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ROCK HEWN ARCHITECTURE SURVEY: THE PROBLEM OF CONSTRUCTION OF THE GEOMETRICAL MODEL

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Abstract
This article is focused on the transformation of the numerical data from laser scanning or image-based modeling in a geometrical model based on known geometric forms. During an international research on rock hewn architecture in Italy and Cappadocia, we made laser scans of some important medieval rock hewn churches. Once the phase of data acquisition is concluded, it is usually followed by the creation of a numerical model (points or mesh) which describes the morphological state of the subject. It is however known that survey is not a mere "registration" of data, but it is a "critical" operation of interpretation that shows the features considered necessary by the surveyor to describe a certain aspect of the subject. An operation usually made on the numerical model is its translation in geometric model: cubes, cylinders, tori, figures generated by translation or rotation; the subject is divided in elements which help its spatial understanding and may show the formal intention of the design process. However, while "built" traditional architecture - realized by elements overlapping - is more easily referable to simple geometric forms, rock hewn architecture, like sculpture, is realized by subtraction of material, and needs the identification of forms "similar" to known elements (vaults, floors, ramps, etc.), to allow the recognition of its forms. In the "translation" of the rock hewn form, into geometric model we therefore need to find a suitable form of geometrization. On the base of the numerical models we want to investigate on the creation of simpler geometrical models which allow the morphological analysis and the comprehension of the physical realization, based on a "geometric" project, in the field of rock hewn architecture.
Keywords: survey, laser scanner, point clouds, mesh, 3D geometrical model, Göreme.

Riassunto
Questo contributo si focalizza sulla trasformazione dei dati numerici provenienti da scansione laser o fotomodellazione in un modello geometrico basato su forme geometriche riconoscibili. Nell'ambito di una ricerca a carattere internazionale sull'architettura rupestre in Italia e in Cappadocia, si sono eseguite le scansioni laser di importanti chiese medievali scavate nella roccia. Una volta conclusa la fase di acquisizione dei dati, questa è, di prassi, seguita dalla formazione di un modello numerico (di punti o mesh), che descriva lo stato morfologico attuale del soggetto archittettonico. E' tuttavia noto che il rilievo non consiste nella semplice operazione di "registrazione" dei dati, ma è un'operazione "critica" di interpretazione, che rende manifesti gli aspetti che il rilevatore ritiene necessari a descrivere un aspetto del soggetto. Un'operazione di solito effettuata sul modello numerico è quella (non sempre esplicita) della sua traduzione in modello geometrico: cubi, cilindri, tori, figure generate per traslazione o rotazione; il soggetto viene scomposto in elementi che ne consentono la comprensione spaziale e ipotizzano le intenzioni formali della progettazione. Mentre però l'architettura 'costruita' tradizionale - realizzata per sovrapposizione di elementi - è più facilmente riconducibile a forme geometriche semplici, l'architettura rupestre, come la scultura, è realizzata per sottrazione di materiale e necessita dell'individuazione di forme "simili" a elementi noti (volte, pavimenti, rampe, ecc.) perchè se ne riconoscano le forme. Nella "traduzione" della "forma rupestre" in modello geometrico si presenta quindi la necessità di stabilire una forma di geometrizzazione adatta. Sulla base dei modelli numerici si vuole pertanto indagare sulla formazione di modelli geometrici sempre più semplici che permettano l'analisi morfologica e la comprensione della realizzazione fisica basata su di un progetto "geometrico" nel campo dell'architettura rupestre.
Parole chiave*: rilievo, laser scanner, nuvole di punti, modello geometrico, Göreme.*

Introduction

The transformation of numerical data from laser scanning in a geometric model based on geometrically recognizable shapes is a well known problem for those people realizing the complexity of architectural survey, that is not only limited to using the current tools of measurement.

This paper deals precisely with the issues related to the post-production phase, which serve as a bridge between the scan and the representation of architecture.

The work is realized in the framework of a research started since 2007 in Cappadocia under the guidance of Prof. Maria Andaloro.

In particular the practical applications are carried out on the case of a rock hewn church in the Open Air Museum in Göreme (Fig.1), the Kizlar Kilisesi: the church of the girls.

The Open Air Museum is an aggregation of small groups of 20-40 people. Each group, independent from the others, is distinguished by a number of autonomous rooms: a religious place (church or chapel); a refectory; a kitchen; service spaces for the conduct of activities during the day and for resting.

The historical hypotheses contribute to date the settlement between the tenth and eleventh centuries, as the moment of maximum glory of this great monastic

Fig. 1: the Open air Museum in Goreme. The red dots evidence investigated churches (image by M. Carpiceci).
Fig. 1: il museo all'aperto di Goreme. I punti rossi evidenziano le chiese analizzate (immagine M. Carpiceci).

city, with an ordered community of autonomous nuclei of various sizes, but all belonging to a single general organization. In the exedra the largest community is that of the Karanlik Kilise. With smaller dimension, but equally important from the iconographic and architectural point of view, is the Çarikli Kilise. In the cones in front of the semi-cycle, there are Santa Barbara, Elmali Kilise and St. Basil. A larger cone, finally, could have been used as the female community. Inside there is the Kizlar Kilisesi (church of the girls) taken as a model of analysis.

Criteria for the geometric interpretation

A laser scanner, like the FARO Focus3D 120, is able to scan its surroundings at a speed close to a million points per second. The parameters which can be set are Resolution and Quality.

Resolution defines the speed of the rotation around the zenith, that is the quantity of scan meridians that the instrument is able to record within 360°, although it in fact performs a rotation of 180° measuring each meridian together with its opposite. The higher definition implies a density, on the horizon, of approximately 41000 points, whilst the longitude between a point and the next one is a little less than 1/100 of a degree. The distance between the points on the horizon varies with the distance; thus, we will have a scan every 1.5 mm at 10 m, up to a distance of 1.5 cm at 100 m.

The second parameter is Quality, which is mainly based on repetition and mediation of the measurement. In this way at each subsequent measurement of the same point there will be a consequent increase in the precision of the radial distance from the instrument and an equally increase of the scanning time even up to almost 2 hours.

The morphology of rock hewn architecture rarely needs very high increase. In order to limit and optimize the on-site operations, within the caves up to 10 m of distance a resolution of 5000 points can be obtained on the horizon for a point-to-point distance of 1.2 cm, while for the outside, up to distances of 20 -30 m, you must avoid to fall below the 10000 points that at 30 m produce a resolution of about 2 cm.

