3D database of the knowledge of material data: analysis of the complex structure of the Pentecoste dome in St. Mark's Basilica in Venice

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Abstract The survey of the wooden domed structures surmounting St. Mark's Basilica in Venice is part of a project of documentation, analysis and representation that the E-Lab laboratory of the Politecnico of Milan has been involved in for several years in conjunction with the Procuratoria di Venezia. Three-dimensional modelling and representation through laser scanner acquisition is the method that best lends itself to gathering information on the conformation and state of conservation of the beams that make up the roof of St. Mark's Basilica, which expresses its enormous architectural character chiefly in its five domes. The database obtained from the survey and processing of the topographical data represents a support on which to georeference the information and valuations of the heritage, directly in a 3D environment.

Keywords 3D Survey, Terrestrial Laser Scanning (TLS), Modelling

1. INTRODUCTION

The three-dimensional digitalization and documentation through laser scanner acquisition is widely used in architectural and cultural heritage survey. Besides offering information on the object geometry, it provides information about its state of conservation directly in a three-dimensional environment. The database represented by the georeferenced point cloud is sort of Space Information System for Architecture on which it is possible to base important assessments for the classification of

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structural elements or for the determination of the state of decay and preservation of each single element of the inquired object.
In this paper the attention is focused on the representative case of the Pentecoste's Dome of the Saint Marc's Basilica in Venice: the 3D data acquisition of its architectural structures has been conducted with the aim to model its detailed geometrical compositive form and for the definition of its deformations, analyzing the main constructive elements of the dome.
At the same time it was possible to tackle the high density range data acquisition and processing in complex environment. The job started from the interior of the St.Mark's temple up to the outside of the bulbs that complete the wooden superstructure of the Byzantine domes. It was the occasion to deal with many topics about TLS acquisition in particular with the behavior of laser with different kind of materials and surfaces (glass mosaics inside the church, wood and brick in the intermediate area between the double domes, lead roof), with the data management and geo-referencing of the point clouds and with surface and solid modeling.
At this point, once developed the geometric component of the database, it's possible to georeference information coming from other sensors, registering and merging different data or analysis also at different scale.
In this way, i.e. the existing woody species can be identified in wooden superstructures, their state of preservation analyzed, but also their static function can be identified in the structural and typological classification. In addition, it is also possible to distinguish degraded parts that require restoration intervention, from more recently added parts. This can be useful for restoration or maintenance purposes and to get an overall dating of the supporting structure.
Many sections can be extracted from laser scanner data and after the automatic or semiautomatic modeling process; the structural thicknesses can be checked and can be detected also the geometric shapes of the venetian double domes can be detected. The possibilities of model investigation are multiple and the representations which can be drawn are as much varied and definable qualitatively and quantitatively according to the chosen level of details.

1.1. The 3D model of the roof of St. Mark's Basilica in Venice

Survey of the general framework of the ceilings and acquisition of the wooden beams of the roof began with an initial campaign of acquisition in 2003-2004.
Before this, the area between the roof and the extrados of the dome and vaults of the Basilica was characterized by the absence of documentation of the complex wooden system. This is why all the spaces had been surveyed, except for the five main domes.

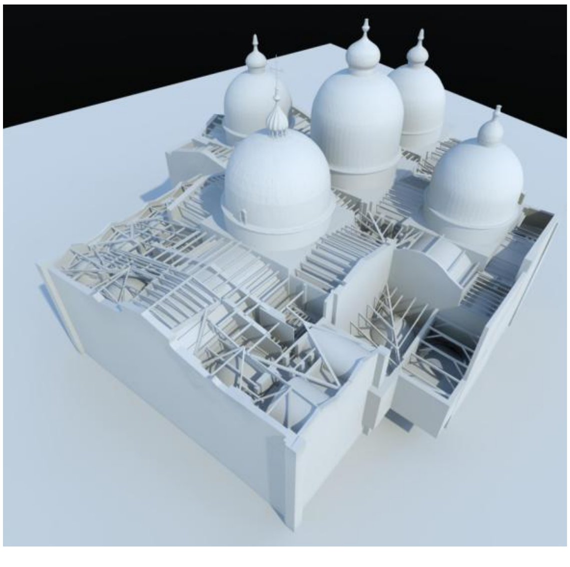


Figure 1 - The 3D model of the roof of St. Marc's Basilica in Venice

This study has included application of traditional survey methods, conducted with the TCRM1101 total station and direct survey, with integrations of high density laser scanning survey only in some areas. The sensor used in these cases was the HDS3000, time-of-flight laser scanners by Leica Geosystem.
This was necessary due to the type of spaces - often denoted by difficult access, small size and narrow or on several levels - and due to the objectives of representation. The model resulting from this survey was executed entirely in a CAD environment and simplified as regards the real form of the beams for the purpose of a 3D hierarchical representation of the wooden elements and to promote system engineering and fire-prevention safety, adapted to a 1:50 scale.
The second survey campaign, carried out in May 2008, in a single day of acquisition involved the spaces inside two of the five main domes of the St. Mark's Basilica.

