COMBINATION OF LASER SCANNER DATA AND SIMPLE PHOTOGRAMMETRIC PROCEDURES FOR SURFACE RECONSTRUCTION OF MONUMENTS

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ABSTRACT

The reconstruction of precise surfaces from unorganised point clouds is an important problem in terrestrial laser scanning applications. The goal of surface reconstruction algorithms is to approximate the correct geometry, topology and features of an unknown surface only through a finite set of sample points. But unless the input data satisfy certain properties required by the algorithms, such as good distribution, density and little noise, then the reconstruction program may produce incorrect or even fail to give results. This is a typical problem with cultural heritage monuments, mainly due to the user time involved in acquiring data from occluded parts of a monument of large usually size rather than the inability of the laser scanner to provide data. This paper proposes a solution to surface reconstruction that is incomplete by applying simple photogrammetric procedures, and specifically the application of bundle adjustment methods using monoscopic measurements of homologue points on multiple images. Thus, without the need of control points, with low cost software that does not require specialisation in photogrammetric knowledge and equipment, the surfaces of monuments can be fully reconstructed. A case study is presented in this paper using data collected by a Cyrax2500 laser scanner and images captured by a SONY DSC-F707 5Mpixel digital camera from a Byzantine church in Peloponnese, Greece. The use of the laser data only in a standard modelling software produced an incomplete surface. A commercial photogrammetric software was also employed to perform the self-calibration of the camera and the 3D surfaces creation by manual selection of boundary points that were pictured in more than three images. The generation of the two different surface models and their combination to create a complete surface of the monument is described.

1. INTRODUCTION

The demand for 3D models of historical monuments is continuously growing in the field of archaeological and architectural applications. Currently, the two main sources of data that can provide detailed and reliable 3D surface models are the photogrammetric processing of digital images and laser scanning point clouds.

Photogrammetry is a mature technology for 3D coordinate extraction of points, through stereo-restitution or bundle adjustment of overlapping images. The number of produced points and the level of automation for close range applications involving complex objects are still relatively low and require time consuming procedures. Although the development of specialized software for direct production of 3D models following simple photogrammetric techniques have broadened the field of applications, yet this does not change the basic characteristics of the method.

The emergence of terrestrial laser scanning and state-of-the art software developments for processing the large amounts of the produced data may lead to the impression that this technology is the main solution for 3D models generation. However, laser scanners still remain quite bulky instruments and difficult to use especially for data collection entailing higher level positions with respect to the ground. Consequently, the existence of occlusions and the lack of data in some parts of the objects are frequent, resulting to incomplete models. Moreover, although there is an autonomy of laser scanning from topographic field work, still this is not always the case; i.e. when there is a need to incorporate a model into a particular reference system, or when the shape and characteristics of the monument do not allow a reliable cloud-to-cloud registration, there is need of surveying measurements. The use of spherical targets for a complete registration of point clouds is often not possible, thus increasing the number of acquired scans in the field.

The combination of products from laser scanning point clouds and products of photogrammetric procedures provides a reliable result with possibly less field work. This paper describes the surface model products obtained from independent photogrammetric and laser scanner data and the generation of an improved hybrid model using proprietary modelling software. The advantages of this approach are discussed through a case study of a cultural heritage monument of a Byzantine church in Peloponnese, Greece.

2. SURFACE RECONSTRUCTION USING LASER SCANNER DATA

Surface reconstruction is a well studied problem in computer graphics with a wide range of applications. With the advent of laser scanner systems, which can provide dense data sets from a variety of objects, the issues of surface reconstruction and modelling of closed surfaces are receiving great attention as they are not completely solved. Moreover, the challenge for surface reconstruction algorithms lies in finding methods which can cover a wide variety of shapes.

