The Volumnis' Hypogeum in Perugia, Italy
Application of 3D survey and modelling in archaeological sites for the analysis of deviances and deformations

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1 Hystorical Notes and Introduction

The Hypogeum of the Volumnis, titled family native from Perugia, has been built almost around the III and the II century B.C., coinciding with the Hellenistic period of Etruscan civilization.The tomb was discovered in 1840, still in original conditions and preserving incineration urns, fact that allowed Scholars to reconstruct a possible genealogic tree. The Hypogeum of the Volumnis represent a quite rare example, together with Cerveteri Tombs (Rome), Puttu Codinu (Sassari) and others, of sepulchre, completely excavated in the soft sand stone and simulating an anthropomorphic environment. The planimetry, in fact, is composed in accordance with the typical features of a civil house: it consists of a large atrium introducing to a final tablinum, two alae and three couples of lateral cellae.

This kind of arrangement of the plan was made to ensure the defunted a comfortable afterlife, similar to the temporal one.The atrium is covered by a two-slope ceiling, realised to resemble the intrados of a wooden hut roof; the entire carpentry is simulated in its components as ridge beams, rafters, joists and boards, carved in the rock in true scale. The studies on the Hypogeum started along with the discovery of the sepulchre and, until 1930's, consisted in several sketches and summary drawings.

The first survey is owed to Armin von Gerkan, German historian of Greek and Roman architecture. Anyway, the measurement work revealed critical because of subterranean conditions and plan's characteristics: consequently von Gerkan's observations and interpretations were consciously limited.

2 3D Laser Scanner Survey Procedure

The 3D survey has been realised with a Leica Geosystem HDS 3000, setting a 1x1 cm grid as point cloud density. This operation required two operators for fourteen hours of work, acquiring 10,7 millions of points in 23 scans by 13 positions. The environmental humidity rate was of 97% in subterranean rooms; the survey has been served out without interfering with the affluence of tourists. The survey of the sepulchre was anchored to a topographic one, consisting in 19 targets and realised with a Leica TCR 1101. In phase assembly of the total model, the overlap of all the partial registrations caused a non homog-enous density of the point cloud, which required the appliance of redundancy filter with minimum radius of 0,5 cm, operation carried out with Leica Cyclone.5.1 software. The model reduced so its amount of points to 7,7 millions. The final point cloud was, then, cleaned of mobile installations such as furniture, alarms, urns.

Figure 1 *View from the atrium towards the tablinum. Photograph and point cloud carried out from 3D survey*

