THE DOCUMENTATION OF THE MEDIEVAL ENTRANCE OF THE RHODES FORTIFICATION COMPLEX

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ABSTRACT:

The documentation and reconstruction of cultural heritage monuments represents a permanent record of the real world object in its original position and has been greatly facilitated with the technological advancements in data collection and processing using digital photogrammetry and terrestrial laser scanning. This paper presents an example of a monumental complex requiring detailed documentation. The purpose is to examine the complete workflow of documenting the Sea Gate of the Rhodes medieval fortification complex. It presents interesting aspects such as complex spatiality, different building materials and architectural decay. A multi-sensor approach was considered as the most suitable for such a complex structure and therefore, surveying, photogrammetric and terrestrial laser scanning techniques were employed. The process to obtain the orthophotomosaic from merging the different data types is explained. Also, the photorealistic texturing of the object is investigated and the resulted orthophoto products are given.

1. INTRODUCTION

The documentation and reconstruction of monumental complexes contributes to the identification of the historic and urban characteristics of sites and enables relevant procedures for their restoration, preservation and environmental upgrading. The main interest for the products of documentation procedures is the detection of erosion through environmental elements and the documentation of a restoration process. Another attractive application is the visualization of reconstructed 3D models in a virtual reality environment.

The photogrammetric textured representations, using mainly orthophotomosaics, have been proved to be powerful products of documentation as they combine both geometric accuracy and visual detail in a 2D or 3D platform. There is still an unsolved problem with the complete orthoprojection of complex objects though, as the description of the analytical shape of the object cannot always be accurate, especially in areas where points with the same planimetric coordinates show different heights. Regular grids integrated by break-lines and DSMs (Digital Surface Models) are the most popular and investigated solutions used to build-up a mathematical shape description of such an object. In both cases complex algorithms and expensive computation times must be used before and during the orthophoto production. It is obvious that for complex structures the accurate and fully automatic capture of all details to create large scale 3D models remains at present, elusive. Therefore, the requirements of each application define the data types and acquisition procedures being followed.

The recently published literature has shown that in many cultural heritage applications the combination of digital photogrammetry and terrestrial laser scanning can supplement each other in creating high-quality 3D presentations. Specifically, laser scanning can produce the dense 3D point-cloud data that is required to create high resolution dense DEM for orthophoto generation and can be considered the optimal solution for a correct and complete 3D description of the shape of a complex object. However, a correct DSM cannot always guarantee the generation of accurate orthophotos or even acceptable photorealistic images. This is due to a number of problems such as the perspective deformations of an image and the relief of the object (i.e. occlusions). When stereopairs are taken with a certain inclination of the optical axis it can result to a different ground resolution over the image and the effect of tilt on the image geometry can cause distortions in the resulted orthophoto. In order to maintain the visualisation effect and have photorealistic models, it is possible to supplement the distorted areas of the orthophoto by texture mapping using both the image and laser data.

In light of this notion, this paper describes the documentation of a significant cultural heritage monument using photogrammetric and terrestrial laser scanning techniques. The documentation of the Sea Gate of the medieval fortification complex of Rhodes in Greece presents many interesting aspects due to its complex spatiality, different building materials and architectural decay. In section 2, a brief summary of the procedure for generating orthophotomosaics and textured models is given and the common approaches are reviewed. Section 3 describes the data acquisition process and discusses the optimization of fundamental resources such as acquisition times, scanner point resolution, number of photographs etc which have to be taken into consideration in order to make any high complexity surveying project feasible. Also, the process to obtain the orthoimage product from the merger of the different data types is explained and the final models of the structure are given. Problems on the produced orthoimage are identified but the visualization effect is maintained through the use of texture mapping. Finally, conclusions are given on the tradeoff between the level of interaction/automation required during the data processing in order to achieve accurate results and the model requirements for documenting heritage monumental complexes.