1.2. Remarks on the history

St. Mark's Basilica, the structure that stands before us today after many centuries, is the third *reconstruction* of the original foundation built between 827 and 829 AD. Built at the behest of Doge Domenico Contarini, it was initiated in 1063 and completed in 1072 by Doge Vitale Faliero and its design was inspired by the Twelve Apostles Church in Constantinople. It was inaugurated only two decades later, however, when they found reliquaries of the saint, which had been lost during the fire in 976 that destroyed the previous basilica. Historic documents refer to this period, using the term *Fundata*, as if Contarini's Basilica had been a radical work of reconstruction, beginning with the foundation plans, contrary to the philosophy of recovery and restoration of the buildings and safeguarding human resources and materials, typical and characteristic of that historic period.
More recent analyses, however found that this process was not defined by an interruption, but rather through a construction practice that did not evolve by extemporaneous accelerations, but rather by a single structural body in continuous change and reuse.
The writings, the analyses made of the documents and innovative survey techniques have since made it possible to identify pieces of the walls of the previous basilicas, incorporated into the present-day building, which clearly prove that the previous architecture was used rather than the old church of the Particiaci having been demolished to build a new one from the ground up, more or less in the place of the previous church, to give a sign of power and to leave an indelible sign of Doge Contarini's legacy.
Therefore, the massive job of structural reorganization owes to Contarini's period, which radically changed the appearance of the basilica and its distribution. The entire structure of the building was renovated, from the foundation to the roof.

1.2.1. The domes of the Basilica

At the current state, documents and sources do not demonstrate with certainty the construction system of the domes, namely, whether they were generated by curves or complete self-supporting domes. Their installation in the 13th century is proven by various sources and by analyses of the construction materials: the fake drums covered on the exterior with stone present a layer of filling with stones to create the continuous supporting surface of the crown by means of the wooden superstructure. Certain iconographic sources identify a span of time of between 1210 and 1270 AD for construction of the raised portions.

Figures 2, 3 - The St. Marc’s domes before and after the built of superstructures in wood and lead

Constructing the domes was indispensable to make them visible from the lagoon beyond the Doge's Palace, which in its reconstruction after the fire in 976 had hidden from view.
Construction can be dated from between 1210 and 1270, estimated by the presence of two mosaic images inside and outside the basilica that describe the form in different time periods.

Figure n. 2, located on the western wall of the south transept, represents the basilica with the Romanesque roof: in this case, the mosaic was dated at 1210 AD. Figure n. 3, located on the façade of the great archway to the left, represents the church with the Byzantine domes, surmounted by the wood and lead structure: the mosaic is dated at circa 1270 AD.

The practice in use at the Basilica involved conservation of the wood superstructures: this is intended to affirm that the maintenance and conservation processes of the individual wooden elements also involved the portions of the domes in our investigation. At the present time, the Pentecoste dome has been submitted to numerous, major renovations over the years, some done recently, with have not changed the type or characteristics of the elements from a structural perspective. Another case is manifested in the Profeti dome, whose present-day appearance dates back to the early 19th century and is in need of a complete renovation intervention.
There are evident signs of structural decay due especially to water seepage. To preclude any further damage, safety scaffolding was installed on the dome. The Procuratoria di San Marco is currently designing a general plan of action for this structure, which includes a piecemeal dismantling and reconstruction/replacement of the load-bearing elements where necessary and renovation and conservation of the remaining parts.

This is the background of the research for the 3D survey of all the elements of these parts.

