model visualization: (a), the points' cloud; (b), rendering image
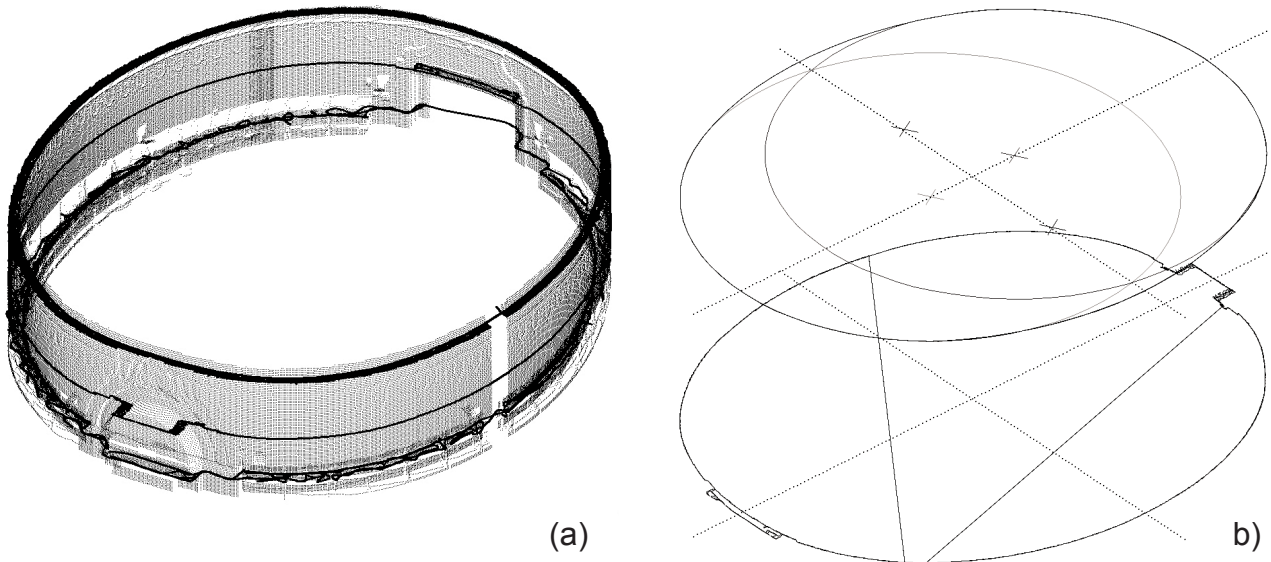
(a)

b)

Figure 4. Determination of the plan geometry. (a), profiles extrapolation from the numeric model (points'cloud); (b), subsequent analytical-geometrical interpretation

Through subsequent steps raw data were checked according to the points distance and intensity, cleaned and filtered in order to reduce noise and remove invalid points.

2.2 3D virtual model analysis

The three-dimensional model so obtained is a digital copy of the real object: it represents an accurate and reliable documentation (the accuracy of measurement is ensured by instruments precision), which allows its analysis and control, as well as its measurement and the evaluation of the dimensional features of all surveyed parts.

Furthermore, it provides the basis for the development of traditional (extracting plans, front views, sections in each point and according to the led study) and three-dimensional (meshes, orthophoto) elaboration, with the advantage, in this case, of being immediately perceived and understood even by not expert people.

The first aim of the research was to recognize the geometrical shape of the vaulted system, to understand its generating rules.

A set of data so full of information allowed us to propose various interpretative hypothesis on shape genesis, suppositions that, if checked, permit to go back to the project aims and to re-build, through mathematical algorithms, the ideal model which corresponds to the shape conceived by the architect (Docci, Gaiani, Migliari, 2001; Migliari, 2001).

Moreover, the numeric-real model in comparison with the ideal model may supply precious information and permits to carry out exact controls (localized settlements, straining, etc.) useful to a possible recovery intervention.

The processing was leaded step by step using different software, specific or not, capable of extracting the essential elements for the analyzed surfaces' mathematical description: the first step was to determine the plan geometry, afterwards we studied the geometrical genesis of the vault's intrados and lunettes.

