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# PHOTOGRAMMETRIC TEXTURE MAPPING OF COMPLEX OBJECTS

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**ABSTRACT:**

Today's continuously growing demand on 3D textured models has given rise to many different methods for the production, maintenance, publication and exploitation of this kind of data. 3D content creation and presentation is currently drawing the interest of all major Information Technology and Research & Development stakeholders given the range of well established and prospective applications on education, entertainment, science, internet, tourism etc. This paper is dedicated to highlighting various aspects of the creation of high quality 3D textured models for various applications, while arguing the advantages of integrating photogrammetric methods in the texture mapping process. Drawing on the authors' experience two example cases of complex objects are presented in order to introduce the reader to the techniques employed, the tools that were developed and the potential of the proposed process.

## 1. INTRODUCTION

3D modeling is currently one of the most active research areas. The number of applications that already exploit or could prospectively employ 3D content is virtually unlimited. Also, the multiplicity of the acquisition systems, processing software and developer background and skills has resulted in a variety of approaches. Many contributions have been dedicated to reviewing various acquisition systems (Beraldin, 2000) and classifying surface reconstruction and measurement techniques (Remondino, 2006). There are also numerous papers on the subjects of texture blending, stitching, registering or mapping in general. In many of the publications authors present methods that automate or optimize a part of the process and describe the approach followed for various example projects. (Berardini, 2002) vividly illustrates the diversity of the various approaches applied, in offering an excellent review on algorithms that have largely been employed for the various steps of the 3D modeling pipeline.

The main objective of this paper is to advocate the use of photogrammetric procedures for high quality texture mapping of complex objects and sites. Although most 3D acquisition systems enable the user to capture the colour of an object either as a native system option or by the use of special gadgets such as custom arms and frames, the colour of the end product may be poor. Besides colour variations due to different illumination conditions, the images required to fully texture a model usually significantly outnumber the required scans. In most cases if only the images acquired from the scan setups are used, texture on the final model may be stretched at highly curved areas, invalid in parts that were occluded or non existent in object areas that may not be acquired or in areas where the acquisition process may fail. In almost all cases geometric information may easily be processed, healed or even artificially modelled in order to have a closed-surface model. However this is not the case with colour. The photogrammetric registration of images with a 3D data model is a process that effectively disengages the geometry acquisition process from the acquisition of images. In this respect, the geometry of an object may be recovered by use of a relatively limited number of set-ups, whereas hundreds of images may be acquired in order to texture the model with high resolution colour. Of course additional point measurements may be required in the field, but the end product is metric, the overall accuracy is uniform and texture is accurately registered. The research presented here also includes information on how the authors properly adapted and combined various photogrammetric and texture mapping software and processes, in order to handle numerous images per object, eliminate color variations and illumination differences, produce seamless high resolution texture maps and create realistic 3D models that are easy to load over the internet and provide free user interaction. Since this paper mostly employs commercial software an extensive review of the related literature would far exceed the scope of this paper. However, the next paragraph includes a few references in order to provide information on related research, highlight the merits and prove the potential of the methods proposed here. Some examples, are given so that the efficiency of the suggested approach is proved. Finally, some conclusions and future research complete this contribution.

## 2. RELATED WORK

3D modeling is invariably related to a significant number of research areas including, among others, electronics, optics, mathematics, software development, computer vision, multiple view geometry, computer graphics and photogrammetry. Photogrammetry has for long been a collection of techniques that enable the production of line drawings, orthorectified images, developments and surface reconstruction of objects or landscapes, through combining images and object measurements. Traditional photogrammetric products such as orthophotos, orthophotomosaics and developments are the metric equivalents of orthographic-view renderings, multi-image-based renderings and texture maps respectively. In the recent years, the great evolution of various 3D sensing systems has drawn the interest of photogrammetrists and resulted to a great deal of research activities with the aim to combine 3D acquisition systems with the photogrammetric processes. Currently the use of e.g. laser scanner data for the production of orthophotos and line-drawings is fairly standard. However, the combination of 3D acquisition systems and photogrammetric methods for the production of high resolution 3D textured models still remains a challenge.