We must also consider that the resolution on the horizon is the minimum one, since increasing the latitude (towards the poles) the distance between the meridians decreases; processing software, however, proportionately decreases the number of points for each parallel in order to make the distribution of points regular in the cloud.

Further, it is known that, while using a total station only a few significant points of the architecture to survey are measured, with a laser-scanner all the points

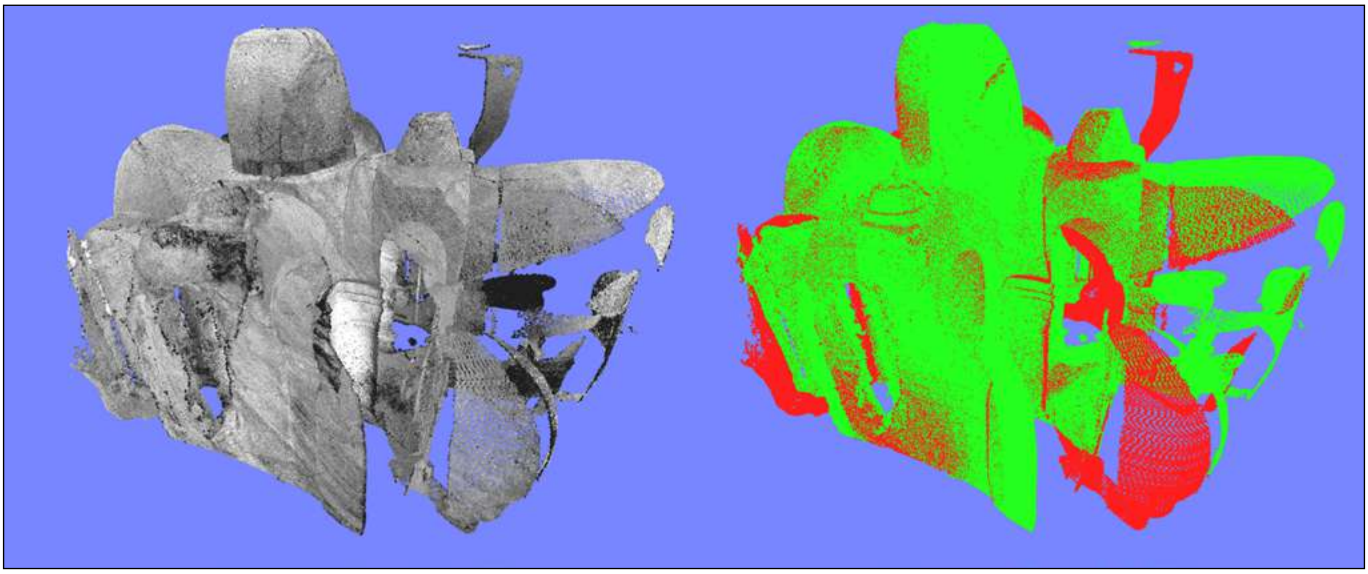

Fig. 2: point clouds are normally affected by discontinuities caused by the approximation of the error. The ICP algorithm reduce the gap of two or more point clouds but does not solve the problem (image by A. Angelini).
Fig. 2: le nuvole di punti sono normalmente influenzate da discontinuità dovute all'approssimazione dell'errore. L'algoritmo ICP ridurre il gap di due o più nuvole di punti, ma non risolve il problema (immagine A. Angelini).

Fig. 3: the panoramic view represents the 2D editable point clouds. Due to the geometry of the image it is possible to modify accurately the central band and not the marginal part (image by A. Angelini).
Fig. 3: la panoramica rappresenta le nuvole 2D di punti editabili. Grazie alla geometria dell'immagine è possibile modificare con precisione la fascia centrale e non la parte marginale (immagine A. Angelini).

of the vertex of a spherical network are recorded. The more dense is the network and the more likely it will be possible to reconstruct the morphology of the subject, despite the (almost certain) lack of the characteristic points.
From the numerical model (made of points) one usually passes to the geometric model, or, better, to the reconstruction of the simple (or complex) geometries capable to describe and understand the subject (Bianchini, 2001, Bianchini, 2007, Carpiceci, 2013a).
This task is long and complex since it involves an interpretation from those who build the geometric model, an operation that is performed in post-production after the scanning procedure, while it was performed on the site in case of a topographic survey.
As an example, we can consider the shaft of a column. All surveyed points will return a pattern of vertices and meshes vaguely recalling a cylindrical shape that will be interpreted as column.
The careful study of the distribution of the points brings, in the following phase, to reconstruct a vertical profile that goes from “imoscapo”, the lower cylindrical portion, to the portion tapered by entasis to the “sommoscapo”.
The rotation of this profile will produce the rotation solid identifiable with the surveyed shaft of the column and described by its geometric components. With a traditional survey we would have measured only a few points, the characteristic ones, able to describe that generator profile.
The decimation is one of the fundamental operations that can aid the elaboration of point clouds. This operation (not always obvious and expected) consists in an accurate elimination of excess vertices or redundant points that are not useful to the morphological interpretation. The most obvious example is a flat wall, in which few points can generate the same geometry of a density of one point per square centimeter. The decimation and the resulting mesh can simplify the model, maintaining however its legibility. The homogeneous decimation applied to the whole records produces a proportional reduction in the points usable only for a lightening and fast use.
However, when the decimation should minimize the loss of information, this must be proportional to the formal variation. Incidentally it must be remembered that the raw measures should always be the starting