The main classes of reconstruction algorithms are based on spatial subdivision, distance functions, surface warping and incremental surface growing (Gopi et al, 2000). The common theme in spatial subdivision techniques is that a bounding volume around the input data set is subdivided into disjoint cells. The goal of these algorithms is to find cells related to the shape of the point set. The distance function algorithms define the shortest distance from any point to the surface. These are the most commonly used algorithms and the approach of Curless & Levoy (1996) is well suited to handle very large data sets such as those obtained by laser data. Warping-based reconstruction methods deform an initial surface to give a good approximation of the input point set. This method is particularly suited if a rough approximation of the desired shape is already known. Finally, the basic idea behind incremental surface construction is to build-up the surface using surface-oriented properties of the input data points.

Regardless of the implemented algorithms, Fabio (2003) defines four steps for the conversion of the measured data into a consistent polygonal surface:

a. pre-processing which involves elimination of erroneous data as well as resampling of points to reduce computational time
b. determination of the global topology of the object's surface, which derives the neighbourhood relations between adjacent parts of the surface; this operation considers possible 'constraints' (e.g. breaklines), mainly to preserve special features (like edges)
c. generation of the polygonal surface whereby triangular (or tetrahedral) meshes are created satisfying certain quality requirements, e.g. limit on the meshes element size, no intersection of breaklines. The triangulation is the core of the reconstruction process and converts the given set of points into a consistent polygonal model (mesh). This operation partitions the input data into simplices and usually generates vertices, edges and faces (representing the analysed surface) that meet only at shared edges
d. post-processing, which involves editing operations applied to refine the polygonal surface.

Nowadays, all the above operations are performed in a number of modelling software packages. The majority of these use polygons to accurately represent the results of measurements, providing an optimal surface description (eg Geomagic, Cyclone, Polyworks etc). On the other hand, there exist powerful 3D modelling and rendering packages (known as "computer animation software") which are mainly spline-based and include tools for 3D object modelling (pre-defined primitives), and texture mapping. These generally do not allow importing 3D point clouds and their final goal is usually the animation of the created model.

A proper reconstruction of the surfaces is possible only if the surfaces are "sufficiently" sampled. Whilst laser scanners provide sufficient sampling in most parts of the surface object, the common artefacts in the modelling appear when the surface is inadequately sampled is the presence of spurious surface boundaries. Manual interference or additional information about the sampled surface (for instance, that the surface is manifold without boundaries) are possible ways to eliminate these artefacts. Sometimes the input data might contain additional information for easier reconstruction. For example, data from laser scanners that generate samples uniformly on a sphere (or a cylinder), adjacent data points have a very high probability of being adjacent to each other in the final mesh (Gopi et al, 2000). The other extreme in the sampling problem is that the surface may be sampled unnecessarily dense. This may occur when a uniformly sampled model with a few fine details can cause too many data points in areas of low curvature variation (Kobbelt & Botsch, 2000). Another issue in surface reconstruction is the presence of noise and outliers in the original laser scanner data. The mode of data acquisition has a direct impact in that the scanner data can be very noisy when the surface is not oriented transverse to the scanning beam. Noisy data introduce high frequency artefacts in the reconstructed surface (like microfacets) and this is a cause of concern for many algorithms.

3. 3D MODELS USING PHOTOGRAMMETRIC SOFTWARE

Photogrammetric stereo-restitution in DPW is nowadays a standard procedure for mass 3D points production, not only in the case of aerial images but also in close range applications and especially at large scale recording of monuments. However, terrestrial photography presents enormous difficulties in automation of procedures, like matching of homologue points and DSM production. Data extracture is almost exclusively manual and time consuming but the creation of 3D models usually results in very accurate and reliable products (Georgopoulos et al, 2003).

As an alternative solution for the production of 3D textured models, software packages incorporating photogrammetric algorithms of multi-image management with bundle adjustment can be used. By pointing manually and monoscopically on homologue points on more than two overlapping images the optimum ray intersections are determined. For better accuracy and more reliable data determination, images should be taken rather with a convergence of 20^o-90^o, instead of the desired normal case of the conventional procedure of stereo-restitution. The creation of the model is achieved by selecting points that create planes or other mathematical surfaces (parts of cylinders, cones or spheres) and by adding geometric constraints in space.