2. TYPES OF DOCUMENTATION PRODUCTS

2.1 Orthophotomosaics

Technological advances in recent years have spectacularly multiplied the variety of sources for collecting metric information at such large scales. In order to fully exploit these data special techniques should be developed. Moreover, the advancements in computer industry have enabled the three dimensional visualizations of the monuments in a virtual world. The compilation of 3D models of archaeological monuments is considerably facilitated by the usage of dense point clouds, which are created by the use of terrestrial laser scanners. Their combined use with photogrammetric procedures, such as the production of orthophotos, allows the realistic 3D representation of complex monuments such as sculptures. In this context virtual reality tours have been created for simple or more complex monuments. This ability has greatly contributed to the thorough study of the monuments, as well as to the creation of virtual visits.

The Geometric Recording of Monuments at large scale, i.e. larger than 1:100, presents several difficulties and peculiarities, which call for special attention by the users. The need for large scale images, the presence of extremely large height differences compared to the relatively small taking distances and the multitude of details usually present on the surface of the monuments combined with the high accuracy requirements are the main sources of these difficulties for the production of the conventional line drawings. The production of orthophotographs presents even more special problems, as it usually is a case of a highly demanding true orthophoto. Special techniques have been developed to address these problems in the best possible way. (Dequal and Lingua, 1999, Mavromati, D. et al. 2002, Wiedemann, A., 2002).

Recording of monuments often demands the production of special products, quite different from those of conventional photogrammetric applications. Among others the 3D visualizations, supported by technological advancements, have added a significant means of representation of the complex monuments. The combination of available data has enabled the construction of highly detailed 3D models, which could convey the accuracy of the original data. Rendering techniques supported by increasing computing power have significantly contributed to the aesthetic appearance of these visualizations. The next step is to enable the performance of accurate measurements on these 3D visualizations.

Terrestrial laser scanning on the other hand provides the user with point clouds, polygon meshes, range images, parametric surfaces and finally 3D models. Although they produce impressive raw data, the extraction of the expected and required information in the end is rather tedious, especially in the case of monument recording. Hence, while point clouds appear easily on a computer screen and undeniably are a satisfactory optical end product for simple shapes and views, they can be interpreted very difficultly in the case of complex shapes, very often present in cultural heritage monuments, and lead to accuracy loss during processing especially in cases of complex monuments requiring large number of scans. Consequently point cloud processing software should be able to provide to the end-user datasets that are usable, the ability to produce additional products, the ability to perform measurements and determine cross sections and automatic vector extraction.

The basic steps for point cloud processing usually include:
Registration or aligning of scans in order to bring all the scans of a monument to a common coordinate system. This may be done using targets, most commonly used with time-of-flight scanning, or without targets just with the clouds or on triangle meshes. For this last case there are a variety of semi-automatic techniques used, like the iterated-closest-points (ICP) algorithm, which finds matching points on two meshes, computes the rigid transformation that minimises the squared distances of these point pairs and iterates until some convergence criterion is met (Besl and McKay, 1992).

Merging is needed in order to integrate registered sets of surface measurements into a single 3D surface model. The generic problem of surface reconstruction is to estimate a manifold surface that approximates the unknown object surface from a set of sampled 3D points, without making any assumptions about the surface shape. The main algorithms applied for this purpose are mesh integration and volumetric fusion (Curless and Levoy, 1996).

The next step is modelling, necessary for the creation of a final 3D solid model of the monument. A very important process is the noise reduction through the use of filtering and smoothing techniques in the model. The existence of noise may be attributed to a number of sources, such as the reflectance of the material, the effect of slight vibrations during scanning etc. There is always a risk that together with the noise slight local anomalies of the surface may be lost.

Rendering or visualization software has been developed mainly for the electronic games. Their capabilities and requirements vary extensively. However there are several packages, such as e.g. 3DStudio Max, that are able to respect the accuracy of the raw data and perform highly reliable renderings. The task of this category of software is to attach raster or texture information to the surface models; hence their existence and interrelation are a prerequisite.