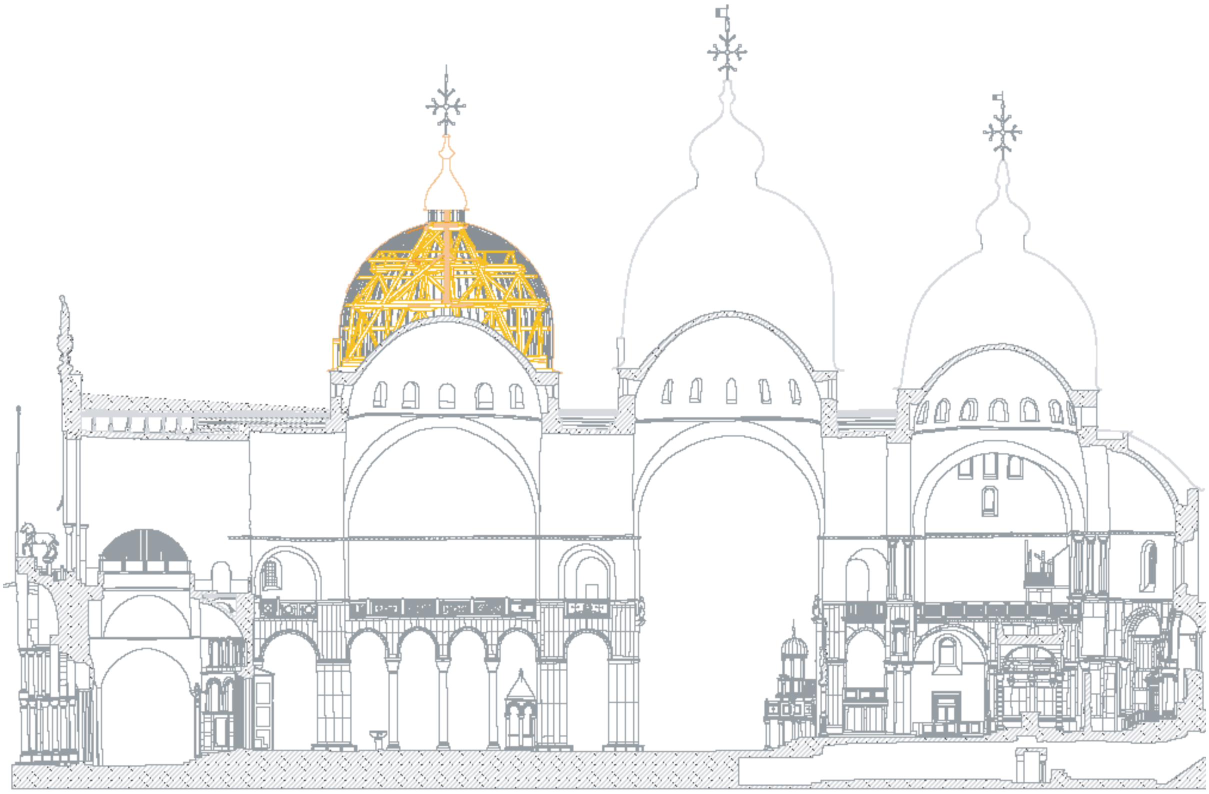


Figure 4 - The 2D representation of *Pentecoste* wooden beams into the Basilica longitudinal section

2. THE SURVEY

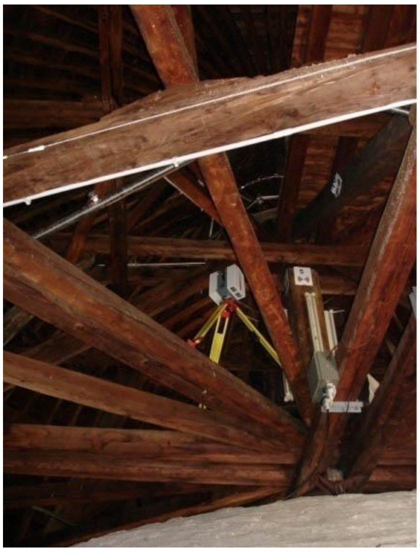
The survey of these fascinating areas was done using the phase differential TLS HDS6000 sensor by Leica Geosystems and with the support of the TCRM1101 total station for the topographical placement of the Basilica in the general reference system.

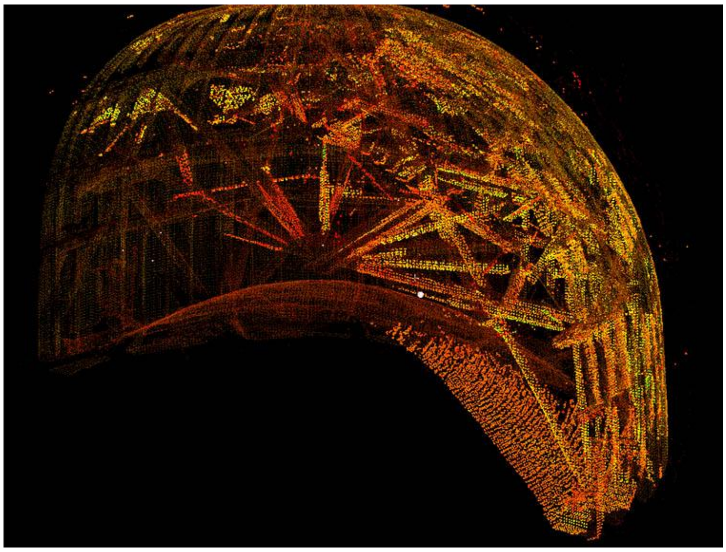
Approximately 18 scans were acquired per dome, at three different levels, in order to appropriately cover the areas of interest.

In the first level, the laser was mounted on a tripod and set on the brick and mortar dome; in the second level, the laser was mounted on the tripod set on the wooden beams; and on the third level, the laser was located directly on the beams for the reduced dimension in height, at the top of the dome.

The acquisition resolution selected for this type of intervention (super-high resolution with point spacing of 3.1x3.1mm at 10 meters of distance with panoramic acquisition of 360x310°) has led to the use of rapid scanning times (approximately 7 minutes per scan) for a total of 65 million points each.

The body of data obtained was very dense and highly detailed, albeit quite heavy in terms of hardware management.