A big advantage of these packages, e.g. PhotoModeler of Eos Systems Inc, 3D Builder and others, is the simplified and user-friendly interface that they offer, since they are made mainly for non-photogrammetrists. The basic problems are the lack of automated procedures, for example matching, which increases the required workload, and the insufficient ways for the assessment of the achieved accuracy. However, it is a cost effective solution with interactive processing for the 3D geometric recording of monuments and without any need for special knowledge of photogrammetry.

For the application described in this paper, the PhotoModeler software package (www.photomodeler.com) was used. This software has the ability of:

- self-calibration or introduction of interior orientation parameters, allowing the use of non-metric cameras
- the use of lines between points for the determination of the delineation of the objects
- imposing constraints, such as collinearity or coplanarity of points, perpendicular or parallel lines
- determining epipolar lines facilitating the location of homologue points
- producing models without control points, while the scale is determined by measured distances
- adding to the model mathematical surfaces, such as cylinders or other second order surfaces
- producing orthoimages at defined projection planes
- creating TIN and wireframe models
- applying texture to the model from images selected manually or automatically, and producing of photorealistic renderings
- 3D viewer, with zooming, rotating and measuring capacity on the model.

Through these capabilities, local or full 3D models using one or more digital cameras or even multiple frames of video recording of the monument can be produced. Speed, ease and the variety of alternatives in data acquisition make the use of such types of software very attractive. However, the production of a detailed and accurate model of a complex building or monument can be a cumbersome and time consuming task. The topography of the surrounding area of the monument and the existence of possible obstacles may hinder the multiple image capturing and thus the effectiveness of the procedure. However, the automatic creation of 3D compact models without holes or gaps is an advantage.

4. CASE STUDY

4.1 Description of data

The case study presented in this paper refers to the modelling of a cultural heritage monument and specifically a Byzantine church dated circa 11th century. This type is a typical example of monuments existing in Greece and other Mediterranean countries whereby their documentation and modelling is important for creating a data base of historical information for usage ranging from maintenance to applications involving the tourist industry.

Three types of data were collected for this monument: digital photo images, laser scanner data and geodetic measurements for control purposes. The digital photo images were captured using the SONY DSC-F707 camera of 5 Mpixel, with a resolution of 2560×1920 pixels. The flat surfaces of the church were covered monoscopically; those with a relief such as the roofs and the dome, were taken stereoscopically. Finally some extra images were taken with appropriate convergence angles (of 20^o-90^o), in order to be used in the modeling through the implementation of the PhotoModeler software. Totally, 134 images were captured, from distances that varied between 8-10m from the object and many control points were pre-signed and surveyed with an accuracy of ±5mm; 35 of those points were used for the photogrammetric creation of the 3D model.

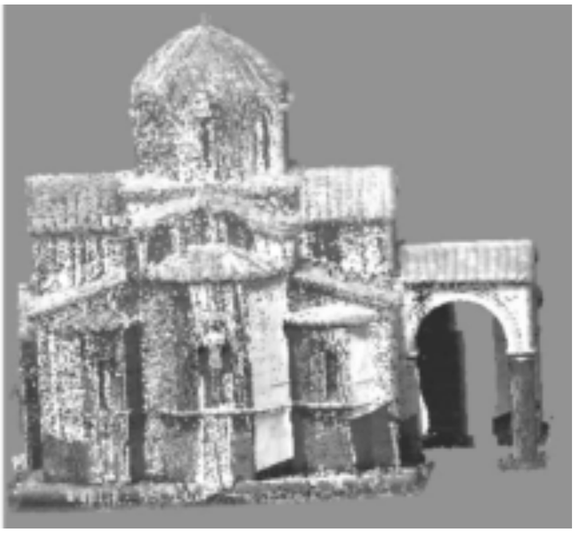
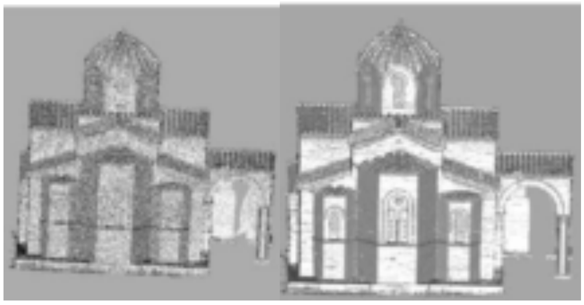