2.2 Textured models

The visualization of a 3D model is often the only product of interest for the users and is therefore, important to have a realistic and accurate visualization result. The photorealistic visualization of 3D models (image-based rendering) is called a textured model. In its basic form, texture mapping lays an image (the texture) onto an object in a scene by mapping a function onto a surface in 3-D. The domain of the function can be one, two, or three-dimensional and be represented by either an array or a mathematical function. The source image (*texture*) is mapped onto a surface in 3-D *object space*, which is then mapped to the destination image (*screen*) by the viewing projection. More general forms of texture mapping generalize the image to other information (Heckbert, 1986).

When mapping an image onto an object, the colour of the object at each pixel is modified by a corresponding colour from the image. In general, obtaining this colour from the image conceptually requires several steps (ibid, 1986). The image is normally stored as a sampled array, so a continuous image must first be reconstructed from the samples. Next, the image must be warped to match any distortion (caused, by perspective) in the projected object being displayed. Then, this warped image is filtered to remove high-frequency components that would lead to aliasing in the final step: resampling to obtain the desired colour to apply to the pixel being textured.

In its simplest form, texture mapping involves the so-called appearance modelling which refers to image perspective techniques (IPT) with direct mapping of photographs onto a 3D model and reflectance modelling. High-resolution colour images can be precisely mapped onto the geometric model provided that the camera position and orientation are known in the coordinate system of the geometric model. The main challenges faced by people in that field are related to the accurate computation of parameters such as lens distortions, estimating 2D camera to 3D-model pose, dealing with hidden surfaces and incomplete views (e.g. Bernardini et al., 2001).

When using images obtained by 2D cameras with standard lenses then the lens distortion parameters have to be compensated at the texture mapping process. Otherwise, distortions will be visible if portions of the 2D image are mapped on wrong locations on the 3D model or at common edges of adjacent triangles mapped from different 2D images. A way to avoid such effects is to transform photographs into orthophotographs and then map them manually onto a 3D model using commercial software. However, any geometrical error in the projection process involved in the use of orthophotographs will diminish the realism that one can attain (Beraldin et al., 2000).

Techniques that map real-scene images onto the geometric model have been developed by using photogrammetric techniques or simple images. Wright et al. (2001) present a hybrid system using photogrammetric modelling techniques with laser acquired range data by incorporating the latter for those parts of the scene that are unmodelled. The salient planar features in the scan are extracted and used to align the models via an ICP-based registration. Rendering is achieved using view dependent texture mapping techniques combined with point-based rendering. The process allows for straightforward integration of multiple range scans. In Grammatikopoulos et al. (2004) an approach is presented for automatically generating orthoimages and perspective views from a 3D mesh, obtained via laser scanning. This is performed by identifying all surface triangles seen in the particular projection as well as recognising which of them appear on each available image. Then, the pixels of the novel image are coloured by weighted blending of texture from all viewing images.

On the other hand, when a 'single-image' texturing approach is implemented, it may result to adjacent surface triangles receiving colour from different images with varying radiometric characteristics, which in turn can cause discontinuity artifacts and radiometric distortion at triangle borders (El-Hakim et al., 2003). In Poulin et al.(1998) it is discussed that the contribution of input images is made according to their spatial relation to the object surface (e.g. distance, angle of view) and their characteristics (camera constant, resolution) in order to assign a unique colour value to each individual surface unit.

Janko and Chetverikov (2004) present a methodology whereby using datasets of diverse origin, ie a number of partial measurements (3D point sets) made by a laser scanner, and a collection of high quality images of the object acquired independently by a digital camera, they can create a textured model. Using genetic algorithms they obtain a precise registration and a complete geometric model is created by triangulation, but it lacks texture and colour information. Initial image-to-surface registration is performed but the images are taken freely from different viewpoints and with varying zoom. So, the problem of seamless blending of multiple textures is solved by a surface flattening algorithm that gives a 2D parameterisation of the model.