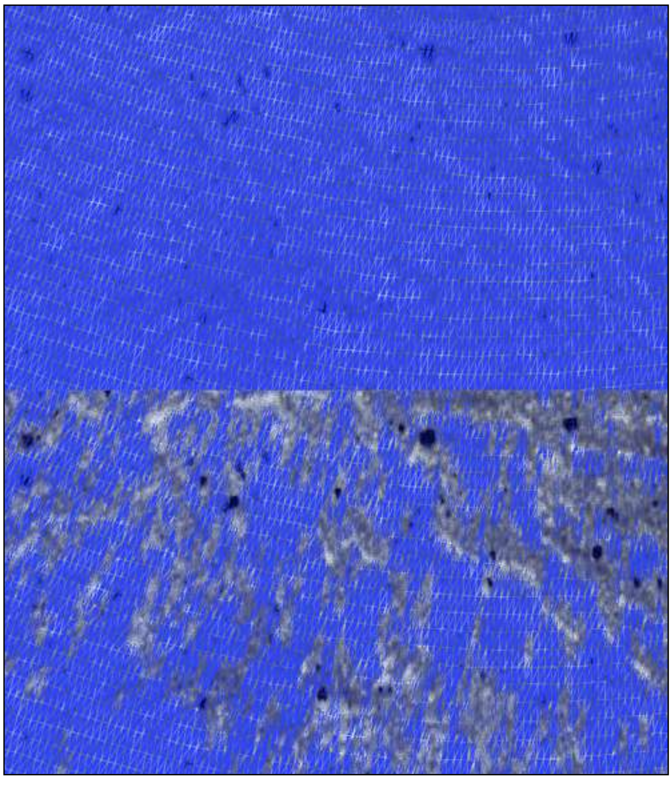

Fig. 4: modifying the value of the angular discontinuities it is possible to get a surface much more defined (image by A. Angelini).
Fig. 4: modificando il valore delle discontinuità angolari è possibile ottenere una superficie molto più definita (immagine A. Angelini).

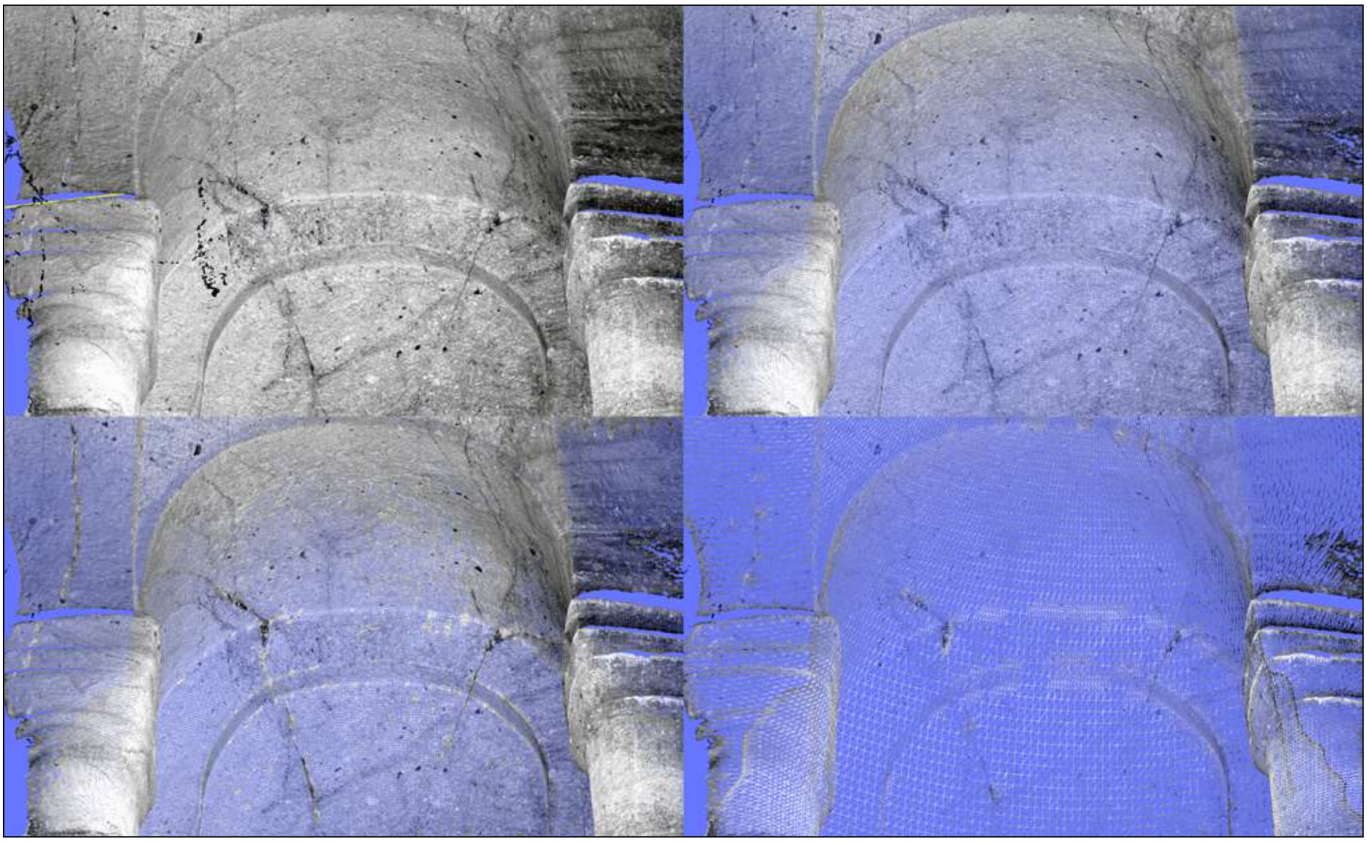

Fig. 5: the image represents the application of different filters for the generation of the multi resolution mesh (image by A. Angelini).
Fig. 5: l'immagine rappresenta l'applicazione di differenti filtri per la generazione di griglie multi risoluzione (immagine A. Angelini).

point for any operation of 'post-production' in order to keep the possibility to check and verify these elaborations, starting from the data acquisition on the field.

Imagine a series of points that describe a profile made of segments, curves and corners.

The numerical model provides a set of scanned points in respect of the resolution set.

A first visualization of this profile can be provided by drawing a line made by linear segments whose vertexes are the scanned points. In this way we can represent with sufficient efficacy the rectilinear parts, but the curved parts will also be defined by linear segments and the corners will be truncated, unless a measured point lies directly on the discontinuity. So the profile is better described by a curve "interpolated" among the vertexes.

The curve remains a valid representation even after the decimation of the points, especially in curved parts where the line made by linear segments could considerably move away from the dense part of the profile made of points .

The edges do not exist in the reconstructions from numerical models; their 'approximation' can be defined by the proportional decimation. A possible algorithm is based on the control of sequences of points.

Imagine to follow the trend of a polygonal chain; if 4 consecutive points lie within a band of rectilinear of minimum thickness defined as 'null', the points inside the band can be reduced to only one and it will be possible to mark for the 3 points a curved section with a radius tending to zero.

If the 4 points lie in a circular crown of minimum thickness defined as 'null' the points inside the band can be reduced to only one and it will be possible to mark for the 3 points a curved section with a defined radius. By comparing the decimated sequence and the raw data it is possible to control where to apply further iterations until the complete maximum decimation without loss of morphological information.