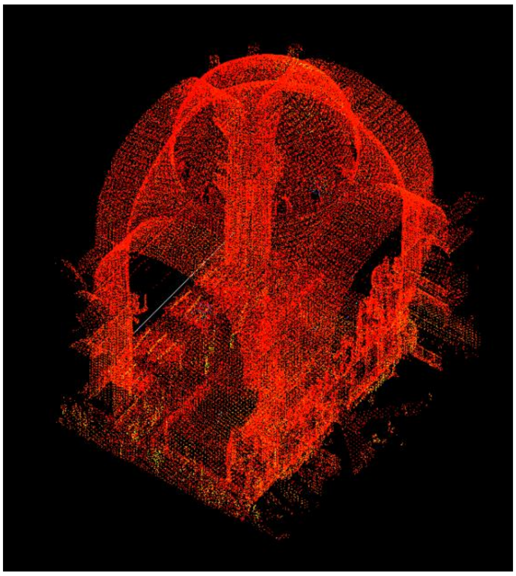


Figures 5, 6 - The survey was done using TLS HDS6000 (Leica)
approximately with 18 scans per dome at three level

The response of the sensor with respect to the wooden material surveyed was as the instrument manufacturer's claims. The wood species present in the documents have given an excellent albedo surface (this wood is dried and seasoned, with a low water content), therefore ensuring a surface with a ±2mm precision.

2.1. Study of deformations

The altimetric monitoring data, yearly carried out in the Basilica, reports a continuous movement of the structures: for a simplified evaluation of the existing structural instabilities and deformations we proceeded to extend the laser scanner survey on the inside of the Basilica.
We cannot clearly explain the causes or the dynamics of damages because this acquisition simply reports the current state, not having previous data. Even if we limit to make hypothesis, in this study we can propose some periodic guidelines of research that allow to study in deep the evolution of the instabilities, if it decides to complete the survey on the inside of the Basilica.
In addition to the geometric data, it was acquired the radiometric information with the digital camera, Canon Eos 450D equipped with a Fisheye lens - 8mm.



Figures 7, 8 - The survey of inside Basilica

The point cloud database, enhanced by the RGB information, allows to fully explore, measure and study the object : it allows to achieve a basic support for the subsequent manual or semi-automatic extractions of profiles and architectonic sections, or the generation of 3D mesh models. Finally it can be used for very communicative educational purposes through the creation of video, three dimensional renderings and interactive navigation environments.

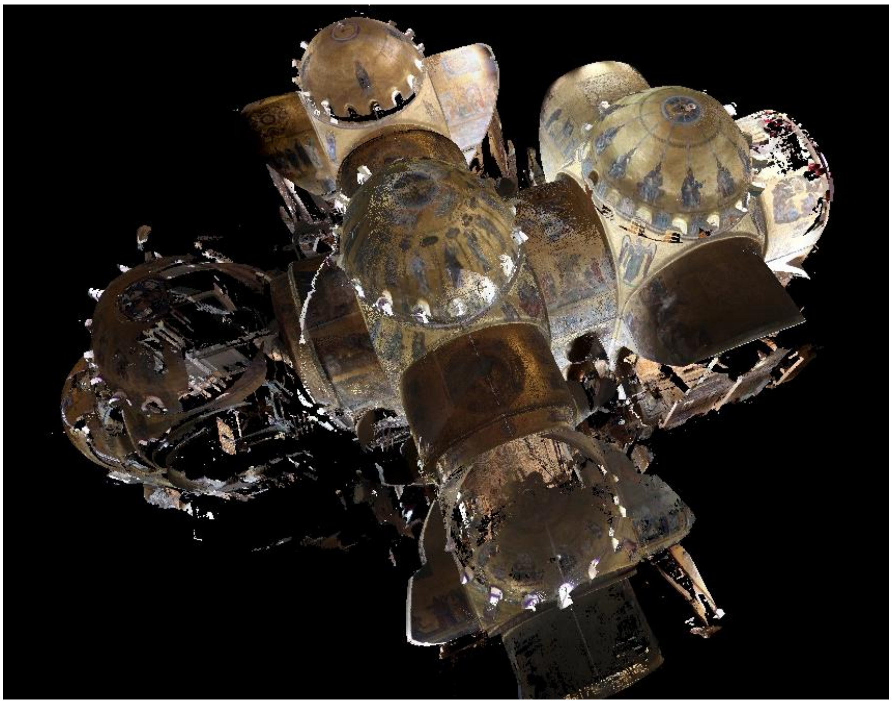


Figure 9 - The survey of inside Basilica with RGB texture

It’s possible to select slices from the point cloud for create control profiles of the structural deformation pattern. The measured deformations are those found in the classical historical buildings, like the S. Mark’s Basilica, with arcs, vaults, domes and pillars.
From these profiles were evaluated deformation phenomena such as:

- Out of plumbs of the columns or pillars;
- Deformations of the curvatures of arches between the columns and pillars;
- Deformations of the curvature of vaults between the pillars;
- Deformations of the curvature of domes.

Through a global analysis of the vertical sections it can evaluate the displacement of the centers of gravity in the pillars along their vertical. Specifically, if we consider the north-south and east-west direction axis along which the sections were performed, plotting the deviation from the verticals of the pillars, it can take these as the displacement vectors from the center of gravity: two components are obtained and their resultant indicates the entire inclination of the pillars.
For the better understanding the magnitude of this angle, it was decided to amplify each value of ten times and make the following three-dimensional representation.