While there are approaches for the creation of textured surfaces, the problem remains regarding the availability of commercial tools for texture mapping onto dense 3D models generated from range images. In light of this notion, the combination of photogrammetric data and laser data for texture information was examined from a user's perspective based on commercial tools. This paper reports on creating a photorealistic model of the Sea Gate from the blending of an orthophotomosaic and a textured laser data surface using commercial software.

3. DATA ACQUISITION AND RECONSTRUCTION

3.1 Brief history

The fusion of different data types was implemented at the monumental complex of the Rhodes fortification. The medieval city of Rhodes was initially established at the end of 7th century AC and the fortification structure was completed at the end of 11th century. Listed as an UNESCO cultural heritage city, the architectural literature considers it as one of the few well preserved structures of the western Mediterranean area presenting great interest with an articulate aggregate of buildings established in Medieval, Byzantine and Ottoman ages. The most impressive and possibly, unique fact is that the fortification of Rhodes has maintained its integrity since 1522 with minor changes during the 430 years of Ottoman and Italian occupation. The main entrance of the fortification complex, named as Sea Gate (Figure 1), suffered severe damages during the 2nd World War, but today is fully restored. The dimensions of the Gate are 20m ×15.5m and the height is 17.5m.

Figure 1: East View of the Sea Gate

3.2 Data

In order to generate both photogrammetric and laser scanner 3D models of the monument, different instruments were employed. The data collection was facilitated by a lifting machine. For the photogrammetric model, a Canon MII digital camera (image resolution 2336 × 3504 pixels) has been used. The size of the Gate required a large number of images to be captured. About 30 stereo-images were needed to cover the gate, of which 6 were used for the entrance and 16 for the towers. The average distance from the camera to the monument was approximately 12m.

In addition, the Cyrax2500 terrestrial laser scanner was used which allows a field of view (40° H x 40° V). Typically, the accuracy of the sensor is about 6 mm (at 50 m distance) but the laser is not able to register the reflected RGB colours and therefore, for any texture mapping it was obligatory to use images from a CCD camera. However, the internal camera of the specific scanner is of very low resolution so the externally acquired images were used in this process. The number of collected scans was 16 for the front part of the Gate. The point density was chosen at 2.5cm for 10 scans and 0.5cm for 6 scans that acquired for the details of the monument. The average distance of the scanner to the object was about 20-30m. The image and scan acquisition required three days and effort was made to optimise the fundamental resources such as acquisition times, scanner point resolution, number of photographs etc which have to be taken into consideration in order to make any high complexity surveying project feasible.

Coordinates of ground control points, as common points for the georeferencing between the two models, were measured with a Topcon total station with reflectorless capability. Initially, a nine-point traverse was established that was connected to three existing survey marks. About 150 control points were measured with an accuracy ranging from 0.5-1.5cm. In order to compare the georeferencing of the laser scanner model using both natural and artificial targets, part of the control points (60) were chosen as easily recognizable features on the monument and further 90 targets were evenly placed on the walls of the monument.

3.3 Preliminary results

The initial scans were examined and cleaned from spurious and noisy data and the registration was performed in Cyclone software using natural targets on the surfaces of the scanned object. The registration gave results with an RMS of about 5mm. Due to the large overlap of the scans and the large volume of the data, decimation was performed in Geomagic software in order to reduce the points from about 12 million to 6 million by using the ‘uniform sampling’ command of the software (Figure 2). The georeference of the registered point cloud was performed through a common coordinate system defined by the total station survey.