The expressed theory holds true even when we move from two-dimensional layer to three-dimensional space, through a simple transformation of geometric entities from points, segments and curves in points, segments, planes and surfaces.

General considerations about the point clouds registration and the meshing process

This part illustrates the elaboration key frame carried out on the investigated 3D models, at the same time aiming at evidencing some considerations on the elaboration methods and the related problems in the post-processing actions. Most people think that the elaboration process is often accomplished after merging point clouds and after the section and projection operation on the models, moving to interpretation phase only in a second phase. The interpretative phase coexists and determines the choices during the elaboration step. The merged point clouds are not the final results, but the beginning of a series of procedures aimed at the realization of understandable digital models, especially in contexts such as rock hewn architectures where the complexity of the surfaces makes difficult a correct description and interpretation

Fig. 6: the mesh model carried out with the application of different filters (image by A. Angelini).
Fig. 6: il modello di griglia è realizzato con l'applicazione di diversi filtri (immagine A. Angelini).

of the architectural characteristics. In most cases, the transformation of the data from point clouds to surfaces is made in order to display digital models on which photographic images at high resolution are projected. The next results are then represented by orthographic outputs of plans and elevations.

In this research the goal was to reconstruct digital models starting from the interpretation of the surveyed point clouds, through the meshing technique and the extraction of the main cross sections, as well as by the aid of a modeling cad software. It is necessary to make the following considerations: the overlap of the point clouds normally generates distinct surfaces, belonging to each cloud. The resolution of the models has been maintained to the original, even though, they have been lightened through the sampling procedures. The point clouds has been mapped with the reflectance rather than internal images, thanks to the high quality of this value.

The first step was to carry out homogeneous point clouds with a very low standard deviation. The actual laser scanner management software are now equipped with ICP algorithm (*Iterative Closest Point*) that starting from a pre-registration data, analyzes the homologous and closest points of two or more scans, rotating and translating them and repeating this operation several times until the achievement of an accurate standard deviation. The overlapped point clouds on one hand increase the accuracy of this algorithm and reduce the distance of the gap, but they do not eliminate it entirely, indeed the problem is well visible both when we associate different color to each scan and when we visualize on the monitor specific areas that contain discontinuity (La Mantia, 2013; Fig. 2).

In order to avoid overlaps that may alter the continuity of the cross sections, it is necessary to clean the clouds reducing the areas of data redundancy. One of the peculiarities of the software (JRC Reconstructor) consists of changing view, passing from the model in 3D space to the model represented in 2D by using a panoramic image that represents the point clouds (Fig.3).

Each selection has the dual purpose of eliminating and keeping the data depending on the individual choices. The double transition from the virtual space to the dynamic image allows to reduce with high accuracy the areas of redundancy between two or more point clouds. Against an increase of the processing time, the advantage of this procedure allows to obtain accomplished models well-finished in every part. The next step was the meshing procedure due to the heaviness of the point clouds. It transforms a set of points in a 3D surface consisting of triangles which connect together the various points, as a function of a series of parameters that can be modified by the user (Ippolito et al. 2013). Normally this procedure is automated without analyzing the filters and the different results that can be reached. The meshing process is certainly useful for projecting images on the model, but at the same time it serves to lighten the point cloud, to relate the disconnected points in connected and continuous elements, and to allow metric and volumetric operations. One of the aim of this procedure was to triangulate surfaces, applying the reflectance resolution, much more defined. The mesh generation is variable and depends on the point

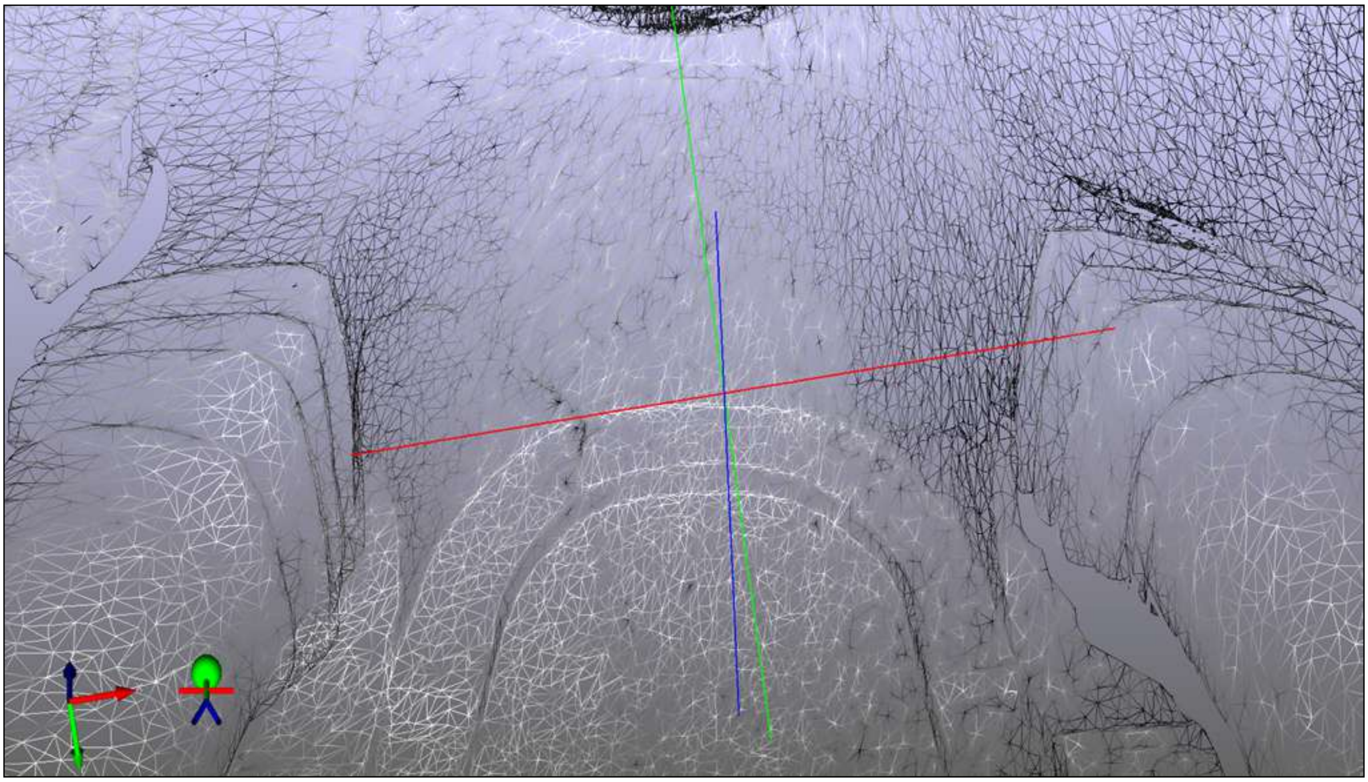

Fig. 7 A decimation of 10% of the triangles can change significantly the weight of the model even if the it maintains the same geometry (image by A. Angelini).
Fig. 7 Una decimazione dei triangoli del 10% può cambiare notevolmente il peso del modello pur manenendo la stessa geometria (immagine A. Angelini).