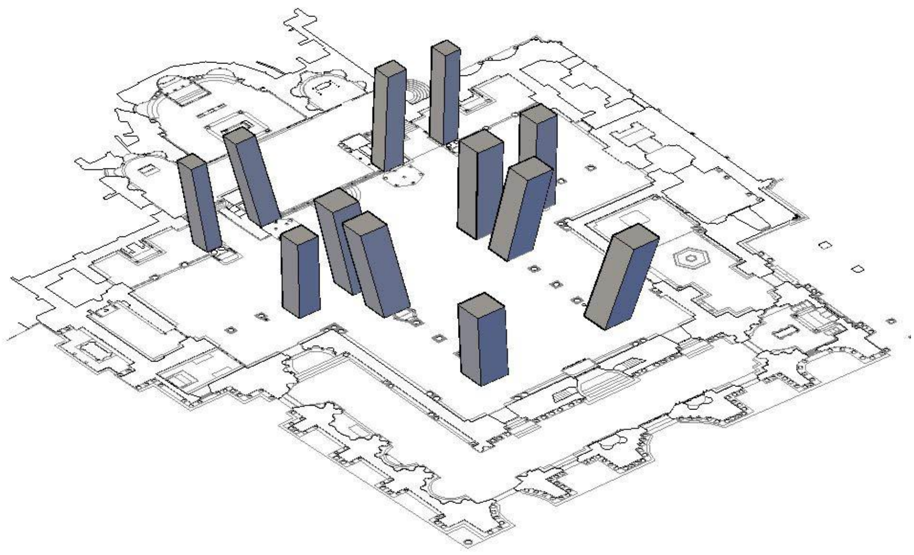
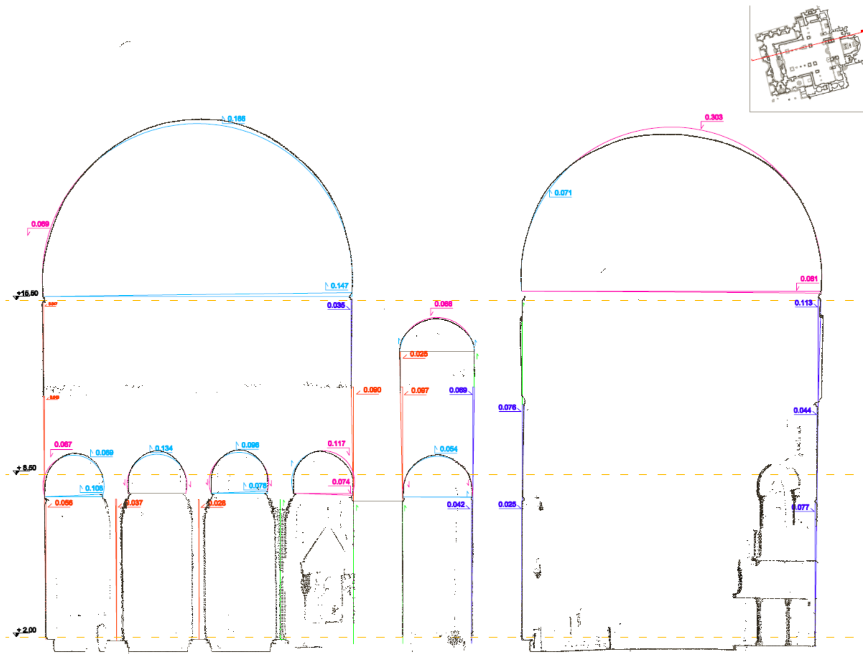


Figure 10 - Analysis of deformation of the pillars

Also for the vaults we evaluated the geometrical deformation compared to a primitive hypothetical direction.

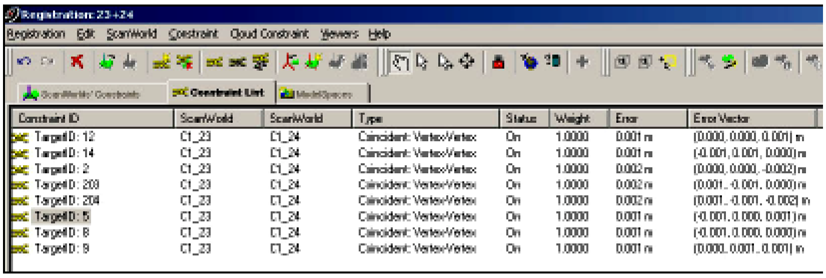


Figures 11 - An example of laser scanning profile with deformations analysis

3. DATA PROCESSING

The noise present in the scans done was generated by elements inside the domes of various material; the temporary safety scaffolding installed on the Profeti dome and the stainless steel pipes of the old fire-prevention system present in both domes have generated a datum in proximity to these elements and in the tangential points with respect to the scanning center with a higher than expected noise.
The first step in processing the data acquired was reduction of these outliers present in these outliers in these unstructured scans. Subsequently, the plan proceeded with a process of segmentation and filtering to eliminate redundant and superfluous data.

The results of the scans were aligned by combining features, vertices and making use of area-based matching algorithms. For example, figure 06 shows the alignment data of a pair of scans (Cup1-23 and Cup1-24) done in the Pentecoste dome in which we see that the high density of the acquisitions enables precision in this process of a maximum of 2 mm in the three components.