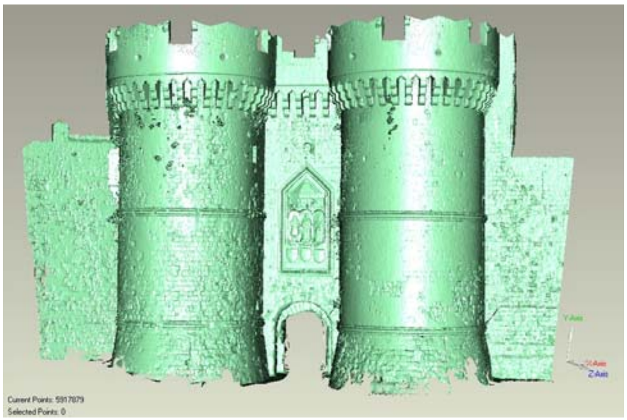
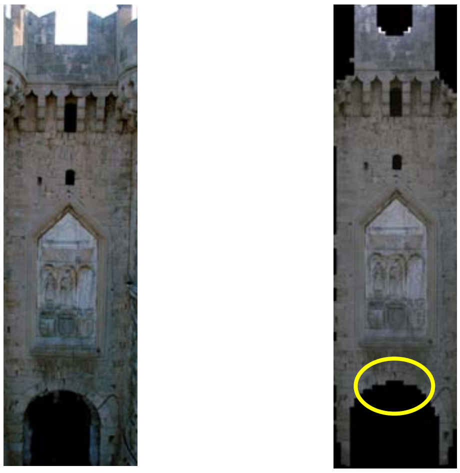


Figure 2: Registered point cloud of the monument

The following step referred to the surface generation; a TIN surface of about 7 million triangles was created in Geomagic. However, due to occlusions and other shadow effects, there were evident some holes in the resulted surface. The majority of gaps were covered by using the ‘fill holes’ command of the same software. The remaining holes are considered that have no serious effects for the following processing steps.

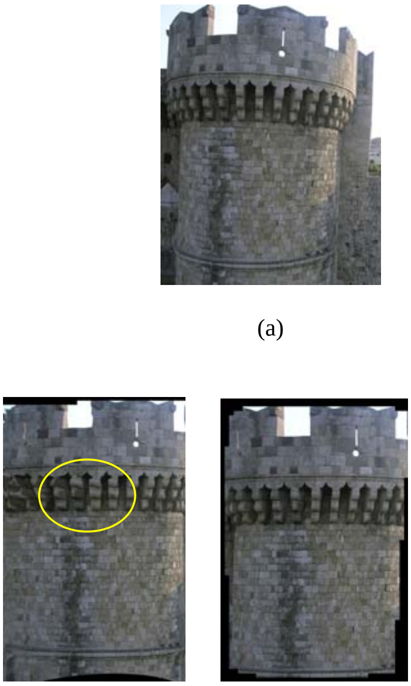
For the orthophoto generation, the most suitable stereo-images were selected from the acquired photos. For the photogrammetric operations the parameters of the interior orientation determined independently were used. The exterior orientation presented some difficulties due mainly to the excessive relief of the object (up to 5m) compared to the taking distance (10m) and the relatively low accuracy of the calculated control points. Specifically, a number of stereopairs were taken with a certain inclination of the optical axis. During the processing it was demonstrated that the relative and absolute orientation for the upper parts of the monument was much harder to achieve due to high relief and the difficulty to determine natural tie points. The resulted RMS of the exterior orientation was in the order of 1.5cm for plane surfaces and about 4cm for surfaces on the two towers which have complex geometry. In Figure 3, it is seen that for plane surfaces the produced orthophoto gives acceptable results with the exception of the entrance where effects of distortions are evident, most possibly due to the DSM which, in this case, did not have manual intervention. The DSM resulting from laser scanner data may contain points not situated on the object’s surface; this often occurs at the edges of a structure. In the case of Figure 3, the DSM describing the edges of the entrance may have been erroneous and caused the poor results in the specific area of the orthophoto. The error cannot be attributed to the collected images because these were acquired viewing the projection plane.



(a) (b)

Figure 3: (a) Image and (b) orthophoto of the central part of gate (plane surface)

In order to create the orthophoto it is essential to have DSM information of the object. For this reason, the registered point cloud was imported in the software. Each stereo pair was checked independently to assess whether there were errors in the DSM and in cases of high relief, manual break lines were introduced. The upper parts of the monument required a higher number of break lines and manual editing of the DSM due to the object geometry. In Figure 4(b) it can be seen that the DSM from the laser data could not fully describe the complex geometry of the tower’s upper part due to occlusions and limited points in the scan. The right part of the orthoimage in Figure 4b is not acceptable and for this reason manual editing of the DSM as well as import of break lines was necessary in order to produce the correct orthophoto of Figure 4c.