Figure 1. Registered point cloud of the church

The collection of the laser scanner data was performed using the Cyrax 2500 instrument. In total, 29 scans were collected out of which 14 were captured at the external part of the church and 15 from the internal part. From the external scans, 9 were collected with the instrument located on the ground and the remaining scans were collected with the instrument being mounted on a mobile hydraulic elevator. The point density was set to 1cm and 45 special reflective targets were used to facilitate the registration and orientation procedures. Furthermore, a Leica TCR705 total station was used to provide common reference system to both the photogrammetric and laser scanner data. The registration of all the scans (Figure 1) was performed in Cyclone software at an accuracy of 1.7cm, mainly due to the noise introduced by the motion of the elevator during the capture of the top parts of the church.

4.2 Laser scanner data processing

The core part of the reconstruction procedure is the triangulation process which converts the given set of points into a consistent polygonal model (mesh). This is a sophisticated and resource intensive process, even for specialised 3D modelling software and is currently under research investigation. In this study the triangulation process was performed using a commercial software package, the Geomagic Studio. There are three basic modules in this software, namely point, polygon, and shape. On point phase editing of point clouds is performed, while the polygon phase carries out the triangulation process and, finally the shape phase executes the NURBS modelling process.



(a) (b)

Figure 2. The eastern part of the model with (a) noise from triangulation process and (b) reduced noise

Although registration can be performed in Geomagic, it was decided to import in ASCII format the already registered by Cyclone point clouds. This is because Cyclone provides better tools for registration along with a number of quality control indicators resulting from the process thus enabling the user to control better the process.

During the point phase, a number of manual operations were executed in order to detect unsystematic or wrong points and delete these. Also, point thinning operation is available in this software but because it was shown that it may cause loss of details in the construction of the model it was decided to avoid this implementation. The triangulation process resulted in models with noise depending on the number of triangles used (Figure 2a) but after experimentation, the final model comprised 5 million triangles (Figure 2b).

However, the triangulation process usually results in a model that contains a number of gaps, holes, slivers, and overlaps. This is extremely common in 3D modelling, and there are a variety of methods used in filling these. Even when a surface is scanned repeatedly from different angles, occlusions may prevent access to the deepest crevices. Surfaces with complex shapes and multiple boundary components are commonly addressed with the problem of holes. Holes can also be caused by low reflectance, constraints on scanner placement, or simply missing views (Figure 3).

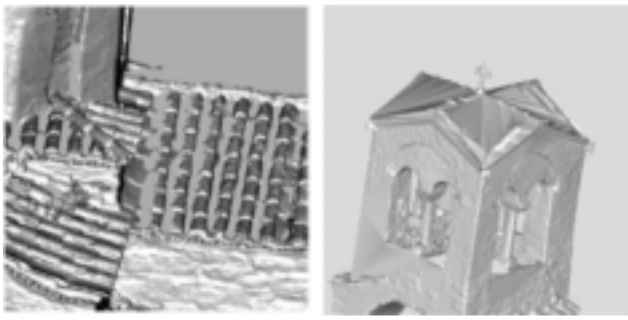


Figure 3. Parts of the model with holes or roughly completed flat surfaces in areas with no original data