clouds definition, but above all on the filters for the definition of the triangles. The filters must be modified in function of the surveyed structure. It is therefore important to carefully choose the values of the filters to have a correct approximation of the surfaces. Among the many parameters for the determination of triangles, such as the resolution and the accuracy, there are two important parameters that determine relevant differences in the surface composition (Sgrenzaroli et al. 2007). The first algorithm is the depth discontinuity, that estimates the distance of the points according to their default values, distinguishing different objects placed on different planes, indeed, the filter determines the difference among the various objects in the visual field of the scan. The other parameter is the angular discontinuity that analyzes the difference of angles between two different points by using the normal information estimated during the pre-processing operations. For instance this filter allows to define different walls of a room. The value of angular discontinuity is very important in the reconstruction of the geometry of triangles, especially if we consider the discontinuities in the rock hewn architecture (Fig.4). The value can be shifted, thus significantly changing the result of the final surface even if we have to set it in function of the representation scale. From the analysis of these filters the software is able to change the size of mesh triangles, generating multi-resolution meshes. The behaviour of the real surface is illustrated by the different filters applied on the point clouds; in this manner flat surfaces are described by large triangles, unlike corner and edges where the triangles are more dense and smaller (Fig.5). Multi-resolution algorithm speeds up the data processing and at the same time makes the point clouds lighter. In a second step it is possible to decimate the model in order to further reduce the data (Figs. 6 and 7). The question, however, is: how does this reduction and interpolation of the data affect the reconstruction of the surface and geometry of the rock hewn architecture? Comparing different models and filters it is possible to see the loss of data on the structures affected by this decimation, but the overall geometry remains more or less the same even if it depends on the representation scale. However, the aim is to achieve a good compromise between data management and an accurate description of the architecture. Only after generating an accurate mesh model it is possible to define section planes. The intersection between model and planes, at different layers, determined on the basis of the architectural features, allows to extract the most representative sections, usable for the next procedure of modeling.

From the mesh to the interpretative model

Since the purpose of a survey is always the deep understanding of architecture, after the progressive simplification of the mesh through automated algorithms, we decided to analyze the geometrical composition of the space of the building we were studying.

The clearly architectural nature of the examined artificial cavity, in fact, makes it necessary to carry out a number of critical operations, interpretation and selection of meaningful data, in order to create a three-

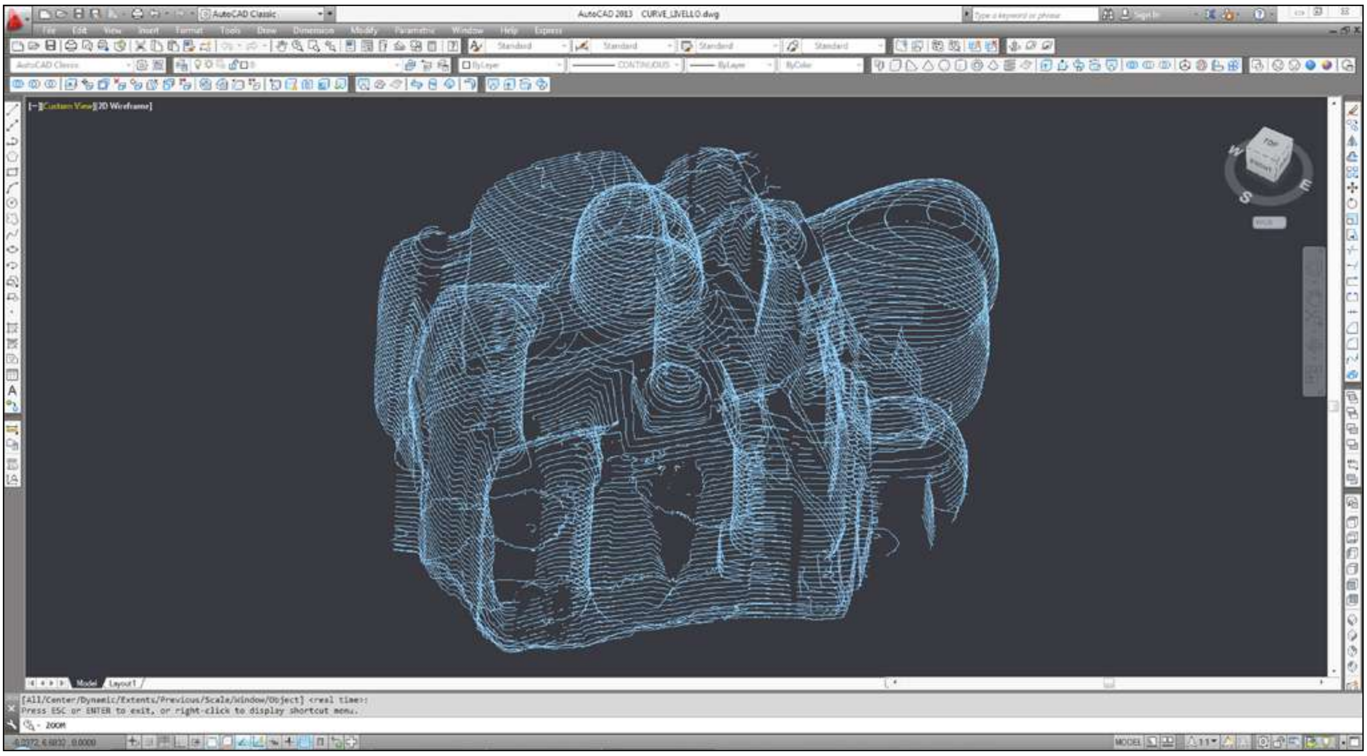

Fig. 8: axonometric view of the level curves derived from the mesh model (image by G. Cresciani).
Fig. 8: vista assonometrica delle curve di livello derivate dalla griglia di esempio (immagine G. Cresciani).