(a)

(b) (c)

Figure 4: (a) Image of right tower (complex geometry) and orthophoto (b) with DSM and (c) with edited DSM

Clearly, to avoid problems like the above it is important to have favourable network geometry. This can be achieved when photos are taken with the same focusing condition of the application case. Also, to compensate the planarity of the test-field, the images should be acquired at different distances from the object.

Even with the improvement of the DSM by manual editing, the resulted orthophoto is not always of acceptable quality. This is mainly because tilted images up to certain limit of angles can give a bad geometry. Also, a bad DSM can cause a disruption and increase the errors at the produced orthophoto. In order to maintain a visually correct result in the problematic areas of the orthophoto, surface patches are created by using texture mapping techniques for these areas which are then blended locally in the orthophoto.

The purpose of texture processing is to integrate the 3D measurements from the laser scanner with 2D information taken with an external camera. In order to project a 3D point into an image and thus assign a colour value, the software needs to know uses a calibration algorithm and requires a set of corresponding 2D coordinates from the image and 3D coordinates from the point cloud to compute the required parameters for external orientation. If several images of the object have to be taken from different viewpoints, it is possible to mosaic them in a single texture, the images need to be balanced on a global per image basis and finally blended locally along the transition between images.

Following a standard photogrammetric practice, texture for visible surface patches is extracted here from one corresponding original image. If more overlapping images are available the source image can be selected according to different possible criteria (imaging distance or angle formed by the projective ray and the surface; size of the imaged surface triangle).

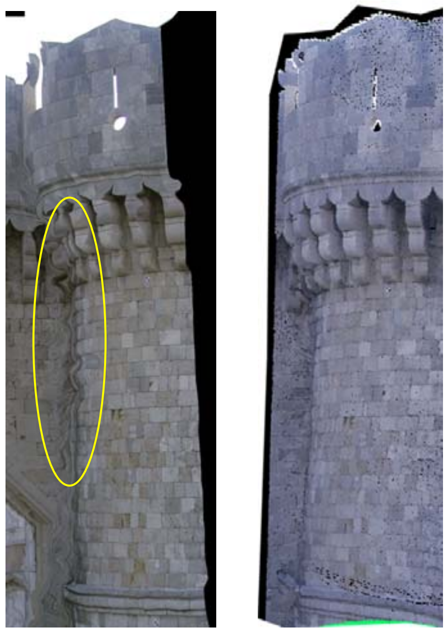


Figure 5: (a) Orthophoto of right tower and (b) blended orthophoto with textured mapped patches

The generation of the blended orthophoto starts with defining the projection plane, the front and back clipping planes, the extent of the orthophoto and its resolution. Then, the scan positions which should contribute to the textured image are specified. It is assumed that all selected scans have to be transformed into one common coordinate system. Knowing all scans to be textured, the following step requires identifying proper photos showing the suitable content. The last function involves the merge of the scans and photos by selecting few points commonly distributed in both. These can be tie points or natural points which in effect serve as a list of correspondence between the 3D laser scanner points and their image coordinates. Figure 5a indicates a typical example of a distorted orthophoto at the edges of the tower and at objects with complex geometry, while Figure 5b shows a blended orthophoto where the distorted areas have been substituted with textured mapped patches offering a visually correct image.

On the practical aspect, it must be mentioned that it is difficult to find a commercial software package that does accurate real scene image (texture) mapping onto general cloud points or onto polygonal 3D models in localised sections and the user will have to rely on ad hoc methods. For instance, it is possible to transform photographs into orthophotographs and then map them manually onto a 3D model using commercial software. Unfortunately, geometrical error in the projection process will diminish the realism that one can attain. This is due in part by the manual alignment procedure involved and the use of orthophotographs. These photographs are constructed in such a way that the effects of perspective and tilt are removed. However, in cultural heritage documentation there is no such problem because of the camera-object’s high distance, the perspective and tilt effects can be minimized.