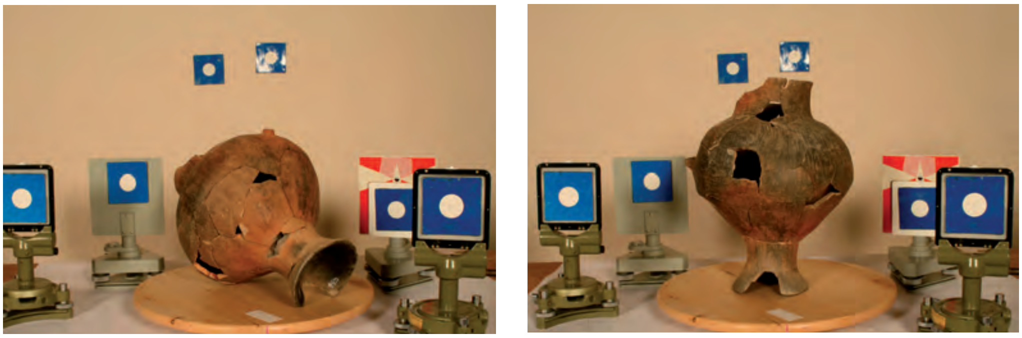

Figure 1: Example of target configuration for different positions of the object

Typically, a 3D modeling workflow can be summarized in three basic steps: 1) surface reconstruction, 2) texture mapping and 3) publication. Over time numerous algorithms for surface reconstruction have been presented, including photogrammetric modeling (Debevec, 1996), shape from silhouette (Niem 1999), structure from motion for uncalibrated image sequences (Pollefeys, 2004), dense correspondence search (Van Gool, 2002) etc. Also, various systems such as laser-, triangulation- and structured-light scanners have been employed for various applications. All of these methods yield low or high density 3D mesh surfaces depending on the resolution of the system employed and the applied algorithms. For this research, data acquired by 3D laser scanners are employed. Also, there are various methods as to how the texture is binded to the 3D surface model. In some cases, such as in (Debevec, 1996) and (Beraldin, 2002) texture is drawn from images that have been registered to the 3D model by a photogrammetric orientation procedure. In other cases, such as in (Pollefeys, 2004) and (Van Gool, 2002) the texture is acquired from the images that were used for the reconstruction of the object surface. Another approach is presented by (Baumberg, 2002) who binds each polygon of a 3D mesh to a single image and processes the seams in all texture images so that no color discontinuities appear. The approach of (Rocchini, 1999) is however one of the most interesting found in related literature as it is one of the few cases where an actual texture map is created from a series of images that are registered onto the object surface with a model much like the collinearity equation used in photogrammetry. Another approach that bears great resemblance to the methods proposed in this paper is that of (Beraldin, 2002), who uses photogrammetrically oriented images to texture the 3D model of a crypt. In that way Beraldin achieves to accurately register detailed images on a high density polygonal model. However the scheme proposed in that paper does not provide a way to correct for reflectance variations and therefore the method would give poor results for highly curved objects or if the original images were acquired for an outdoor application, where the lighting conditions are not controllable. Moreover, since a fairly simple photogrammetric projection algorithm is applied in order to map the 3D coordinates of the mesh vertices onto the original images the problem of occlusions is also not addressed, making the application of the proposed method unsuitable for highly complex objects. In order to address the problem of inconsistent reflectance, the approach proposed in this paper employs a zippering method for fairly simple objects; in case of highly complex objects, a texture map is employed. Furthermore, in an effort to address the problem of occlusions an algorithm has been developed in order to explicitly check for object-camera visibility.