To recognize the plan geometry, we extrapolated some section-profiles (2d polylines) by sectioning the cloud of points with horizontal planes, and used them as a basis for the geometrical study: it is a polycentric oval whose bending rays differ in a few centimeters (1,5-2) in comparison with the ideal curve.

To re-build the vault's geometric model in the computer virtual space, it was necessary to comprehend the mathematical law which subtends its shape; in this specific case, it was basic to go back, through a handbooks' detailed study, to the building techniques used for tracing the basin vaults' intrados and then find out the mathematical algorythm capable of describing this surface making use of computer.

As a matter of fact, Donghi writes, "*le volte a bacino, o a calotta o a cupola semplice si adoperano per coprire spazi circolari, ellittici od ovali. La loro superficie di intradosso suole essere [...] un mezzo o una porzione di ellissoide od ovaloide di rivoluzione, [...] un ovaloide o un ellissoide a tre assi quando l'area è un ovale*" (Donghi, 1925).

So, it was necessary to understand if it were an ovaloid of revolution or a three axis ovaloid.

Sectioning the numeric model by vertical planes parallel to planes passing through major and minor axis, along both directions, we found out curves assimilable to ovals. If the intrados surface had been an ovaloid of revolution, the sections through planes parallel to the rotation axis should have been ovals, whereas the ones through planes orthogonal to the rotation
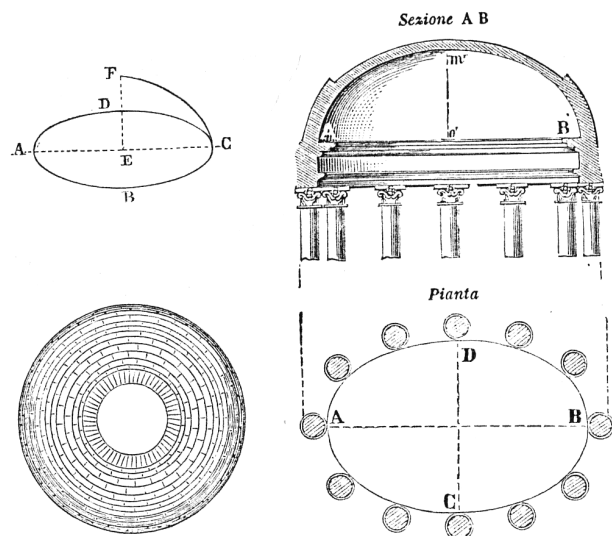

Figure 5. The tracing rule of a three-axis ovaloid (from Donghi's *Manuale dell'Architetto, 1925*)

axis should have been circumferences: it may hence be inferred that the intrados surface is a three axis ovaloid.

We still had to recognize the mathematical law corresponding to the building rules according to which the intrados of a such surface was carried out in a building yard.

Once again, it was Donghi's *Manuale dell'Architetto*, in the chapter concerning the building yard methodologies for bacin vaults' graphic construction and tracing rules, to suggest a possible solution: beginning from the realization of the vault's rise (half of the third axis), the subsequent longitudinal section along major axis (bending) and the transversal section along minor axis, the three axis ovaloid construction is the geometrical locus of all semi-ovals which take form by intersecting with transversal planes the basic oval (vault's springer) and the semi-oval which constitutes the vault's bending (longitudinal section). Hence, the intrados surface would be the different transversal sections adjoining (set at a constant distance from the others in order to ensure the fillet continuity), which corresponds to the centre frameworks set in the building yard.

The mathematical algorythm that 1) interpolates generatrix curves placed on a set of parallel planes, 2) forms a set of directrices and 3) plots the surface is the so called lofting one.

According to these remarks, we extrapolated from the numeric model different transversal sections with a constant stepwidht (25 cm); beginning from the real profiles, we re-constructed the ideal curves (the semi-oval transversal sections) which had been the basis for the generation of the mathematical-ideal model.

After building the ideal geometrical model, the two models (the real and the ideal one) were compared in order to verify possible analogies and differences: on the one hand the reality of the surveyed cloud of points, whose space co-ordinates describes the real object in CAD virtual space, on the other its mathematical abstraction.