dimensional model that takes into account the identity of the detectable architectural elements (Fig. 8).
It should be noted that, before any other operational phase, the intervention of the critical interpretation of the surveyor is essential, by the use of the tools provided by geometric- architectural and historical knowledge, that allows us to decode and examine the surveyed space by relating it with spatial ideal reference-modules.
In our case study, moreover, the almost total absence - and, where present, the bad condition - of the paintings, "justifies" the focusing of study and experimentation on the geometric space structure of the building, ignoring those aspects related to the survey and representation of color, often indispensable for a proper documentation and knowledge of architecture (Carpiceci, 2011).
In the present case it is clear that the church is a space with three naves, each of which made of three spans, separated by columns and covered by vaults and domes; there are also a central apse, larger, and a side apse, at the end of the right nave (the left apse, probably present in origin, has been compromised over time by falls).
Once we understood the reference space-typology, we went on by choosing section planes that could allow to underline fundamental profiles, necessary to create the three-dimensional model of each architectural element, such as domes, vaults, arches, columns, capitals, etc. (Canciani et al., 2013).
It has to be considered that the profiles obtained from the mesh are constituted by linear segments - being the intersections between the vertical planes of section and the mesh, formed by triangular flat faces - even where the perceptual experience would identify surfaces, and therefore sections, which are continuous and curves (Fig. 9).
During the necessary phase of analysis and re-drawing of the portions of profile-section aimed at generating models of the different architectural elements, therefore, it is up to the operator to determine the degree of adherence of the "final" profiles to the starting ones, to mesh derived from the points cloud, and to assess how their simplification can keep the final result "exact" in comparison with the real surveyed element (Docci, 2009).
The construction of the three-dimensional geometric model takes place, for any object to be represented, on one hand by extruding significant profiles or by rotating them around an axis, on the other by generating surfaces which are the interpolation between curves and profiles variously positioned in space. These operations, in the case of excavated architecture, were less immediate and obvious than they are in the practice relating to "built" architecture, and therefore have made it necessary to make several "attempts" and approximations.
The resemblance of the real space, and its three-dimensional model, to the ideal model, the prototype-space that appears to be underlying the creation of the architectural space, can, in the case of rock hewn architecture, only be partial: while, in fact, "built" architecture plans and realization - up to stereotomy of the parts used in the creation of the single elements - both follow well-defined and well-known geometrical principles and rules, in the rupestrian one the construction technique itself, being based on removal of material, does not allow a strict control of fundamental geometric conditions such as perpendicularity,

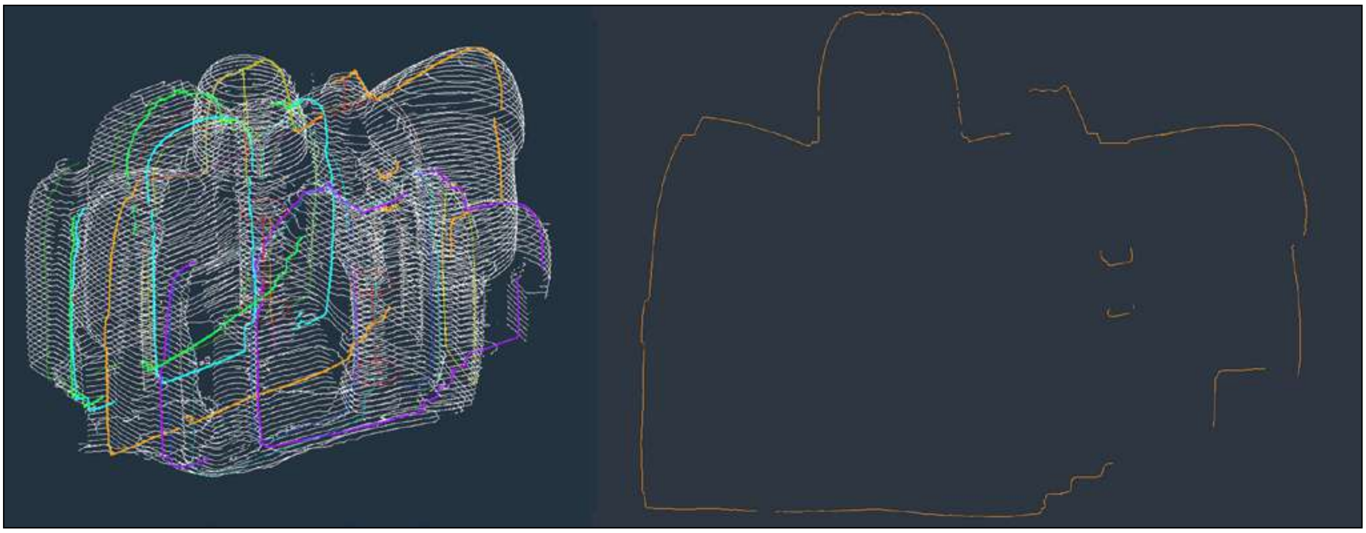

Fig. 9: view of the level curves with some of the sections used to study the architectural elements (left); longitudinal central section before any kind of processing and discretization of partial profiles (right) (image by G. Cresciani).
Fig. 9: vista delle curve di livello, con alcune sezioni usate per studiare gli elementi architettonici (a sinistra); la sezione centrale longitudinale precede qualsiasi tipo di lavorazione e discretizzazione dei profili parziali (destra) (immagine G. Cresciani).