Hole filling can be performed as a post-processing operation, usually applied after surface reconstruction. Davies et al (2002) define three main categories of algorithms for hole filling. The algorithms for hole-filling as a post-process are applied in an already constructed surface aiming to fill each hole with a patch that has a topology of a disc. However, for holes having multiple boundary components, many topologies are possible and therefore, the problem becomes more difficult. When hole-filling is performed using mesh-based methods, it is required to have knowledge of scanner lines of sight, and it performs poorly if these lines of sight do not adequately cover the volume outside the object. Although, additional lines of sight can be obtained by scanning backdrops placed behind the object, these solutions may be difficult to deploy outside the laboratory. The third method for hole-filling is point-cloud based which treats the union of all the scans as an unorganized set of 3D points to be fit with a continuous surface.

Usually the methods involve interpolation of the original samples using alpha shapes, crusts, or balls, or methods that evolve a surface over time until it approximates the data or fitting a set of 3D radial basis functions to the data. However, interpolation may not be appropriate for noisy data, and these algorithms may fail if sample noise approaches sample density, which in practise it happens. Also, in algorithms based on alpha shapes or balls, it may be difficult to find a single alpha (or ball radius) that bridges holes without also bridging fine surface details.

While the above techniques are applicable mainly in cases that require a watertight surface that bounds a volume of space, for example fabrication of physical replicas, there are other applications whereby a surface reconstruction method that preserves the geometry where it exists and smoothly transitions to plausible geometry in unobserved areas is more appropriate. An uncomplicated solution to bridging holes can be the use of external data in the form of either points or patches which are integrated in the triangulation process in order to connect the surface boundaries. Based on this idea, the use of photogrammetric data may be employed to form the topology of the object and maintain fidelity of the original shape when combined with the surface from the laser data.

4.3 Construction of hybrid model

In this case study the external surface of the church has been modelled using the Photomodeler software, independently from the laser data. The two models, created by different types of data and different methods were compared with respect to time, completeness, and accuracy. In addition, the ability to creating a hybrid model that would be free of gaps and holes, by extraction of selected parts of the photogrammetrically produced model and incorporating those into the Geomagic software was examined.

The following steps were followed within PhotoModeler:

- All available overlapping images were entered into the project. The positioning accuracy of the selected points is increased when the number of images on which the particular points are shown is increased. Acquisition of digital images is an easy and fast task, and it does not need the use of platforms of special size and stability; a characteristic of significant importance for the parts of the monument of high elevation. However, the demarcation of each point in each image is performed manually, thus the required time for this aspect of processing should be also considered.
- Parameters of the inner orientation of the camera were directly entered, without a self-calibration procedure, since they were previously known.
- Homologue points and objects were marked and matched on the images, by use of point, line and edge creating tools that are available in the software. Also, particular obvious constrains are entered, mainly referring to the parallel and vertical lines on object surfaces. Simultaneously, together with the point matching the model is created automatically.
- Available control points were entered into the project and marked in all images. The existence of control points on every image is not necessary; besides, the concept of stereo-pairs does not exist in this processing. For the accurate absolute orientation of the model very few control points and/or distances are needed practically; for the particular project many more (35) than the necessary control points were used.
- The 3D coordinates of the points were calculated automatically and mathematical surfaces were added, such as cylinders for the columns of the western facade.
- Object surfaces were defined and the 3D textured model was created.
- Orthoimage production is possible after the determination of the projection plane and required resolution. The user has the possibility to choose the suitable image(s) for the ortho-mosaic production.

In this study, the hybrid model production was mainly focused on two parts of the external surface of the church, which had totally different characteristics:

a. On the eastern façade of the church, the laser data were very dense and covered almost all surface details; the model produced from these data had only small local holes (Figure 2b). In this case, the study focused on whether the introduction of external data is practically improving the model or not, and whether this additional work is time and cost worthy. For the production of this part of the model in PhotoModeler, 26 digital images were used; a view of the final product is given in Figure 4.