Through some superimposition (overlay) and sectioning both by horizontal and vertical planes (along the major and minor axis), we succeeded in verifying the shifting between the real object and the ideal model of reference, so that we could advance preliminary hypothesis concerning these anomalies' reasons. We noticed both bending variations due to tracing errors, and localized depressions owing to the strains caused by collapses due to the passing of time.

After settling the geometrical shape of the domed vault, we felt the urgency of studying the lunettes geometry in order to accomplish the mathematical-geometrical model.

Lunettes' geometry has been determined by extracting different profiles from the cloud of points along planes passing through diagonal arches, parallel to planes passing through the springer arch and orthogonal to it.

Once more, building techniques assisted us: indeed, the groin was carried out after settling springer and diagonal arch, so that the lunette vertex would be higher than the key-stone arch. The result was a ruled surface with director plane vertical and orthogonal to the plane passing through the springer arch: each section practiced with planes parallel to the principal plane is formed by the segment which joins the two points individuated from that plane on the springer and the diagonal arch.

2.3 Decorative elements modeling

After obtaining a geometrical-mathematical reconstruction of the analyzed vaulted system, the following step was to study and represent the stylistic-formal elements (friezes, decorations, mouldings, volutes) which contribute to architecturally set out and connote the Refettorio Piccolo's room.

They are sculptural decorative motives whose generating mathematical law can't easily be found; these motives, for the detail accuracy and the surface's complexity can be well
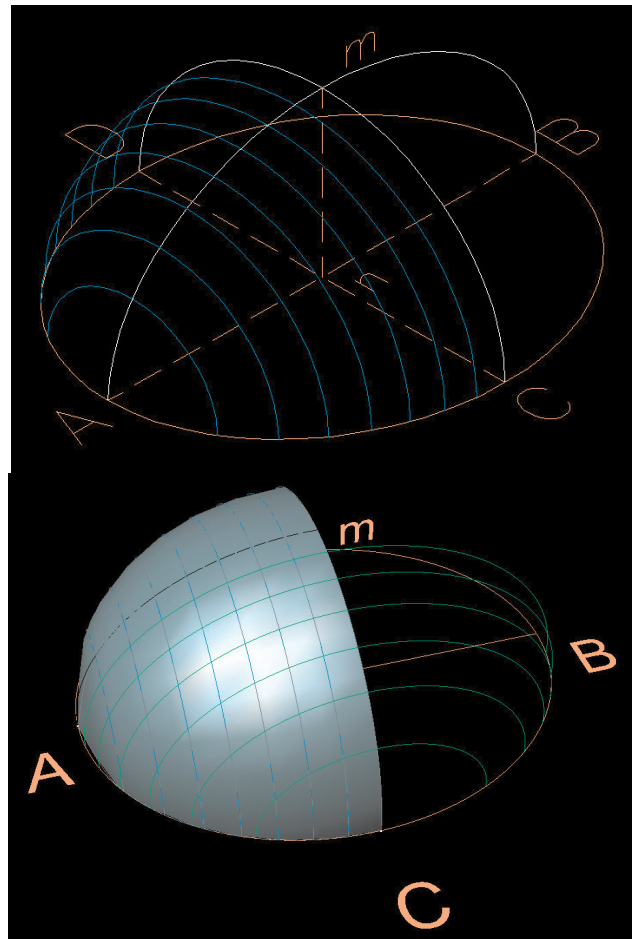