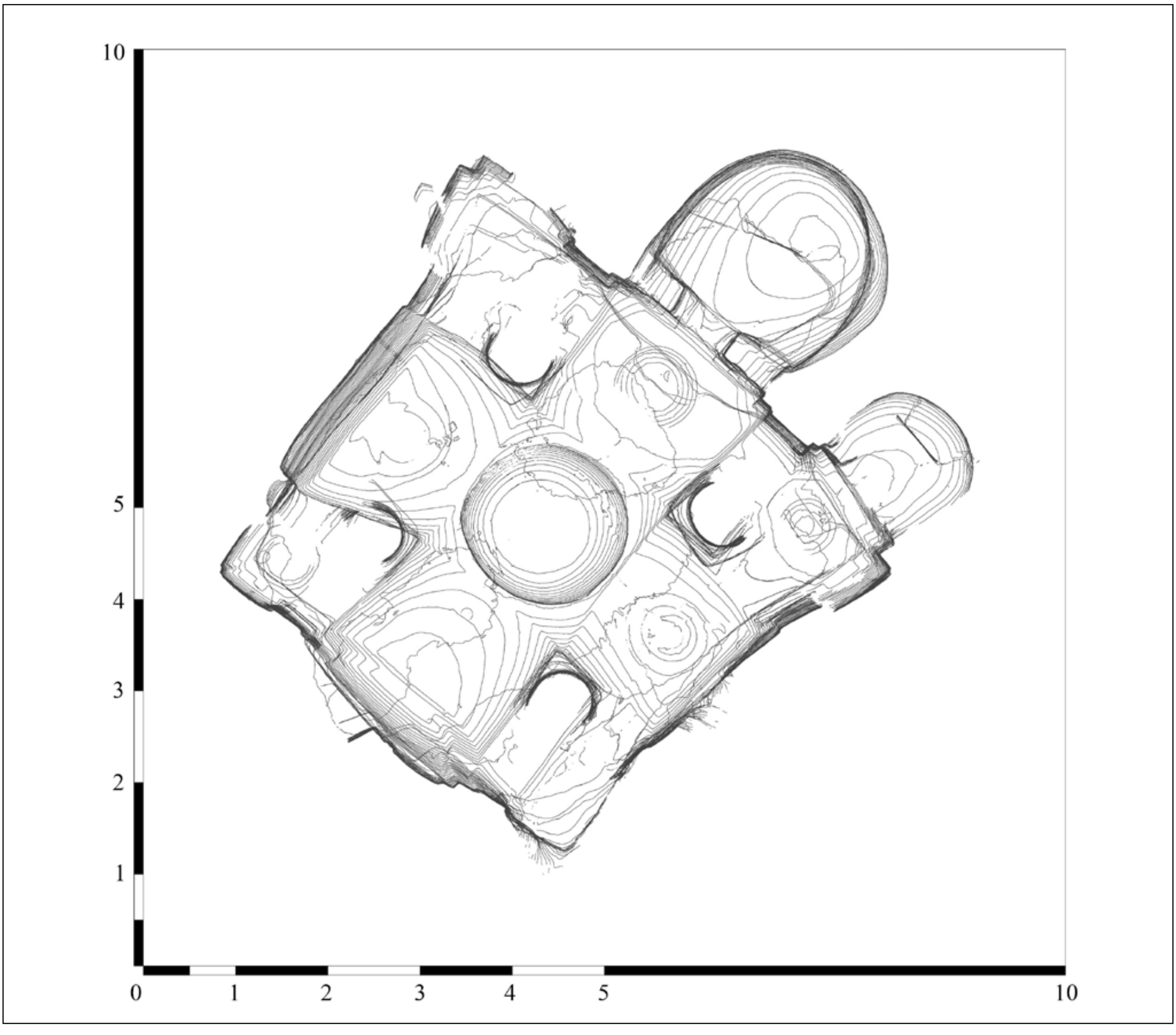

Fig. 10: zenithal view of the level curves: the irregularity of geometries is clearly shown (image by G. Cresciani).
Fig. 10: vista zenitale delle curve di livello: l'irregolarità delle geometrie è chiaramente visibile (immagine G. Cresciani).

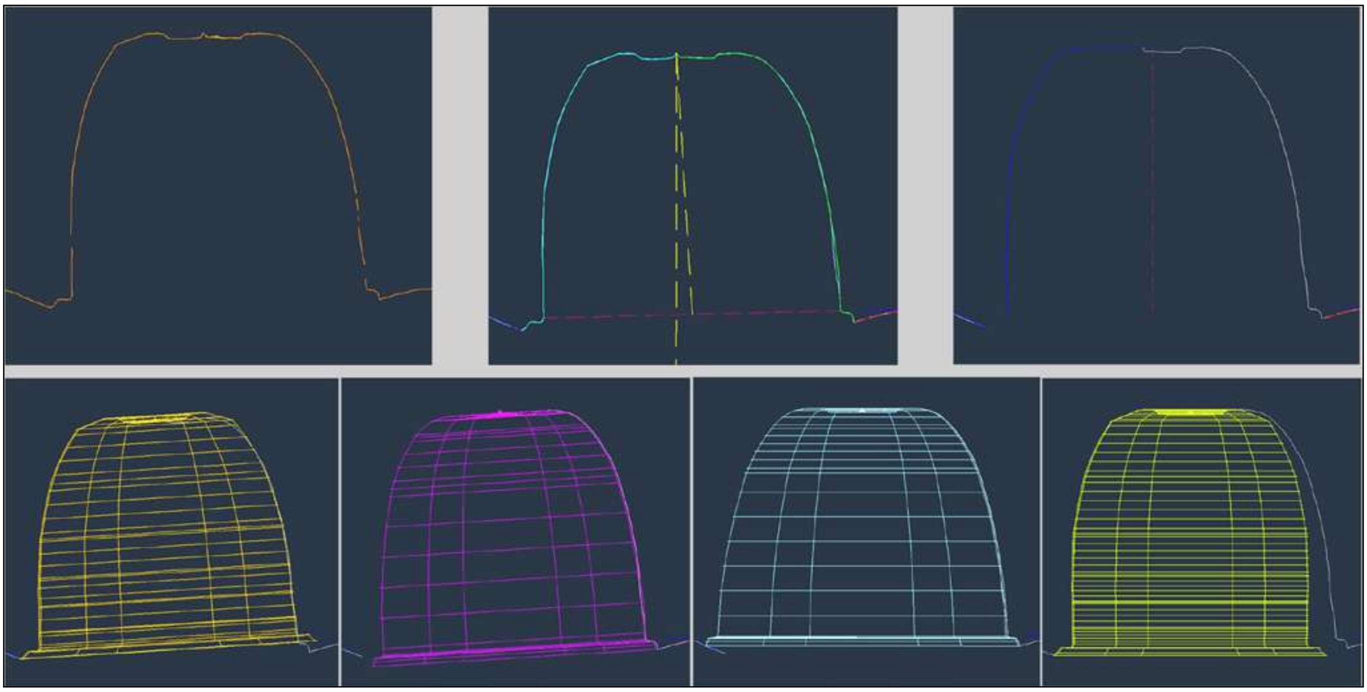

Fig. 11: central dome: work of interpretation of profiles and axes (above) and some of the different 3d models of the element, obtained by revolving differently drawn profiles around different axes (the last two having a vertical axis) (image by G. Cresciani)
Fig. 11: cupola centrale: lavoro di interpretazione dei profili e delle assi (sopra) e alcuni dei diversi modelli 3d dell'elemento, ottenuti ruotando profili diversi tracciati intorno a diversi assi (gli ultimi due ad asse verticale) (immagine G. Cresciani).

verticality, and horizontality.