Figure 4. The eastern part of the textured model produced in PhotoModeler

b. On the bell tower, the model produced from the laser data had many gaps and large holes at the tower sides and mainly at the roof. This is because there were practical difficulties in acquiring data from those parts of the monument. Additional data derived from other sources are needed here for the completeness of the model (Figure 5). For the production of this part of the model, 14 digital images were used in PhotoModeler; approximately 2,500 homologue points were marked and calculated. A view of the photogrammetrically produced model is shown in Figure 6.

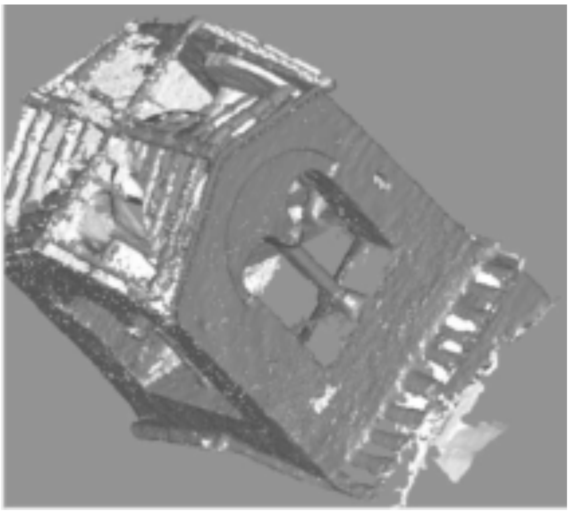


Figure 5. A view of the bell tower model produced from laser scanning data

Prior to the integration of the two models in Geomagic, appropriate transformation was implemented in order to unify the different coordinate systems. Characteristic points (corners, edges, etc) or targets which are shown on both models, were used. Texture information is lost after the extraction from PhotoModeler, only geometric information is preserved. The two models vary significantly in data density and features. There is high data density in the model produced by laser scanning, which gives the representation of the surface pattern; on the other hand an increased number of local errors are caused. In the model produced in PhotoModeler there are: well-defined points, few in number though, and correct positioning of the object surfaces, thus resulting to the construction of a 3D model consisting of comparatively large mathematical surfaces (planes or curved surfaces). So, the simple addition of the two models does not give acceptable results in terms of quality. Additional processing or production of a textured model, using images or technical texture, to give a homogenous view of the model is desired.

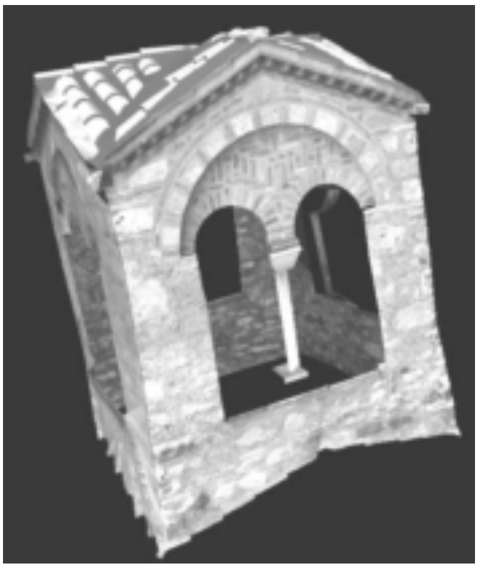


Figure 6. A view of the 3D textured model of the bell tower produced in PhotoModeler