Figure 6. Mathematical interpretation of the possible tracing rule of a three-axis ovaloid
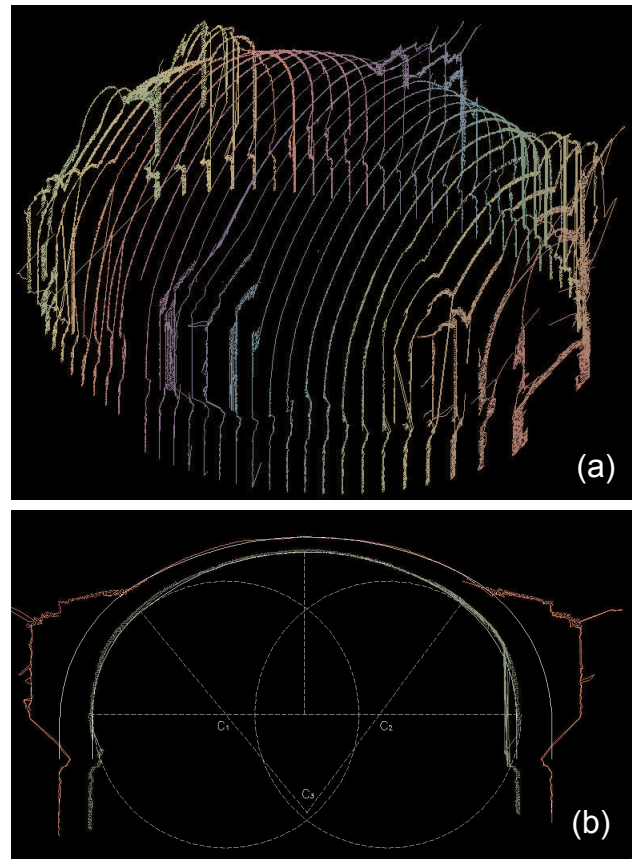