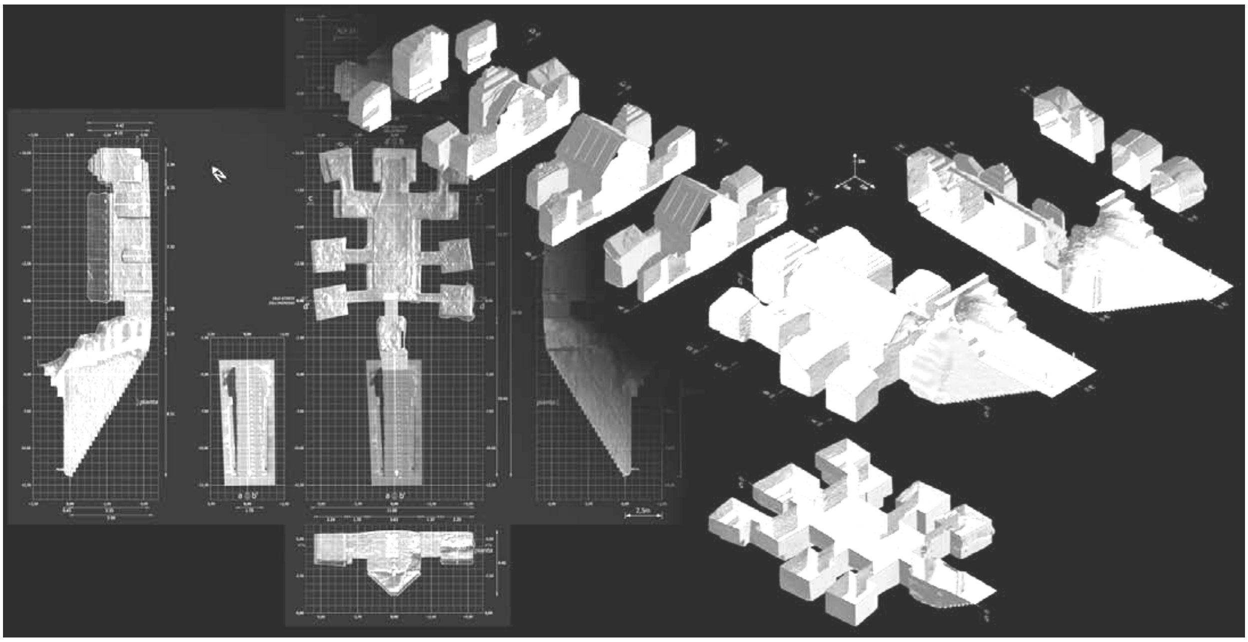

Figure 2 *The organic triangle meshed model. Plan set and exploded axonometric view*

3 The Organic Model Mesh

The firs step to evaluation of distortions and deviations of the structure was to create a mashed model, following the 3D modelling procedure with the Technology RapidForm 2004, running on a standard PC platform. That meant the triangulation of the point cloud, previously divided in 11 parts, due to the logical morphology of the monument, cutting through the section of the short corridors. This division was made necessary to avoid overloading computer memory during the mesh calculation, which nevertheless remained critical. During the meshing operations it has been possible to integrate scan shadow-areas introducing homogeneous point grids adopting Rhinoceros software. After that, the meshed model portions were gathered, decimating to 60% flat areas; than the sewing procedure required an overall decimation to 80%, in order to flattern the joints and obtain a handy model of 2,9 millions triangle surfaces, corresponding to a 48% reduction of the original.

4 Summarizing 3D Surface Model of the Main Ceiling

In order to put in evidence and quantify distortions and distinguish between decay of a 2000 years old architecture and deviation tendencies, a summarizing model was built on the main ceiling of the organic triangle meshed model with straight surfaces. These were created by intelligent choice of anchor points, considering each carpentry member and its logical deformed configuration under load condition, in order to intermediate the surface on its restraints (pondered average) and not on intermediate and eventually flexed parts (arithmetic average). To ensure the correct orientation of the straight surfaces on single conditioned anchor points, an average position of three points per short edge was chosen. This method consented to obtain an homogeneous global overview, resulting flexing carpentry curving below the ideal (straight) carpentry members.

5 Application of Industrial “Deviation Check” to the Archaeological Site

The overlay of global meshed and summarizing models allowed to put in evidence distortions and deviances in the structure. The “deviation check” procedure, usually adopted in industrial production to control the effective quality between CAD model and final product, was in this circumstance experimented on architectural scale to visualize global deviation tendencies in the elements constituting the ceiling. Overlaying the models of the complete two-slopes ceiling the presence of flexion under load condition appears clearly.The same steps were applied to each category of carpentry, which rafters, ridge beam, joists, boards and closures. Evident global tendencies of flexion could be noticed in the main categories. The rafters (visible dimensions: approximately 230x41x8 cm) show an average flexion of 2,1 cm and a maximum of 3,2 cm with the peak in the centre line area. The section line on the selected section appears close to a circular segment similar to the lay under condition of vertical distributed load with hinge re-straints at top and bottom.The ridge beam (visible dimensions: approximately 745x33x7 cm; 671 cm length between corbels) shows a flexion peak of 3,1 cm, the centre line section shows a deformation analogous to a wooden beam with hinge or maybe joint restraints subjected to distributed load. Nevertheless the curve isn’t symmetric, in fact the peak is located at 105 cm from the centre of the beam: this lets suppose a further decentred