4. CONCLUSIONS

Geometric recording of monuments is a highly demanding task in many ways. All techniques of field data acquisition, however sophisticated, have proven unable to meet the demands of such a task single handed. Experience has shown that only by integration of multi-source data is it possible to provide the necessary information with the required accuracy and completeness. Especially in the case of large and complicated monuments parallel use of geodetic measurements, photogrammetric data acquisition and terrestrial laser scans has proven the ideal combination for the desired result.

It has been clearly shown that for the complete 3D representation of a complex object in large scales a multitude of methods and data sources is advantageous. There are cases where the fieldwork required to produce an acceptably rendered 3D model leads to uneconomical solutions. In these cases texture mapping is an option in order to improve the aesthetic result. However, it should be used cautiously, as -in most of the cases- it cannot convey metric information correctly.

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References:

Bernardini, F., Martin, I.M., and Rushmeier H. 2001. High-quality texture reconstruction from multiple scans, In IEEE Transactions on Visualization and Computer Graphics, 7, 4, 318-332.

Beraldin, J.-A., Blais, F., Boulanger, P., Cournoyer, L., Domey, J., El-Hakim, S.F., Godin G., Rioux M., and Taylor J. 2000. Real world modelling through high resolution digital 3D imaging of objects and structures, *ISPRS Journal of Photogrammetry and Remote Sensing*, 55, 4, 230-250.

Besl, P. and N. McKay, 1992. “A method for registration of 3D shapes”. *IEEE Trans. PAMI*, vol. 14(2), pp. 239-256.

Dequal, S., Lingua, A., 2001. True orthophoto for architectural survey. *Proceedings 18th International Symposium CIPA*, Potsdam. p. 269-276.

El-Hakim, S., Gonzo, L., Picard, M., Girardi, S., Simoni, A., 2003. Visualization of frescoed surfaces: Buonconsiglio Castle – Aquila Tower, ‘Cycle of the Months’. Int. Workshop on Visualization & Animation of Reality-Based 3D Models [on CD-ROM].

Grammatikopoulos, L., Kalisperakis, I., Karras, G., Kokkinos, T., Petsa, E., 2004. Automatic multi-image photo texturing of 3D surface models obtained with laser scanning. In: Proc. CIPA International Workshop on *Vision Techniques Applied to the Rehabilitation of City Centres*, 25-27 October, Lisbon [on CD-ROM].

Heckbert P.S., 1986. Survey of Texture Mapping. IEEE Computer Graphics and Applications, November, p. 56-67.

Janko, Z. and Chetverikov, D., 2004. Photo-consistency based registration of an uncalibrated image pair to a 3D surface model using genetic algorithm. In: Proc. 2nd Int. Symp. on 3D Data Processing, Visualization & Transmission, p. 616–622.

Mavromati, D., Petsa, E., Karras, G.E., 2002. Theoretical and practical aspects of archaeological orthoimaging. *International Archives of Photogrammetry and Remote Sensing, Vol. XXXIV, part 5. Proceedings ISPRS Commission V Symposium Close-range imaging, long-range vision. September 2002, Corfu*. p. 413-418.

Poulin, P., Ouimet, M., Frasson, M.-C., 1998. Interactively modelling with photogrammetry. Proc. Eurographics Workshop on Rendering ’98, pp. 93-104.

Wiedemann, A., 2002. Challenges and solutions on the generation of digital surface models of facades using image processing techniques. *International Archives of Photogrammetry and Remote Sensing, Vol. XXXIV, part 5. Proceedings ISPRS Commission V Symposium Close-range imaging, long-range vision. September 2002, Corfu*. p. 479-483.

Wright, M., Watson G. and Middleton, R., 2001. Archetype: Towards the Integration of Photogrammetric and Laser Range Data for Architectural Reconstruction.", *Proceedings of the International Symposium on Virtual and Augmented Architecture,* p 255-266.