

# GENERATION OF A SPATIAL INFORMATION SYSTEM FOR ARCHITECTURE WITH LASERSCANNING DATA

L. Fregonese, M. Scaioni, L. Taffurelli

Politecnico di Milano, Dept. BEST-SITECh, Piazza L. da Vinci 32, 20133 ITALY  
e-mails: {luigi.fregonese; laura.taffurelli; marco.scaioni}@polimi.it

**KEY WORDS:** Cultural Heritage, Terrestrial Laser Scanning, Modelling, Geo-Database

## ABSTRACT:

In architectural and cultural heritage documentation, laser scanning technology today offers several opportunities to approach the object to study and to extract manifold information levels from it. These account for point-clouds, 3-D models, and other data about the state of conservation. Georeferenced point-clouds can be adopted as the spatial framework of a Space Information System for Architecture, integrating all spatial information acquired by TLS, photogrammetry, geodetic surveying and direct survey, but also from other investigation techniques (e.g. GPR, thermal cameras, etc.). Such information system allows to make assessments that are important for the classification of structural elements or for the determination of the state of decay or preservation of each architectural element. With reference to the survey of two wooden domes of San Marco Basilica in Venice (Italy), the completion of the 3-D model of their complex structure is presented here through the description of its main stages, i.e. data acquisition, registration and modelling. The final 3-D model is then assumed as a 3-D database which clarifies the shape, the composition, the state of conservation and the structural function of the wooden beams of the domes.

## 1. INTRODUCTION

Three-dimensional surveying, modelling and representation through *terrestrial laser scanner* (TLS) has become a widely used technique for documentation of architecture and cultural heritage. In addition to provide information about the geometry of the investigated object, TLS makes possible to analyze the state of conservation directly in a 3-D environment (Beraldin *et al.*, 2002).

Creation of models whose objective is defined in the framework of geometric, spatial, and temporal knowledge implies taking a complex approach to the analysis and organization of the information, which frequently are left out of the normal survey applications. The data archiving proceeds by subsequent accumulations of information which are filled in a unique database. This should be organized to make possible to analyze the information content and to establish relationships. Finally, the appropriate knowledge is expected to be properly retrieved (Remondino *et al.*, 2009). The database offered by the georeferenced point clouds represents the Spatial Information System for Architecture (SISA, Gianninetta *et al.*, 2005). This allows important assessments for classifying structural elements or determining the state of decay or conservation of any element that makes up the object under analysis. The SISA might integrate all georeferenced data coming from other geometric sources: photogrammetry, geodetic surveying techniques, direct survey. In addition, outcomes of other investigation methods can be added up as well, including from example *ground penetrating radar* (GPR) analysis or *thermal imagery*.

This research project has involved a "hidden" part of the San Marco Basilica in Venice, Italy, whose monumental façade, sculptures, wall and floor mosaics surprise and enchant admirers and whose architectural space is topped by its great, majestic domes. The form and function of the superstructures present in these domes is the focus of investigation of the

architectural space that ties the interior of the domes of the Basilica with the volume perceived on the exterior.

The study presented in this paper deals with the TLS survey of the domes and the contiguous areas of the Basilica, more specifically, the "Pentecoste" and "Profeti" domes. The project includes the acquisition and modelling of their underlying wooden "skeleton" structure which is covered by the each dome's roof. In such particular context, the acquisition of a 3-D model of the complex, multiple-part load-bearing structure of the domes, achieved using semi-automatic and manual techniques, makes it possible to understand the form and composition of the beams and represents the basis for creating a 3-D database on which to georeference all spatial information (Lorenzini, 2009). It is then possible to identify the wood species used, the state of conservation of the beams, as well as the static function in a typological and structural classification. In addition, it was possible to distinguish the poorly preserved parts requiring rehabilitation from the more recent sections, which were added as replacements for other parts in restoration and maintenance, in order to date the entire load-bearing structure.

Modern needs of systems management (electrical, plumbing and fire extinguishing systems) and maintenance of this historic heritage also require planning based on a survey that is appropriate to these areas, which considers the 3-D shape of the structures. Indeed, the availability of a SISA data infrastructure enables to schedule a maintenance programme in a easier and more complete way.

The 3-D model realized demonstrates the advantages of laser scanning techniques to obtain a solid 3-D representation. These account for accuracy and completeness of data, speed of acquisition and processing (after making a necessary cleaning and editing of point-clouds), capacity to integrate data coming from other sensors and at different scales.