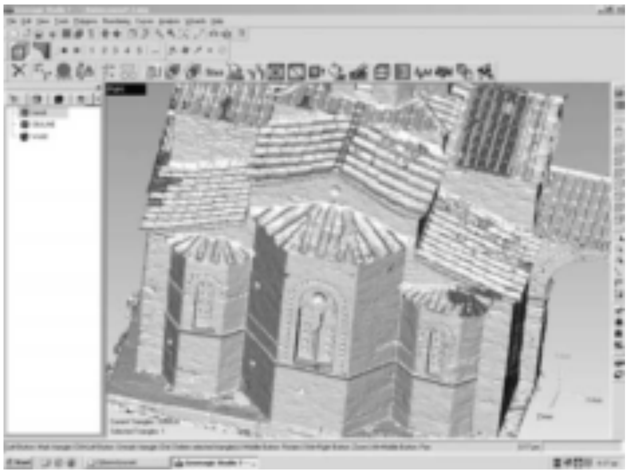


Figure 7. Screenshot of Geomagic during the generation of the hybrid model of the eastrern facade

The creation of the hybrid model of the eastern part of the church was proved to be an especially demanding and time consuming process. Additions of small surface patches into the model derived from laser scanning data diminish the fundamental advantage for fast production of a general 3D model using photogrammetric techniques. A number of local adjustments are needed, which result in many manually derived points in PhotoModeler. Finally, the addition of external information from the PhotoModeler was only proved useful for the tiles of the roofs, where there were curved surfaces without points derived from scanning (Figure 7). In all other cases it is preferable to use the automatic filling of gaps and holes.

On the contrary, at the bell tower, the need for additional information to the model produced from the laser data was profound. Almost the whole roof was replaced by the photogrammetric model, improving extremely the result (Figure 8). Obviously, the details of the tiles (which actually had to be marked manually almost one by one) and of the ending parts of the roof were produced by significant extra work load to the procedure of PhotoModeler, and consequently to the production of the hybrid model.

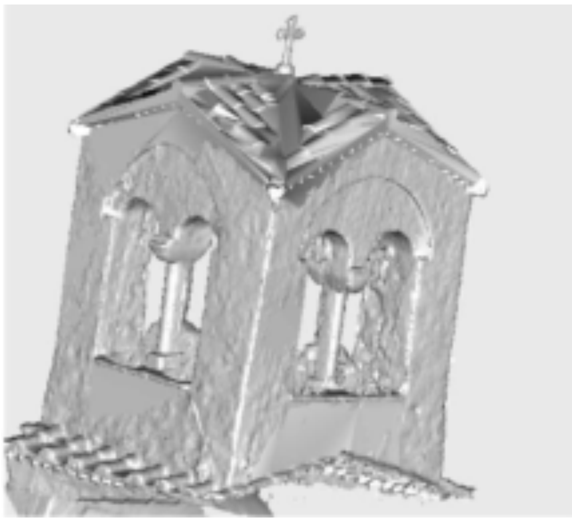


Figure 8. Hybrid geometric model of the bell tower

5. CONCLUSIONS

The growing demand for creating 3D models of objects has been greatly facilitated by the emergence of terrestrial laser scanning technology. However, a proper reconstruction of surfaces is possible only if the surfaces are densely sampled. Because this is practically not possible for surfaces of monuments of large size, the generation of 3D models may include manual interference or additional information about the sampled surface.

This paper has examined the use of simple photogrammetric techniques along with the laser data for a complete and high quality 3D model production. It was shown that high resolution image acquisition, which is the primary data in photogrammetry, becomes an easy and fast procedure using light digital cameras. On the contrary, the use of laser scanner is more time consuming and there is a demand for stable construction in order to facilitate the data capturing from positions above the ground. However, the 3D model production from laser scanning point clouds is a relatively automated procedure, while there are also techniques for automatic filling of holes. On the contrary, the photogrammetric procedure is mainly manual, but provides the possibility for textured model production.

There are some cases such as the examples presented in this paper, that the combined use of independently produced models from the two methods provides the best alternative solution. Laser scanning can give a detailed basic 3D model of the monument, while the addition of the photogrammetrically produced model may focus on the completion of the 'difficult' parts. There is today a great availability of commercial software packages that perform modelling and production of a complete model but the performance of the software is strictly related to the implementation and the available hardware.

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