Figure 7. From the numeric model to its geometric abstraction: (a) real profiles extraction; (b) ideal curves tracing
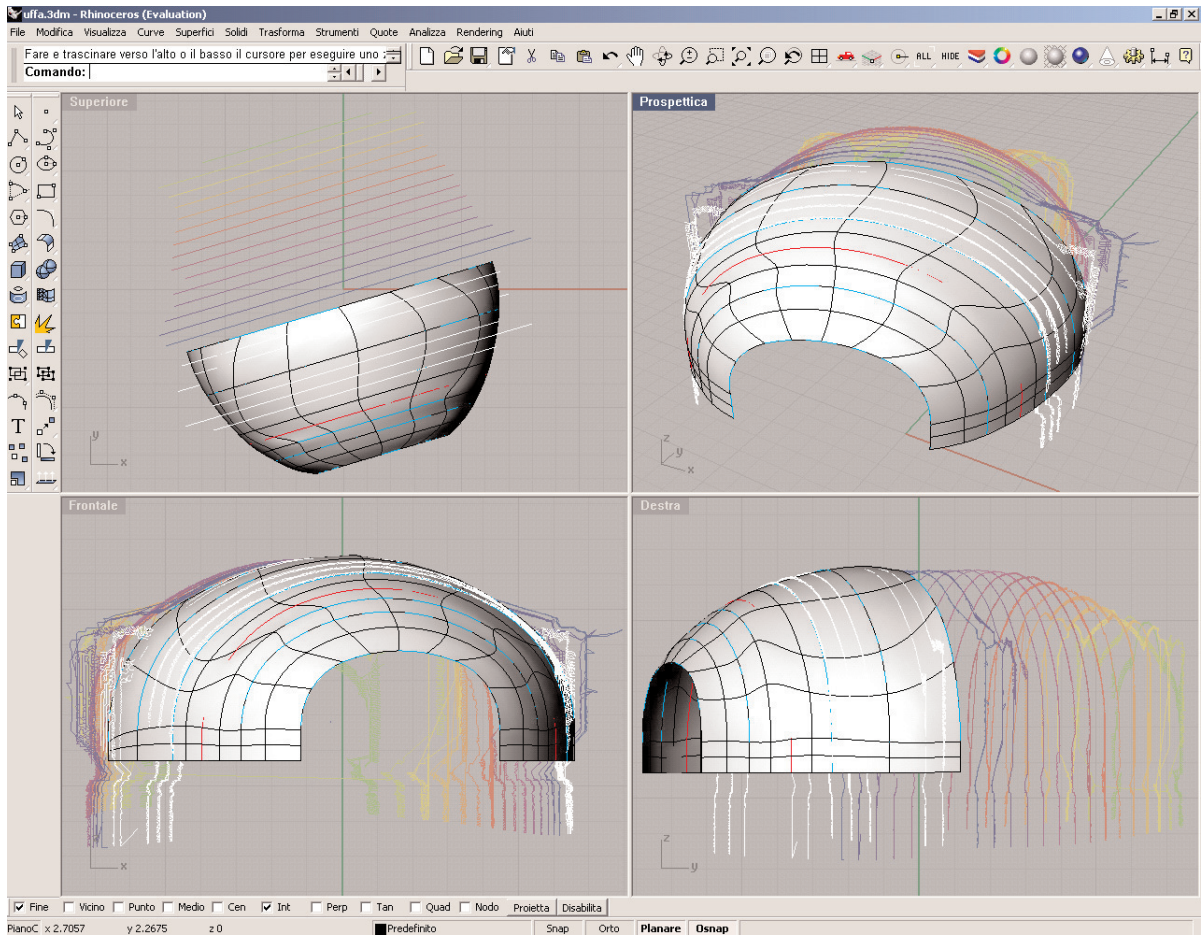
Figure 8. Genesis of the lofting surface corresponding to the vault's intrados
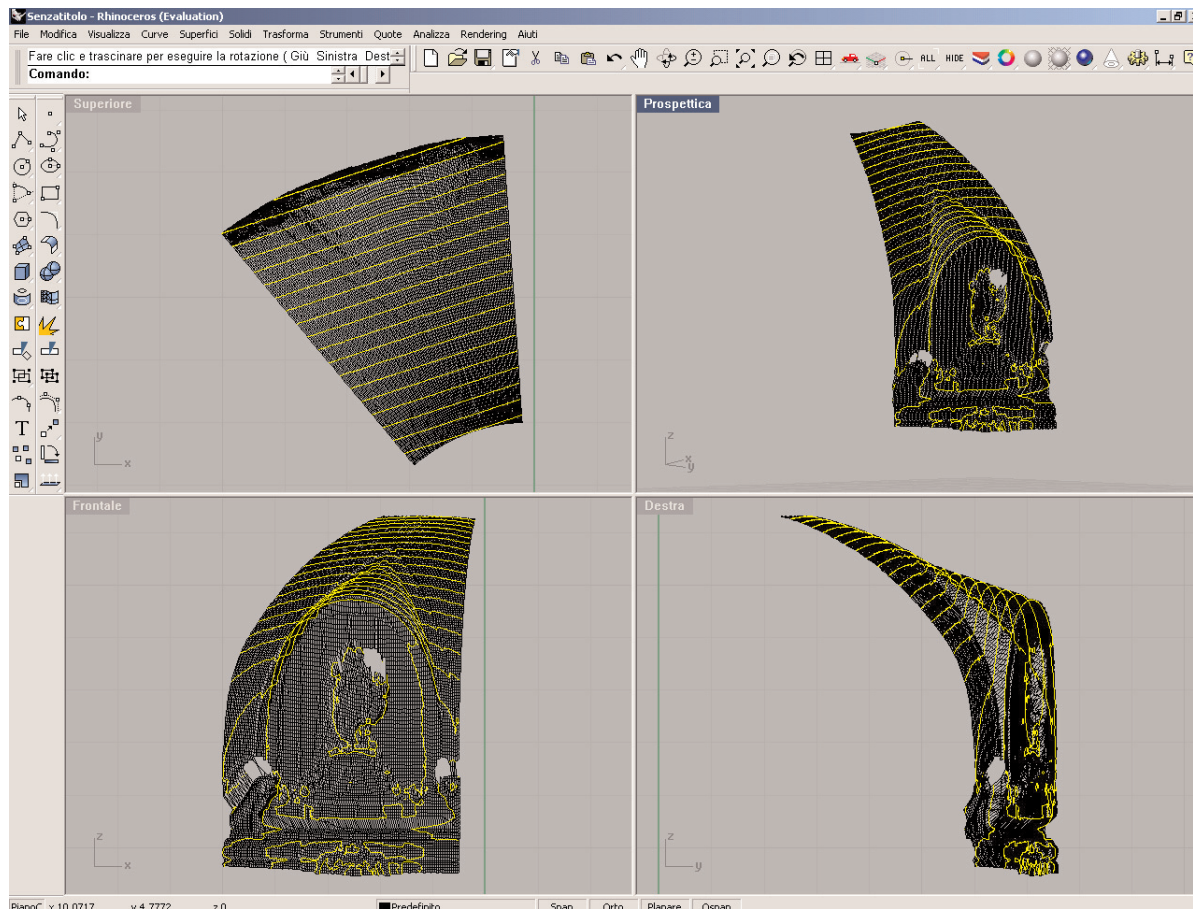