Regarding publication, i.e. the way chosen to present a 3D model there are two dominant alternatives: 1) image based rendering or 2) creation of an actual 3D textured surface model in a suitable format. Image based rendering, is a way to create view specific renderings of an object combining surface and image data. In this respect one may create a few frames that may be combined with a restricted object motion. Therefore, although, this method is suitable for the creation of virtual or augmented reality visualizations while obliterating the need for explicit 3D surface reconstruction, it does not allow for free user interaction. On the contrary, although the creation of an actual 3D textured surface model may be quite elaborate, it certainly enables free user interaction and provides content for high quality photorealistic visualizations. These very requirements i.e. high user interaction and high quality visualization lie at the heart of this research and define all of the steps of the process as presented in this paper. To this end, this paper proposes an approach that employs 3D acquisition systems, photogrammetric algorithms, texture mapping methods and various data formats. The main advantages of the methods presented is that they enable: 1) the accurate, metric and detailed acquisition of an object or a space by employing various scanning systems, 2) the accurate registration of high resolution images throughout the object space by means of photogrammetric methods, 3) the efficient and realistic creation of real-life materials for complex objects through texture mapping and 4) the potential of employing realistic 3D models in visualizations, interactive applications and various platforms by publication in various data formats.

## 3. PHOTOGRAMMETRIC TEXTURING

This paper demonstrates the proposed methods by use of two examples i.e. a piece of pottery and a rather large and complex monument. In both cases, surface scans were obtained by a laser scanner and high resolution images were acquired by a calibrated digital camera. Also, various targets and points were measured so that photogrammetric orientation of the acquired images would be enabled.

### 3.1 Texturing small objects

Typically, in order to apply photogrammetric orientations, special targets or points of detail are measured during the data acquisition process from several setups around the object of interest. In this way a local network is established and the coordinates of the nodes and the measured points are calculated in a common reference system. This process allows for the acquisition of numerous point measurements and enables the accurate registration of the digital images onto the object surface. Therefore, these methods are ideal for large objects such as monuments or even entire spaces such as archaeological sites, buildings etc. However, when working with small artefacts of historic value it is absolutely forbidden to attach any kind of targets directly on the object surface and it would be very laborious and inefficient to measure points of detail of the object surface since this would require the acquisition equipment to move several times. Furthermore, even if one decided to actually rotate all of the acquisition equipment around a small object, there would still be aspects such as the bottom or the top that would require moving the object in order to acquire the entire surface. Therefore, an alternative acquisition approach was developed to accommodate data acquisition for small artifacts. Each object was placed on a turntable and several targets were placed at fixed positions around the table (Figure 1). The scanner and the camera were also placed at fixed positions. For each scan the object was placed centrally of the turntable taking care that the targets were not causing occlusions both for the scanner and the camera. For every scan the scanner would acquire the surface of the object at 1mm resolution and a digital image was also acquired. For a given position of the object, scans were obtained by rotating the table 45$^{o}$ at a time and all of the targets were acquired at the beginning and the end of every cycle. For different objects the positions of the targets, the focus of the camera and the scanner would be properly adjusted. Later, offline, each scan is processed so that points corresponding to noise or to the background are deleted. Each scan was exported in ascii format along with the positions of the acquired targets. The data corresponding to the 45$^{o}$ scan-cycles were specially processed by a routine developed in Matlab whereby the 8 scans of a cycle along with the positions of the acquired targets were approximately transformed into a common reference system. This was necessary in order to provide a good initialization to the registration algorithms. This data was later imported in the form of point clouds in Geomagic were surface registration was performed. After the registration of the scans, the new transformed positions of the targets were exported so that they could later be used for the photogrammetric registration of the acquired images onto the object surface. Since all scans were registered, the object surfaces were modeled as 3D meshes. The resolution of the 3D meshes was that of a 3-4 mm so that the final model would adequately represent the shape of the object (for medium size objects i.e. 30-60 cm) and the data file would also be small enough for presentation of the textured model through the internet.

In order to texture the 3D model, the photogrammetric software Image Master of Topcon was used in this case. Image master is a program that was originally designed to couple and enhance the functionality of an imaging total station. Nevertheless, this inexpensive software is one of the few photogrammetric programs that allow the user to import a 3D mesh in the form of a DXF or a TIN file and apply textures on the surface based on images that are photogrammetrically oriented. In Image Master one may import a 3D mesh, a series of point measurements and digital images. Each image is associated with a camera that may be calibrated by the calibration module of Image Master or the required values may be given manually for the parameters of a chosen calibration model. In Figure 2 an illustration of the measuring environment of Image Master is presented.