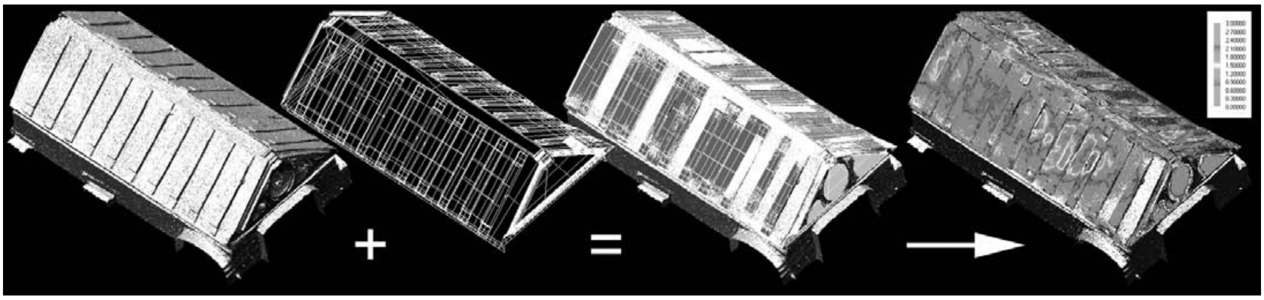

Figure 3 *Inspection procedure. Overlap of the two models and application of "deviation check"*

punctual load.This could be consisted in a hanging oil lamp of the atrium, found at the moment of the discovery, as attested by Giovanni Battista Vermiglioni in 1840s through his own description about the condition of the original interior set of the tomb. Vermiglioni clarified that the terracotta lamp, alike another one situated between the atrium and the tablinum, was found crashed on the ground, but, hanging above it, there still was the suspension stick fixed to the ceiling. Anyway, it is discussable if a six flames oil lamp, traditionally made in bronze in Etruscan houses, could cause a flexion in the beam. It is not possible to notice a clear tendency of deformation in joists and closures.In Armin von Gerkan 1930's survey are already reported some observations about a not perfectly vertical disposition of the rafters,due to execution error or a partial collapse of the soft sand stone surface, happened already during the construction works, in the hypothesis proposed by the historian himself. If this was correct, than we should suppose to notice in the laser scanner survey a gradual error reduction until the last couple of rafters, which should lay on the vertical plane. Nevertheless the overlaying of the two models showed that the inclination, departing from the inner tympanum, starts at 3,2° (omitting the first couple, with 1,3°), gradually increases to 4,7° and ends at the opposite tympanum reducing 3,4°.The detailed investigation on the cross section of the ridge beam showed that it changes, on 745 cm length, of about 1,8 cm, starting at the outer tympanum with 33,6 cm and finishing at the opposite one with 31,8 cm. It runs against the logical expectation, considering that the smaller cross section poses on its corbel at 1,4 cm lower than the major one, causing an inclination of the ridge beam. This particular can be explained considering the symmetrical raising of the floor from the entrance in direction of the tablinum, amounting to 30 cm on its overall length: extending the centre line of the lower surface of the ridge beam and the corresponding on the floor plane it is possible to individuate a focal point, determined at the intersection of the two layer, at 127 m in the mountain, measured from the entrance. In the mean time, the extended centre line on the side faces of the ridge beam converge in a theoretical focal point 125 m far in the mountain.

6 Studies on the Covering System

The Hypogeum of the Volumnis present a two-slope roof on the atrium and a square corbelled coffered ceiling on the tablinum and the right ala.

The two-slope ceiling of the atrium

The slopes have an unusual emphasized inclination of 47° and are supported by lateral beams at the bottom (725 x 23 left / 27 right x 12 cm, 4 cm overhanging from the walls) and at the top by a ridge beam (725 x 33 x 7 cm) which itself is laid on double corbels.The slopes have an extension of about 730 x 230 cm and can be divided in four categories of carpentry members (with average visible dimensions): 11 raf-ters (230 x 43 x 8 cm), 2 joists next to ridge and bot-tom beams (visible in 10 spots between the rafters, 25 x 25 x 4 cm), boards (visible in 10 spots between the rafters, 166 x 25 cm) and 20 small closures at the ridge and the bottom beams. The pediments have rafters that directly rest on the ridge beam and have a bottom beam (inner pediment: laid above the bottom beams of the slope; outer pediment: no level change) and are 25 cm high in section, with 4 cm overhang from the walls. The experimentation of an ideal reconstruction of the two-slope roof carpentry based on the true scale summarizing model, together with observations of Armin von Gerkan, conduced to the following thesis: the main supporting structure is given by a non-joint disposition of bottom beams fixed with the larger face of the cross-section on the surrounding walls, and the triangular shaped ridge beam supported by double corbels. The corbels are anchored directly in the wall structure and the rafters of the pediments work as spacers to disable the horizontal movement of the ridge beam. The previously identified rafters and boards could both consist of equal boards (280 x 43 x 8 cm) staggered in two layers. The joists result as inserted boards between the first layer of rafters in order to keep them in position during the execution of the work. The small closures are shaped boards and work as spacers between ridge beam and joists.