Figure 9. Extrapolation of transversal profiles from the lunette triangulated model

approximated and graphically represented by using mesh surfaces (triangle one). In this way creating a triangle for each adjacent trio of points the effect is to generate a coherent visual surface beginning from a discreet point cloud model.

In this step, data has been elaborated using JRC Reconstructor software by Inn. tec. srl.

Setting pre-processing and triangulating parameters (such as mesh triangle dimension, number and density) according to drawing surfaces features, it was possible to obtain a good sculptural elements' representation and documentation, simplifying surfaces without losing decorative and plastic details.

The holes due to missing data (the pronounced sculptures overhung hided the visibility of some object's portion) could be filled with additional scanning to complete the surveyed model. However, where possible, they were filled through proper algorithms which automatically created triangles in the shadow areas.

The method was useful to explore the vaulted system spatiality, choosing different points of view and the best kind of mesh's visualization (wireframe, flat or textured), according to the analysis to be carried out.

The acquisition of material, chromatic and degraded data was obtained through the projection of the photographic images on respective point clouds, collimating several well distributed and visible equivalent points and the successive application of the projected images on the continuous mesh model, in order to take the best advantage from the high resolution of photos.

3. CONCLUSIONS

The research developed up to now has permitted to use laser scanning and the subsequent 3d digital model in a critical and optimized manner. The result has been: on one hand the possibility of a documentation exclusively aimed to the accuracy of measurement and to the punctual reproduction of the studied object, on the other one the opportunity to formulate different hypothesis on the shape genesis in order to simulate and to recognize the project idea (Migliari, 2001).

Therefore the study will be prosecuted towards the definition and realization of possible virtual models apt to document and convey the geometrical-morphological essence and the formal outline of the inquired vaulted space.

In fact, through the synthetical view given by a digital 3D model an immediate approach to the object is assured so as to make easier both its communication and understanding even to not-expert people.

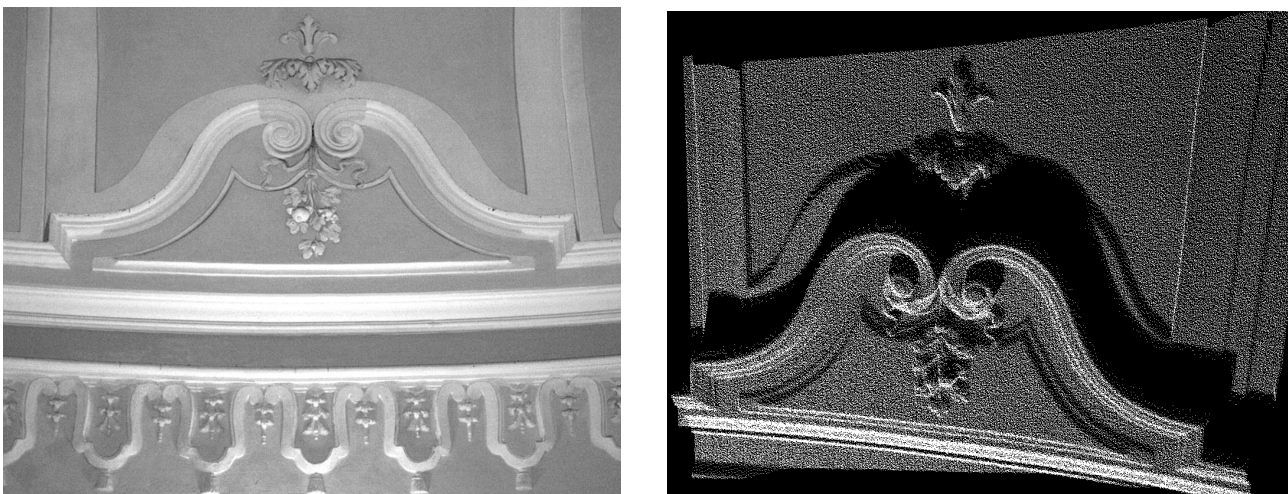Figure 10.Groin detail: (a) photographic image; (b) rendering image