Constraint ID	ScanWorld	ScanWorld	Type	Status	Weight	Error	Error Vector
TargetID: 12	C1_23	C1_24	Coincident: Vertex-Vertex	On	1.0000	0.001 m	(0.000, 0.000, 0.001) m
TargetID: 14	C1_23	C1_24	Coincident: Vertex-Vertex	On	1.0000	0.001 m	(-0.001, 0.001, 0.000) m
TargetID: 2	C1_23	C1_24	Coincident: Vertex-Vertex	On	1.0000	0.002 m	(0.000, 0.000, -0.002) m
TargetID: 203	C1_23	C1_24	Coincident: Vertex-Vertex	On	1.0000	0.002 m	(0.001, -0.001, 0.000) m
TargetID: 204	C1_23	C1_24	Coincident: Vertex-Vertex	On	1.0000	0.002 m	(0.001, -0.001, -0.002) m
TargetID: 5	C1_23	C1_24	Coincident: Vertex-Vertex	On	1.0000	0.001 m	(-0.001, 0.000, 0.001) m
TargetID: 8	C1_23	C1_24	Coincident: Vertex-Vertex	On	1.0000	0.001 m	(-0.001, 0.000, 0.000) m
TargetID: 9	C1_23	C1_24	Coincident: Vertex-Vertex	On	1.0000	0.001 m	(0.000, 0.001, 0.001) m

Figure 12 - An example of alignment results

The next phase of georeferencing the point clouds with respect to the general reference system of the St. Mark's Basilica, was done on the basis of targets, acquired with the total station, after the scans were aligned with each.
In this case, the values of the absolute transformation have provided residuals of approximately ±3mm, slightly more than the previous one. The data expected and verified demonstrate how it supplies a similar accuracy of the control points (±3mm) even the use of forced centering systems in the topographical placement done using traditional instruments and typical operating techniques (total station and prisms set on tripods).
Cyclone 6.0 software was used to elaborate the acquisitions done on three levels for a total of 380 million point clouds.

4. MODELLING

The 3D reconstruction of the space under the wooden domes atop St. Mark's Basilica was adapted to the type of final model required by the project, which has a different nature depending on which dome is being studied.

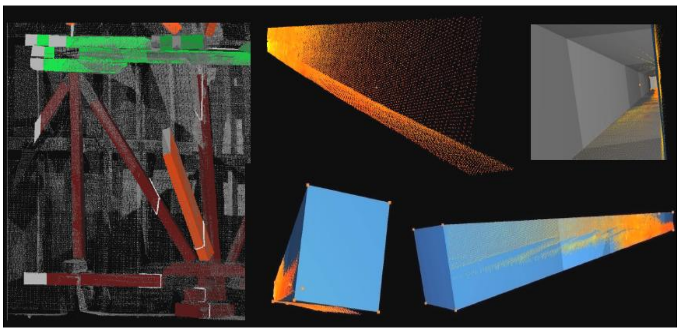
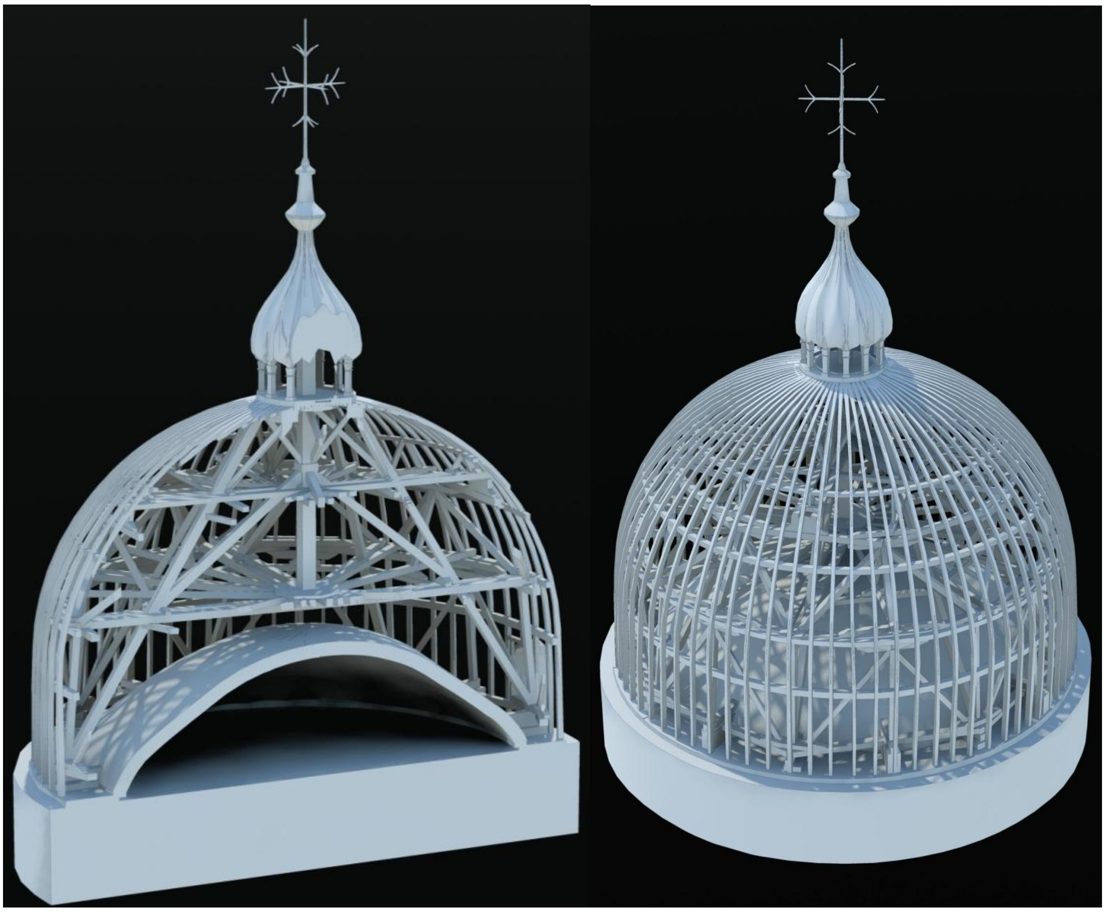