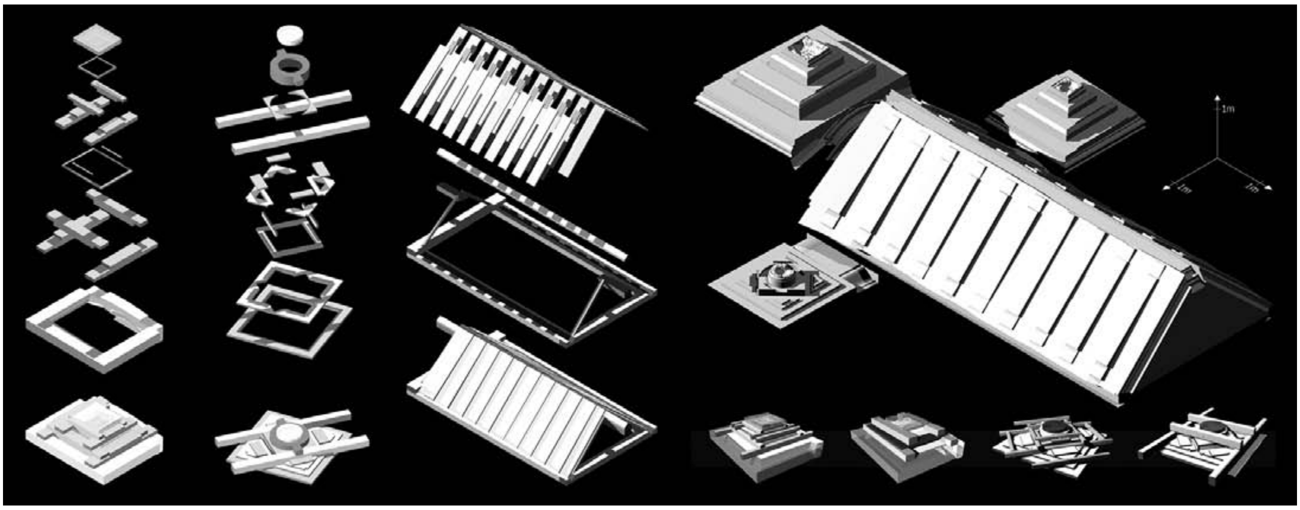

Figure 4 *Solutions for ideal carpentries' reconstructions. Summarizing model of the main ceilings*

The squared corbelled coffered ceilings of the tablinum and the right ala

The ceilings built on rectangular plan are arranged with two overhanging orders of each two parallel couples of joint beams (4 cm level change per couple) and a top closure with a framed sculptured head. The transitions to the orders are closed with shaped frames. During the investigation on the coffered ceilings it was clear that the data available today, based on a simulation in rock-cut sandstone of the inner surface of a wooden structure, was not sufficient to determine a final solution of the original carpentry set. Therefore it was reasonable to work out a number of solutions which differ not only by arrangement of elements, but as well by system and material. Some of the proposals for the original carpentry set could be discarded due to the direct dimension control handling with a true scale model, but are still considerable as functional carpentry systems. Finally, three different carpentry systems for the squared corbelled coffered ceilings have been worked out:

-visible squared partially joint beams, wooden frames and closure stone plate;
-roughly squared eventually joint beams, panelling, wooden frames and closure stone plate;
-visible squared beams and partial panelling, interposed stone plates and closure stone plate.