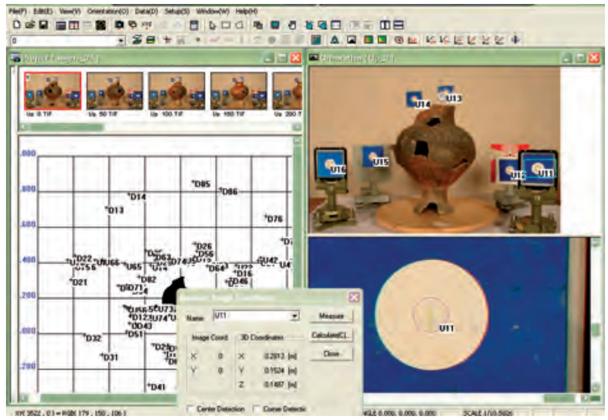

Figure 2: The interactive measurement environment of Topcon's Image Master

The orientation and measurement procedures in this program are rather straightforward. However several drawbacks in the texture mapping process have been identified. For instance, each image is projected onto the object surface and the related texture map is calculated based on the current view of the model probably by employing some kind of orthographic projection scheme. Also, if an image is selected to texture a model, all of the polygons that fall into the image projection cone are associated with the given image. Moreover, although it is possible to employ multiple images in order to texture an image, the results are not satisfactory. Additionally, if an object is large and an image covers only a small part of the surface, the size of the texture map that is created, depends on the size of the entire object and the view chosen at the time the texture mapping command is given. In order to overcome all of these problems, and considering the requirements of the application (i.e. creation of high color quality textured 3D models for web-based user interaction), all of the steps of processing were especially adapted. Specifically, with the aim of creating high resolution texture maps, the 3D mesh surface of the objects was cut into several large pieces. Considering that the texture maps created with Image Master are view dependent and parts of the surface that are imaged poorly for a given view are also textured poorly, the surface was cut so that each piece could be viewed in approximately uniform resolution and without severe deformation from a given point of view. Additionally, the positions of the original images were also taken into account before cutting the object surface. Since each part of the surface would be associated with a single texture map, and in an effort to ensure colour continuity, each piece was selected so that its main colour would be drawn from an image acquired facing the central part of a piece, whereas images acquired from nearby positions would be used as seams for the borders of each piece. Applying this concept, for each piece of the surface, an appropriate view point was selected and all associated images would be used for the creation of texture maps. Each piece was in this way associated with 3 or more texture images depending on the number of its immediate neighbouring surface pieces. The texture images created for each piece were later manually processed and merged into a single texture image through Photoshop (Figure 3).

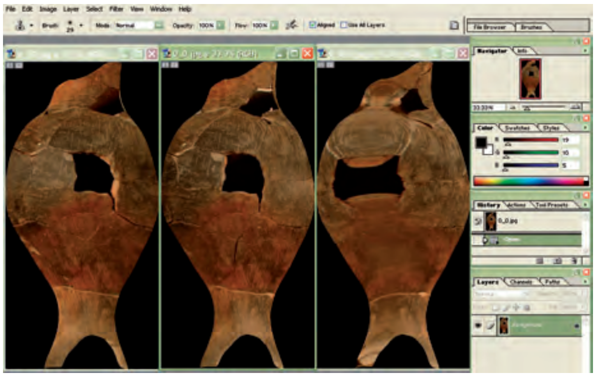

Figure 3: Texture images created for the synthesis of a single texture map for a part of the object surface

The final model was exported in VRML format and the texture images were associated with the respective 3D mesh pieces. This process enabled the creation of 3D models of sufficient geometric detail and high quality color, i.e. uniform and high resolution, high contrast, seamless integration of images, no stretched areas, no false-textured areas and no discontinuities. Also, all of the information was successfully recorded in a relatively small-size file in a very popular free data format that allows for high user interaction through freeware widely available on the internet. An example is given in Figure 4 by means of a snapshot of the final 3D textured model in the Cosmo VRML.