Figure 13 - Automatic generation of solids from laser data

As regards the Pentecoste's dome, the first visible dome from the main façade of the church, the purpose of the survey was to document the structure in its entirety in order to understand the construction methods and static situation, to realize a 3D database on which to georeference multiple types of information. The primary and secondary wooden beams were realized through the use of primitives, with automatic generation of solids or patches of the point cloud, thanks to the use of best fitting algorithms of the spatial surfaces.



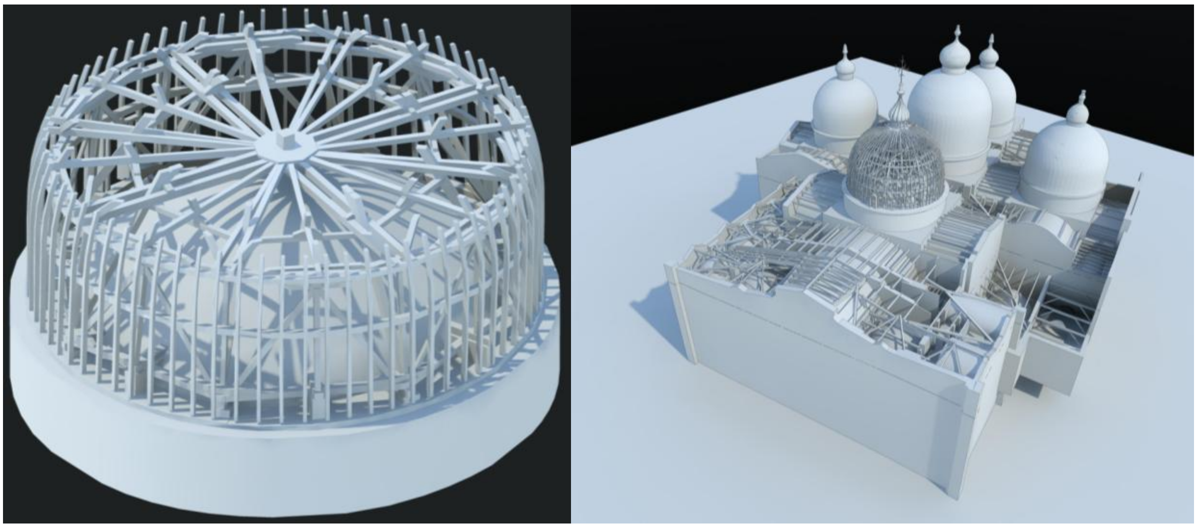
Figures 14, 15 - Visualization and rendering using 3DStudioMax 2009

This procedure has inevitably led to simplification of the complexities that characterize these elements, made up of a "living" material such as wood, distinguished by defects or deformations and twisting induced by the static behaviour of the structure as a whole.
Where the deviations of the real geometry of the surface were considered acceptable, the process was conducted in the semi-automatic mode, working in the Cyclone environment, while in the other cases, modelling was done in CAD (Autocad 2008 – Cloudworx 3.2), through the use of cross -section profiles along the directions chosen.

Visualization and rendering of the final model was executed using 3DStudioMax 2009 software by Autodesk.

5. REPRESENTATION AND USABILITY OF THE DATA

Representing the object through the use of models makes it possible to simulate very faithfully three-dimensional images that the human eye is unable to distinguish from perspective photographic representations. In our case, the models for representing the hidden parts, which up to now have been considered empty or devoid of architectural definition due to the lack of information, take shape and can be studied, analyzed and interrogated through product repertories.
A cognitive model in the architectonic environment can be described as a collection of structured objects, identified through a precise vocabulary that diversifies the meaning, building an abacus of the 3D entity or an abacus of the types.



Figures 16, 17 - Visualization and rendering using 3DStudioMax 2009

The concept of intrinsic usability meets the principle of efficiency; the more simple the structure of the model is, the more usable it will be. It would be wrong to confuse simplicity with a lack of information or superficiality, in which not all things can be explained using simple words.
This efficiency is reached by classifying the elements through a division into levels:

a. the general level, for example the dome, vault, skirts, connections, etc, in the case of architectural representations;
   In particular, the space under the roof and the domes are divided onto levels of environments and in each one are subsequently classified the objects contained in it. For example the Pentecoste dome is split into three levels, with a hierarchical structure that starts from the connecting ring of the circular beam, to the central post at the top.
b. the topographical level, which involves the way in which the various parts are divided and connected to each other; this category includes a division of the elements associated with the general class level, according to a distinction that can concern the behaviour in the structural case. The first level of the Pentecoste dome is divided according to the structural behaviour in: the structural support beam, trestles to divide and unload the tension on the support walls, connecting beams used as windbrace tension members, support brackets located up high for the second level
c. the metric level, or the way that the objects occupy the space, with what shape and what dimensions. In this level are the geometric characteristics of the form and the properties associated with it (deformation, decay, others).