Interactive visualization and navigation of the model also provide access to information about the form and dimensions of this architectural heritage, in addition to the history and all

types of information that can be georeferenced in it. These instruments can be exploited by operators who work on its conservation and by the thousands of tourists and art lovers that can make a “virtual visit” to the site, which would be inaccessible otherwise.

In the following subsections, first an outlook on the history of the Basilica is given (Sub-sec. 1.1); then a review of previous survey works is reported in order to insert the current project in the mainframe of the ongoing documentation process (Sub-sec. 1.2). Other sections will deal with the different phases of laser scanning survey and modelling (Sec.s 2,3,4). Finally some considerations on the possible usage of the final 3-D model are given (Sec. 5), and final conclusions and future work addressed (Sec. 6).

### 1.1 Remarks on the history

The current structure of San Marco Basilica 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. 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 (Vio and Lepschy, 1991). More recent studies, however have found out 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 (Cecchi, 2003).

Analyses made on the documents and innovative survey techniques have made possible to identify some pieces of the walls of the previous basilicas, incorporated into the present-day building. This discover clearly proves that the previous architecture was used rather than the old church of the Particiaci had been demolished to build a new one from the ground up, to give a sign of powerfulness 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.

#### 1.1.1 The domes of the San Marco 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 13<sup>th</sup> 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, estimated by the presence of two mosaic images inside and outside the basilica that describe the form in different time periods.

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.

The mosaic in figure 1 (left), 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. The mosaic in figure 1 (right), 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 approximately dated at 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 19<sup>th</sup> century and requires 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, the body managing the conservation of the Basilica, 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 as well as 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 1. The San Marco Basilica’s domes before (left) and after (right) building of superstructures in wood and lead

### 1.2 The 3D model of the roof of San Marco Basilica

Survey of the general framework of the ceilings and scanning of the wooden beams of the roof began with an initial data acquisition campaign 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 the reason all the spaces were surveyed, except for the five main domes.

This study has included application of traditional surveying techniques, leaded with a total station Leica TCRM1101 and direct survey, with integrations of high density laser scanning survey only in some areas. The sensor used in these cases was the HDS3000, a ToF laser scanner by Leica Geosystem. The use of scanning was necessary due to the type of spaces - often featuring difficult access, small areas where positioning the laser scanner, also distributed on several levels - and due to the objectives of representation.

The model resulting from this survey was executed entirely in a CAD environment. It has been simplified as regards the real form of the beams for the purpose of a 3-D hierarchical representation of the wooden elements and to promote system engineering and fire-prevention safety. The scale of the final model was 1:50 (Fig. 7).

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 Basilica.

## 2. DATA ACQUISITION

The survey of these fascinating areas was carried out by using the phase-shift TLS HDS6000 sensor by Leica Geosystems. A total station Leica TCRM1101 was used to measure a set of GCPs aimed to register each scan into the Global Reference System (GRS) spread out over the indoor and outdoor area of the San Marco Basilica.

Approximately 18 scans were acquired per each dome, at 3 different levels, in order to appropriately cover the areas of interest. At the first level, the TLS was installed on a topographic tripod and directly setup on the brick and mortar dome. At the second level, the TLS was installed on the tripod again and setup on the wooden beams (Fig. 2). At the third level, it was located directly on the beams because of the reduced height at the top of the dome.

The point-cloud resolution selected for this type project (“super-high” resolution with point spacing of 3.1x3.1mm @ 10 meters and FoV of 360°x310°) has led to the use of rapid scanning times (approximately 7 minutes per scan) for a total of 65M points each. The body of data obtained this way was very dense and highly detailed, albeit quite heavy in terms of hardware management (Fig. 3).

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 gave an excellent albedo surface (this wood is dried and seasoned, with a low water content), therefore ensuring a surface with a ±2mm precision.



Figure 2. On the left, a picture taken during scanning at the second level of the “Pentecoste” dome; on the right, the point-cloud made up of the 18 scans captured at 3 different levels.