The diagonally corbelled coffered ceiling of the left ala

The ceiling built on an approximate square plan is arranged with two overhanging orders without level change between the parallel couples, a 45° rotated diagonal framework which remains in the same level of the second order and a joint centre torus with a framed sculptured head. All resulting triangles are sheet covered and framed. The diagonally corbelled coffered ceiling is to be considered a very similar system with the difference that the supporting structure can be done by partially visible squared beams with panelling or roughly squared beams with complete panelling. The last one lets open several variations of the supporting structure.

7 Statistical Analisys of Repeated Elements in the Two-Slope Roof of the Atrium

The last step in the analysis of the two-slope ceiling consisted in the statistical analysis based on the Gaussian distribution, thanks to the repetition of several elements in the two-slope roof, which the rafters. The non linear rotation around a perpendicular direction to the axis of the ridge beam induce a different interaxis between the couple of rafters, at their bottom level, while this keep a substantially constant value at the top; that shows how the ceiling has been carried out starting from the ridge beam, prosecuting to the bottom ones. Considering that a real wooden roof is executed arranging the rafters along the ridge beam at a determined distance, it appeared correct to effectuate the statistical analysis by means of three logical measures, which the interaxis of the rafters measured in the summarizing model above the centre line of the ridge beam, the left distance between rafters and the width of the rafters themselves. The interaxis results of 679 mm with a standard de-viation of ± 14 mm calculated with 19 imputs; the distance between rafters is 253 mm ± 18 mm with 20 imputs; the width of the rafters is 428 mm with 20 imputs.The measurement system chosen to check the values were Roman foot (296 mm), proposed by Matteini-Chiari, the Etruscan foot (324 mm), proposed by Hallier, and finally the nameless unit noticed in several tombs in the area of Chiusi (200- 210 mm), reasoned by the big influence of this city on Perugia.No good results of compatibility that allow to prefer a unit more than the others for rafter distance and width have been found. A good compatibility was found for the rafter width 428 ± 14 mm with the units from Chiusi 400- 420 mm.

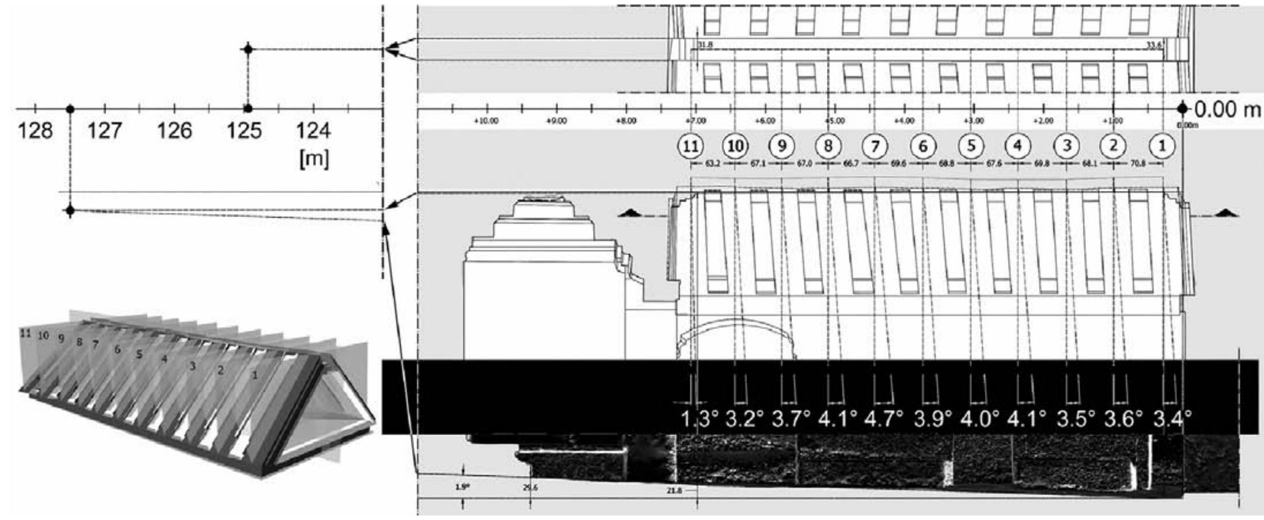

Figure 5 *Two-slope ceiling. Inclinations of rafters, focal points and determination of average planes*