In this way, even complex models can be known and analyzed.

6. CONCLUSION

The modelling process will fulfil the geometrical component of wooden roof database of the st'Marc Basilica and will be able the georeferation of all information about it.
The acquired process of knowledge, and that will derive from the realization of this database, will be able to satisfy the documentation and representation requirements, that fits well with it's made in rest of Basilica, and it will be able to promote greater control and planning of conservative operation.

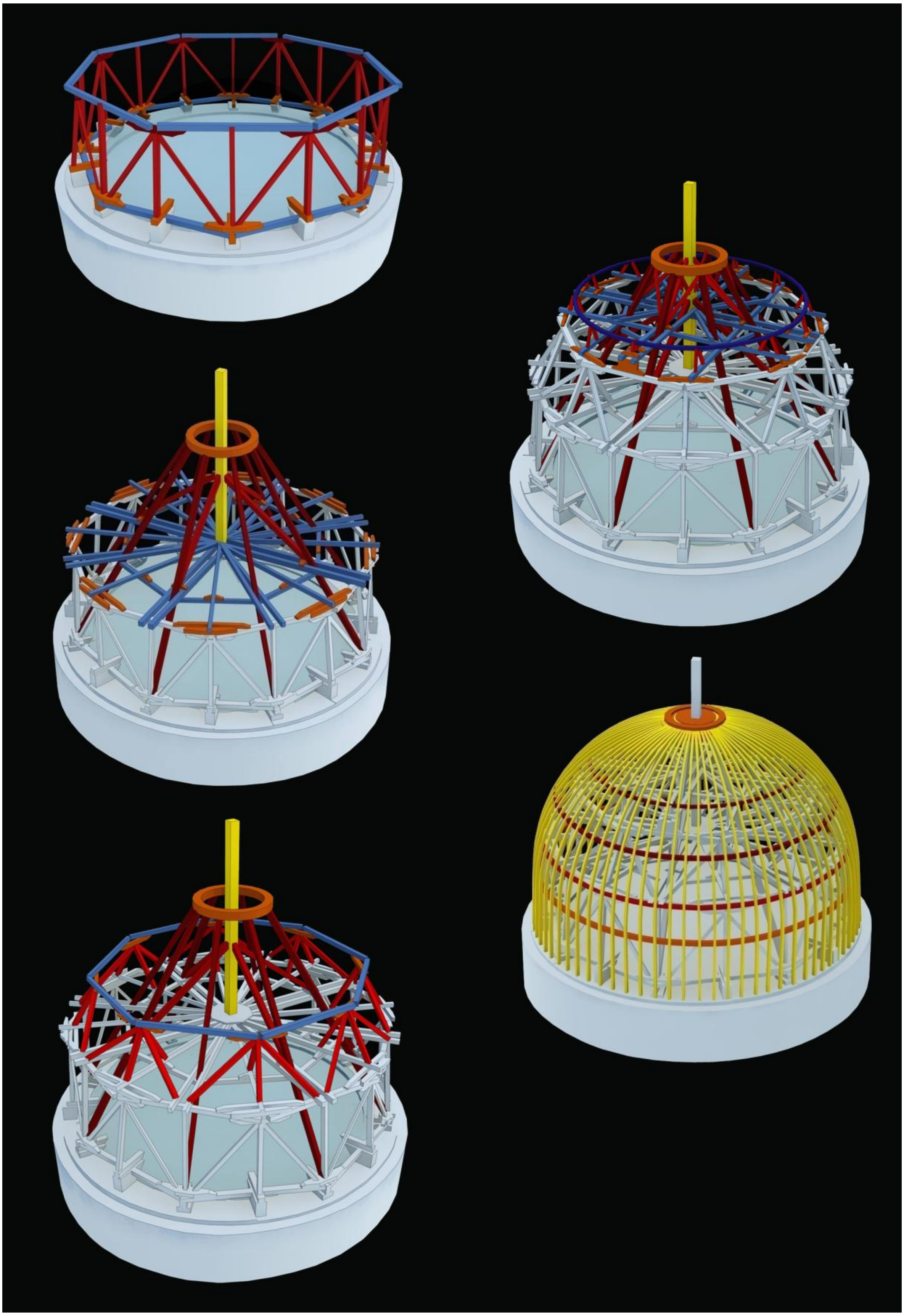


Figure 18 - The classification of beams in according to the structural behaviour

The measurement and diagram types of covering elements may facilitate the study of the involving of the static over time.
The possibility to interface to virtually model by several types of users, also make possible the access to places not visible to the non- experts, but of great interest and fascination.

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