		SCAN	POINTS ACQUIRED	MODALITY	BYTE OF MEMORY
PENTECOSTE's dome	TOTAL	18	= 738 MILLION	HIGH	2,79 GB
	LeVel 1	8		6,3X6,3mm at 10mt	
	LeVel 2	5		4 minutes	
	LeVel 3	5		360°X310° FOV	
	1 ZFS	EACH SCAN		40891000	
PROFETI's dome	TOTAL	13	= 522 MILLION	HIGH	1,94 GB
	LeVel 1	8		6,3X6,3mm at 10mt	
	LeVel 2	4		4 minutes	
	LeVel 3	1		360°X310° FOV	
	1 ZFS	EACH SCAN		40150000	

Figure 3. Information about data acquisition

## 3. PREPROCESSING AND SCAN GEOREFERENCING

The first stage after completion of data acquisition was the editing of each scan to eliminate those elements that had been scanned but they did not belong to the dome’s structure. These included the temporary safety scaffolding installed on the “Profeti” dome, the stainless steel pipes of the old fire-prevention system present in both domes. The first step in data processing was the reduction of these outliers present 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. The high density of data acquisition enables precision in the pairwise registration of scan featuring with residuals of 2 mm in the 3 components.

The next step was georeferencing the point-clouds w.r.t. the GRS. This task was achieved by using GCPs, which consisted in Leica target tapes. The registration on GCPs was carried out by considering the block of scans as a whole. In this case, the transformation into the GRS gave residuals of approximately ±3 mm, slightly more than the previous one. This result agreed with the accuracy of GCP measurement.

The software Cyclone 6.0 (Leica Geosystems) was used to perform all steps of data processing. Totally, 380M points were processed in all scans.

## 4. MODELLING

The most relevant limitation of laser scanning application to cultural heritage documentation is the still limited capability of automatic modelling the georeferenced point-clouds. This task consists in replacing and interpolating points with geometric primitives. The objects under investigation features some properties which can be positively exploited for modelling, due to presence of many regular structures (e.g. the wooden beams) that can be replaced by solid primitives (Budroni and Böhm, 2009).

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

As regards the “Pentecoste” dome, the first visible dome from the main façade of the church, the purpose of the survey was to document the entire structure order to understand the construction methods as well as the current static condition.

The modelling of the “Profeti” dome is still in process.

Then 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. This procedure has inevitably led to a simplification and regularization of the



complexity that characterizes these elements. Indeed, these are 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 spatial primitives to be fitted from the real geometry of the surveyed surface were considered acceptable, the process was conducted in the semi-automatic mode (Fig. 5). The modelling process was carried out in the Cyclone environment. In the other cases, modelling was done in a CAD environment (Autocad 2008 – Cloudworx 3.2), through the use of cross-section profiles along the directions chosen.



Figure 4. The 2D representation of "Pentecoste" wooden beams into the Basilica longitudinal section

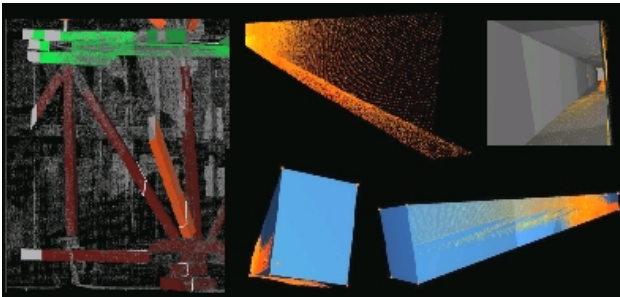


Figure 5. Automatic generation of solids from laser data

Visualization and rendering of the final model was executed using 3DStudioMax 2009 software by Autodesk. In figure 6 and 7 a final visualization of some parts and on the whole roof of the Basilica are shown.

## 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 can distinguish with much effort 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 queried through product repertoires.

A semantic 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 3-D objects or an abacus of the types. 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 matters can be explained using simple words. This efficiency is reached by classifying the elements through splitting them into levels:

- the *general level*; in the case of architectural representations: domes, vaults, skirts, connections, etc.; 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;
- the *topological 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;
- the *metric level*, or the way that the objects occupy the space, with what shape and size. 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.