Observing a zenithal view of a series of horizontal sections (level curves) realized with an equidistance of 10 cm (Fig. 10), it is evident how the sections of the domes and those of the columns are not, as one would expect, circles (Carpiceci, 2013b). For this reason the operation of rotating a profile around an axis will create a model that will be an approximation and an abstraction of the actual physical-geometric consistency of the architectural elements taken into consideration.

Another factor to be taken into account is that the axes of the mentioned architectural elements, as confirmed by the examination of transverse and longitudinal sections, are not vertical and, therefore, the introduction of a vertical axis of rotation in the creation of the model constitutes a distance from the real material aspect of the surveyed object, and makes the result closer to the ideal prototype to which it refers (Fig. 11).

We can make the same kind of considerations about the walls that delimit the examined space - which are almost never perfectly vertical and flat surfaces - or about the arches which separate the single spans - mostly irregular, polycentric and almost never symmetrical with respect to a central axis.

In the case of rock hewn architecture, therefore, the construction of a three-dimensional “reasoned” model, whose elements are identified according to a geometric and architectural logic appears essentially as the search for a compromise between the “exact” and rigorous description of the surfaces that delimit the surveyed space - made possible by the use of laser scanner - and the necessary critical-interpretative operation, essential for a full understanding of the architectural phenomenon (Fig. 12).

If, in general, the operative procedure is methodologically identifiable and improvable, the balance between the descriptive aspect and the interpretative one must necessarily be pursued in each case, as the quality and effectiveness of the three-dimensional final representation, obtained by the described process should be assessed.

Acknowledgments

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This paper is also the result of the collaboration of the authors. In particular Marco Carpiceci developed the paragraph *Criteria for the geometric interpretation*, Andrea Angelini *General considerations about the point clouds registration and the meshing process* and Giovanna Cresciani *From the mesh to the interpretative model*.

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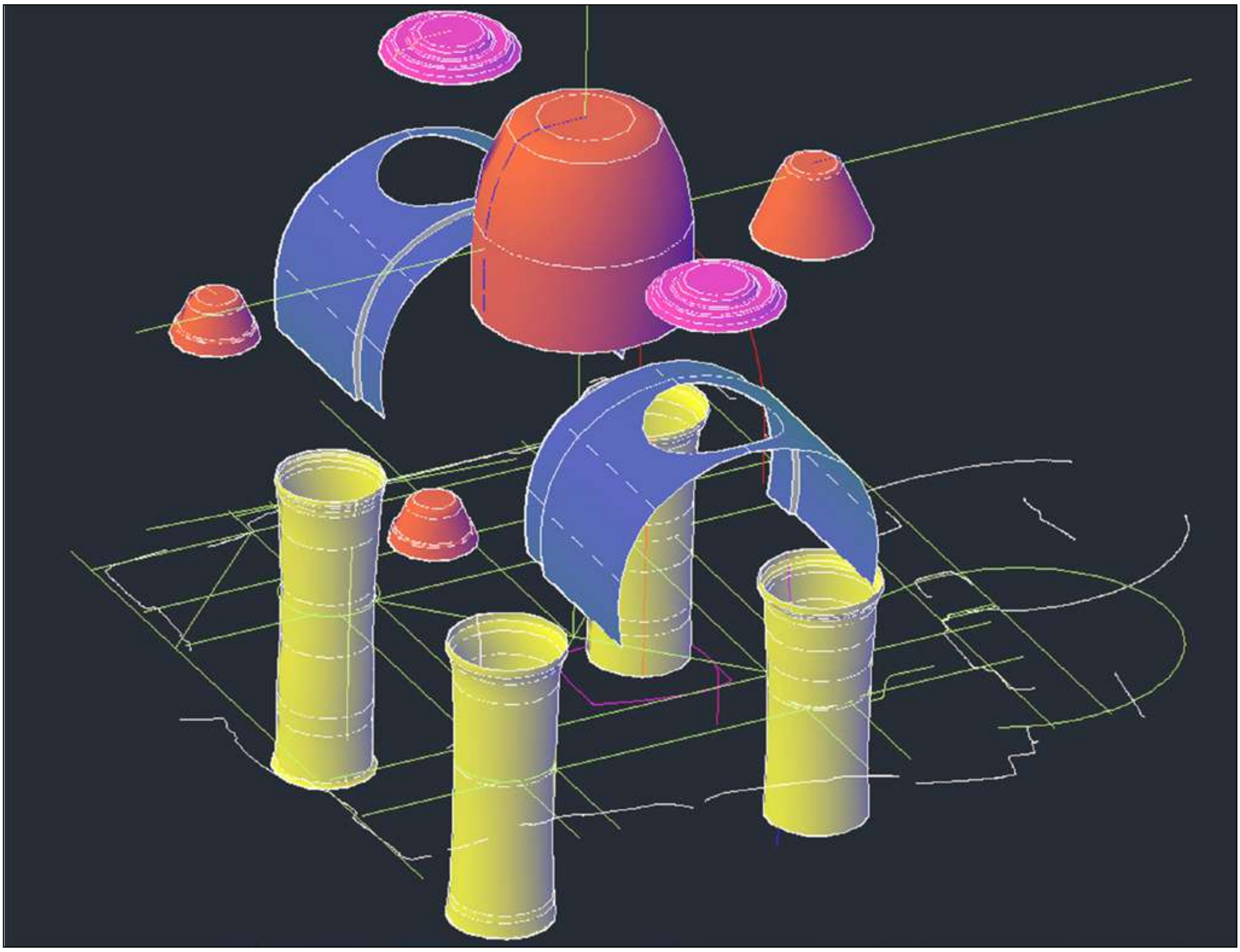

Fig. 12: work in progress of the construction of the geometrical "reasoned" model: elements are separated, rotation axes are assumed vertical, vaults and arches are made regular and symmetric (image by G. Cresciani).

Fig. 12: lavori in corso di realizzazione di modello geometrico "ragionato": gli elementi sono separati, gli assi di rotazione sono assunti verticali, volte ed archi sono regolari e simmetrici (immagine G. Cresciani).

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