8 Conclusions

The combined appliance of 3D laser scanner survey and triangular meshed model allowed to update the 2D canonical documentation elaborated by Armin von Gerkan in 1930's, showing the variation of regularity between atrium, alae and tablinum. The followed steps have been chosen according to the principle of simplicity and easy execution in the elaboration and handling of databases and models. The "deviation check", methodology proper to industrial activity but applied in archaeology through laser scanner survey and triangular meshed model, permitted to appreciate global deformation tendencies for ancient architecture with overall phenomenon of decay. This procedure has been fundamental to define the representative section planes. No univocal results have been found to exclude many hypothesis about different questions, but the informations here acquired represent a starting point to discuss them. It's not possible to exclude to attribute the flexion of the elements to a systematic error due to execution techniques of Etruscan workers, but it's still compatible with analogue funeral architectures of even older communities of Central Italy and surrounding, such as Cerveteri Tombs and Domus de Janas in Sardinia. Even the truth of the enhance perspective effect, given by the ridge beam and floor inclination, is not verifiable: to verify this we should notice the behaviour of bottom beams, but this is not possible. In fact in some photograph of the early 1900's, it is possible to see that the right bottom beam is missing because of probable decay; by means of this we can guess that the actual one is a modern reconstruction and we have no information about the disposition of the original one. The same problem exist for several other elements. The rotation of the rafters gives a slim, further optical effect of depth of the atrium, but it is not possible to totally exclude an accidental error. Anyway the thesis of optical effect in the Hypogeum of the Volumnis family is supported from investigations on contemporaneous architecture as the Parthenon in Athens, realised 1996 by the Greek archaeologist Manolis Korres, who revealed optical corrections handled by light inclin ation of the outer columns with different focal points vertically above the temple. Similar correction haven't been observed in Etruscan architecture yet and this thesis should be discussed by archaeologists. Since optical corrections in Etruscan architecture hadn't been observed, yet, this thesis should be further discussed by archaeologists. At least, we can state that in the case of the Volumnis' hypogeum it could be possible, from a chronological point of view.

References

AA.VV. 2003. *RapidFormTM 2004 User Guide & Tutorial*. Seoul: INUS Technology Inc.

BLERSCH D., 2006. *The simulated timber structure of the Volumnis hypogeum in Perugina, Italy*; *paper for Structuran Analisys of Historical Construction 2006 Conference in New Delhi*.

CENCIAIOLI, L. 2002. *Ipogeo dei Volumni e Necropoli del Palazzone*. Perugia: TSM.

CONESTABILE, G. 1855. *Dei monumenti di Perugia etrusca e romana, della letteratura e bibliografia perugina. Nuove pubblicazioni precedute da un discorso intorno alla vita, agli studi ed alle opere di Giambattista Vermiglioli: Il sepolcro dei Volumi* 2. Perugia: Bartelli.

DI GUGLIELMO, E. 1998. *Soffitti intagliati e architettura domestica in Etruria*, Florence: Olschki.

FRÖHLICH, C. METTENLEITER, M. 2004. *Terrestrial laser scanning. New perspectives in 3D surveying*. Wangen: Z+F.

HODGE, A.T. 1960. *The woodworks of Greek roofs*. Cambridge: CUP.

KORRES, M., PANETSOS, G.A. AND SEKI, T. 1996. Parthenon. In M. Korres (ed.), *The Parthenon. Architecture and conservation*. Athens/Osaka: CCAM Publisher.

OLESON, J.P. 1978. Technical aspects of Etruscan rock-cut tomb architecture. *Römische Mitteilungen* 85(1). Mainz: Zabern.

OLESON, J.P. 1982. *The sources of innovation in later Etruscan tomb design (ca. 350 - 100 B.C.)*. Rome: Bretschneider.

TAMPONE, G. 1996. *Il restauro delle strutture di legno*. Milan:Hoepli.

TAMPONE, G. 2002. *Le strutture di legno. Cultura, conservazione,restauro*. Milan: De Lettera.

VON GERKAN, A. MESSERSCHMIDT, F. 1942. Das Grab der Volumnier bei Perugia. *Römische Mitteilungen* 57, p. 122-235. Munich: Bruckmann.