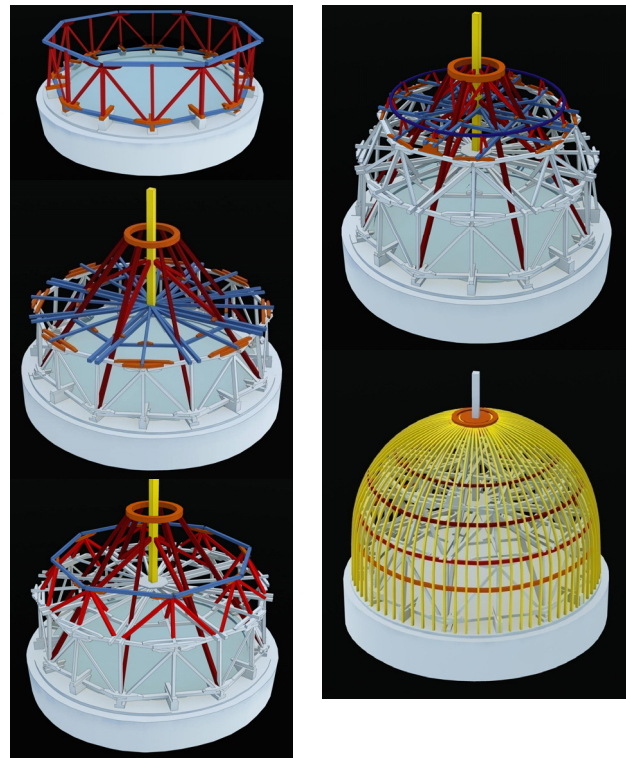


Figure 6. The classification of beams in according to their structural behaviour.

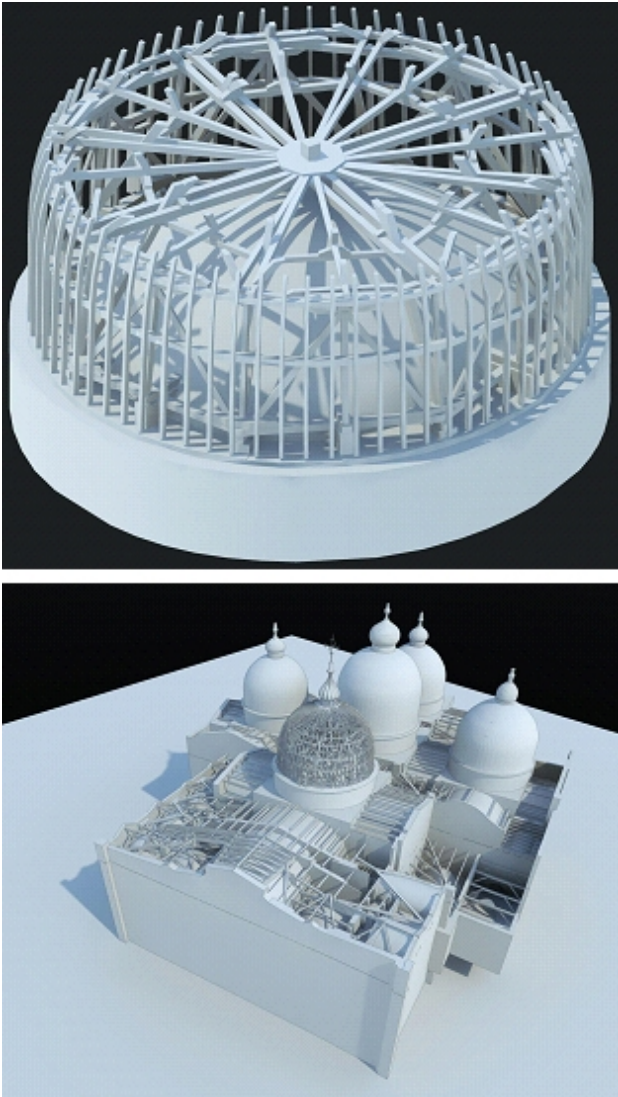


Figure 7. At the top, visualization and rendering of a view of the “Pentecoste” dome wooden structure; at the bottom, the whole roof’s hidden structure of San Marco Basilica, including also areas that were surveyed in previous stages (see Sb-sec. 1.2); all rendering have been performed in 3DStudioMax 2009 environment

## 6. CONCLUSION

In this paper a case study concerning the TLS survey of two domes of the well known San Marco Basilica in Venice, Italy, has been presented. For one of them, the “Pentecoste” dome, the modelling process has been fully completely at the moment of writing. For what concerns the other (the “Profeti’s” dome), processing is still ongoing.

The aims that have been demonstrated through this applications are twofold. First, laser scanning data fulfill the requirements for the surveying and modelling of bearing structures of architectures, because of their completeness, accuracy and high mass of data enabling semi-automatic modelling.

Secondly, the obtained 3-D model can be assumed as a Spatial Information System for Architecture (SISA) where all information on diverse elements can be archived and organized. At the current state of the project, the structure of the three-

dimensional spatial database is still limited to the definition of 3-D shapes and on their main attributes. Much work, from both conceptual and practical points of view, has be still carried out on the topological structure of the database, i.e. on the definition of relationships between different simple objects.