In conclusion, although in this case the 3D surface was acquired by some equipment that was not designed to also provide high quality color with each scan, texturing of the final model was enabled by the integration of photogrammetric techniques in the modelling workflow. Such a solution could be employed for systems that may provide poor or no color. Moreover, this process may employ commercial software, but the problems highlighted here are rather common and the functionalities required to address these problems can also be found in other commercial software or may easily be programmed in a scripting language environment such as Matlab.

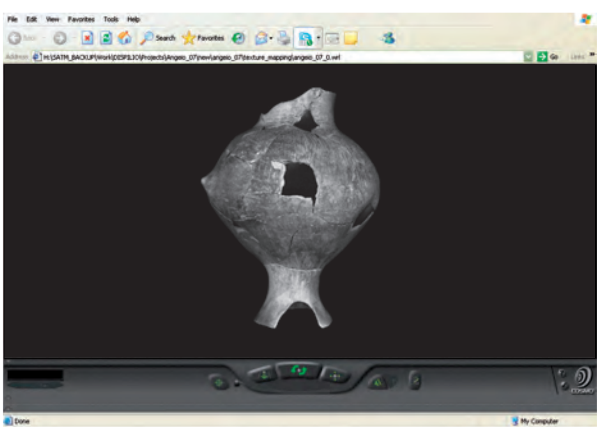

Figure 4: Snapshot of the final textured model in the Cosmo Player VRML plug-in

### 3.2 Texturing large objects or complex sites

By applying the methods described in the previous section, the authors have achieved to create 3D textured models for a variety of object shapes. However these methods needed to be revised for the case of a large monument such as the Zalongon complex of sculptures. The main reason is that in order to texture a large object and retain a predefined amount of detail (e.g. details of 5mm to be visible) a great number of pictures must be acquired. Also, depending on the complexity of the object to be modelled, it may be required that the model surface is divided into a significant amount of pieces.

The monument of Zalongon is an 18m long and 13m high complex of sculptures designed and built in the 50s by George Zongolopoulos. The related project involved the geometric documentation and 3D modeling of the monument in order to guide the restoration process and create media for presentation and dissemination purposes. With regard to the restoration procedure, several specially adapted processes were designed and applied, including: the production of the required line-drawings, orthophotos, leveling information for the foundation of the scaffolding that would be used, detailed photogrammetric surface acquisition for the destroyed upper parts of the two taller forms, CAD surface representation and reconstruction, data production for the creation of a scaled model, scanning and registration of scaled prototypes for the destroyed parts and various area and volume calculations in order to accurately estimate the amounts and the cost of the materials and the special conservation actions of the restoration process. Although these processes are very interesting in their own right a more detailed description would far exceed the scope of this paper and therefore the reader could refer to (Valanis, 2009) for more information. Here, the focus remains on the processes employed in order to create the 3D textured model of the monument. In this case high quality color and free user interaction were required also.

Scanning the monument involved a total of 16 scans that were registered through a specially designed process (Valanis, 2008). The meshing operations resulted to a 3D model of approximately 700K polygons, since a resolution of 3cm was dictated by the project requirements. Also, a total of 239 images were acquired at two stages, i.e. originally images were acquired from the ground and at a later stage, when the scaffolding was set, another set of images were acquired for the upper parts of the monument. All images were acquired by calibrated cameras and with use of appropriate lenses, chosen according to the acquisition distance so as to ensure that the desired amount of detail would be captured in all images. Here it must be noted that for all photogrammetric products, a scale of 1:20 was designated, i.e. details of 5mm (human eye resolution multiplied by the scale factor, in this case: 0.25mm x 20 = 5mm) should be visible throughout the object surface. Also, during field measurements, a total of 327 control points were acquired.