Figure 11. Decorative motif detail. The suggestive representation by means of point's cloud (b) compared with the photographic image
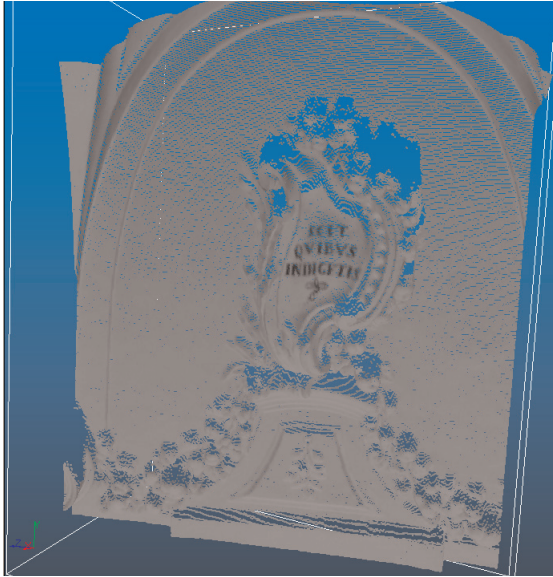
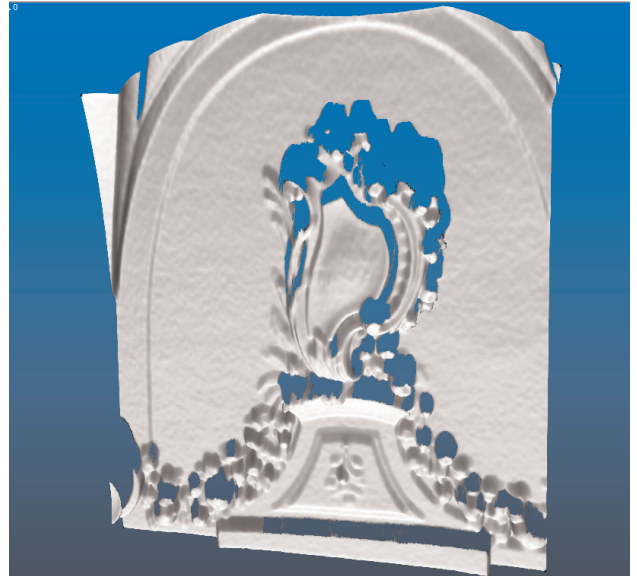Figure 12. Decorative motif cloud of points

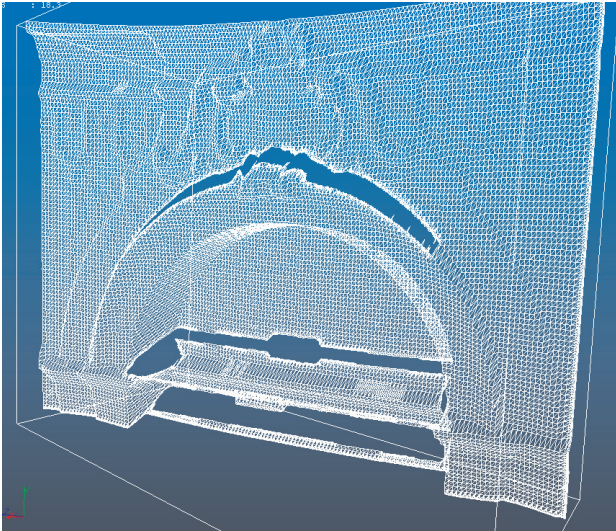Figure 13. Decorative motif map shading model

Figure 14. Decorative motif wireframe model

Figure 15. Decorative motif map shading model

Figure 16. Decorative motif map shading model

Figure 17. Decorative motif textured model

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