However, such instrument already fulfills the documentation and representation requirements of the San Marco Basilica, and it will be able to promote greater control and planning of conservative operation.

The measurement and diagram types of covering elements may facilitate the study involving the changes of the static function over time. Furthermore, the option to interface the virtual 3-D model by several types of end-users, also make possible the access to places that are usually not visible to the non-experts, but that are of great interest and architectural value.

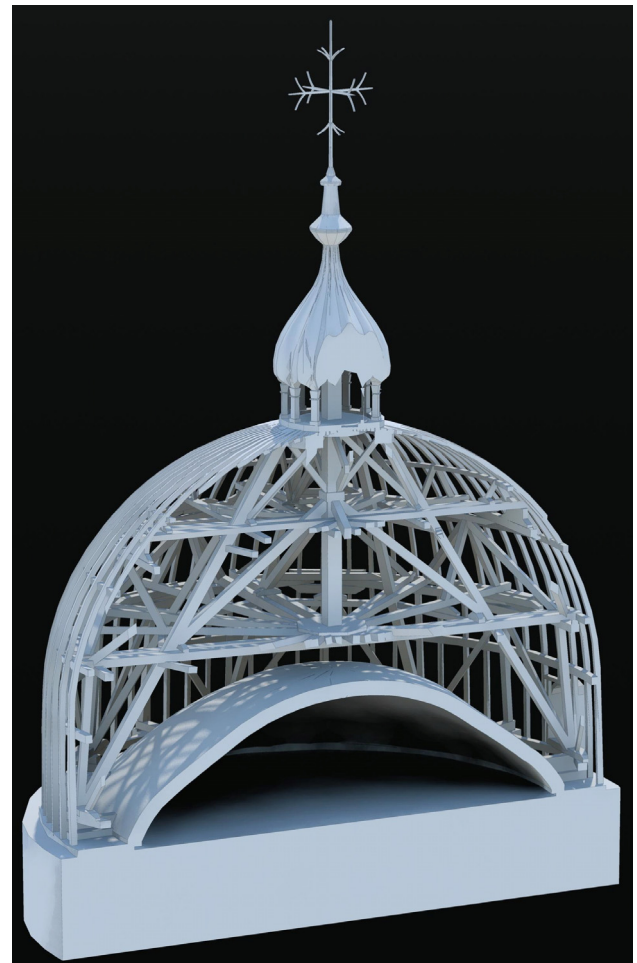


Figure 8. Visualization and rendering of the “Pentecoste” inner dome by using 3DStudioMax 2009.

## 7. ACKNOWLEDGEMENTS

We thank arch. Ettore Vio and Ing. Davide Beltrame for their cooperation and willingness to allow us to work in the San Marco Basilica places. We also thank Roberto Picelli for his work in this research project.

## REFERENCES

Beraldin, J. A., Picard, M., El-Hakim, S. F., Godin, G., Valzano, V., Bandiera, A. and Latouche, D., 2002. Virtualizing

a byzantine crypt by combining high-resolution textures with laser scanner 3d data. In: Proc. of VSMM, NRC 44959, Gyeongju (South Korea), pp. 3-14.

Budroni, A., Böhm, J., 2009. Toward automatic reconstruction of interiors from laser data. In: IAPRSSIS 38(5/WI), pp. 8, on CDROM.

Cecchi, R., 2003. *La basilica di San Marco, la costruzione bizantina del IX secolo. Permanenze e trasformazioni*. Ed. Marsilio, Venezia, Italy.

Gianinetto, M., Giussani, A., Roncoroni, F., and M. Scaioni, 2005. Integration of Multi-Source Close-Range Data. In: IAPRSSIS 36(5/C34), Torino (Italy), pp. 304-9.

Lorenzini, M., 2009. Semantic approach to 3D historical Reconstruction. In: IAPRSSIS 38(5/WI), pp. 8, on CDROM.

Remondino, F., El-Hakim, Girardi, S., Rizzi, A., Benedetti, S., Gonzo, L., 2009. 3D virtual reconstruction and visualization of complex architectures – The “3D-ARCH” project. In: IAPRSSIS 38(5/WI), pp. 8, on CDROM.

Vio, E., Lepschy, A., 1999. Scienza e tecnica del restauro della basilica di San Marco. In: Atti del Convegno Int. di Studi Venezia 1995, Istituto di Scienze, Lettere ed arti, Venezia, Italy.