For any application of photogrammetric documentation, a significant amount of data is always acquired. The total amount of images and control points is always a function of the object complexity and the desired scale of the final products. In the case of the monument of Zalongon both factors favoured the acquisition of hundreds of images and control points. However, although for a typical 3D modelling process these amounts of image data may be intractable, standard photogrammetric processes such as orthophoto production, may easily accommodate even significantly larger data sets (Tsingas et al., 2008). In this respect, and in order to accurately texture the 3D surface of the model all of the acquired images were photogrammetrically oriented. The photogrammetric processing that was carried out mainly through the Image Master software where all of the images were imported, control points were measured wherever visible, tie points were also measured and all of the measurements were processed in bundle adjustments.

Figure 5: Example of the input and output of the photogrammetric texture mapping module created in Matlab

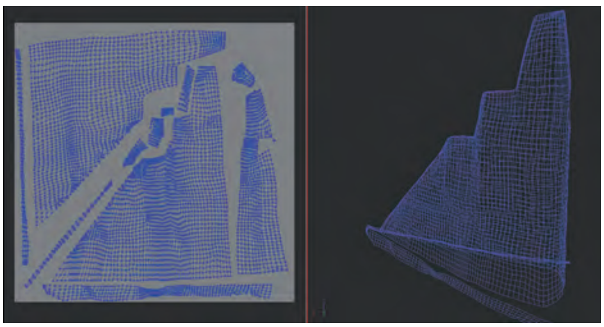

Figure 6: Part of the constrained mesh created for the monument of Zalongon as illustrated through the UV mapping software

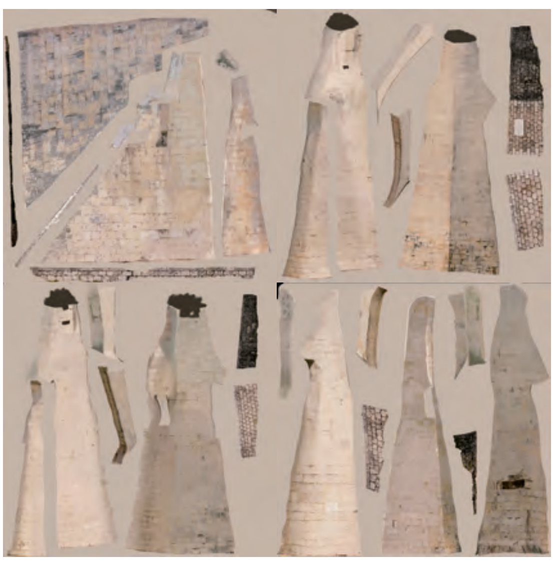

Figure 7: Texture maps created for the main body of the Zalongon complex of sculptures. Each map is 4K x 4K

The processing described in the above resulted to the calculation of the orientation parameters of all of the acquired images. This data was later on used so as to accurately register the images with the 3D object surface. Out of the 239 images that were acquired, a subset of approximately 100 images was selected for the texturing process. All of these images were processed with a script that was created in Matlab in order to project each image on the mesh surface and associate 3D nodes with the corresponding texture coordinates. The model used for this purpose was the collinearity equation including the appropriate correction parameters for radial and tangential lens distortion. The algorithm based on the orientation of each image defines the image bundle and excludes all areas that fall outside the bundle. Also, depending on the relative orientation of the principal axis camera vector and the normal vector of a surface triangle, all backfacing triangles are rejected based on an evaluation of the angle formed between the two vectors in each case. Finally, the algorithm checks for occlusions by projecting all of the remaining triangles onto the image plane and rejects nodes that fall within other triangles based on a comparison of the node-camera and triangle – camera distance. This algorithm given a series of images and a 3D model results to a set of .obj files such that each image functions as a texture map for the corresponding part of the surface. An illustration of the processing and the outcome of the Matlab module is given in Figure 5.

Obviously there is significant overlap between the acquired images and the respective .obj files and there are significant intensity variations even for sequentially acquired images. Therefore, in order to effectively integrate all of this information and facilitate texturing the model, a texture map is required. For a given 3D mesh, commercial software solutions exist in order to create a basic UVW texture map and associate 3D coordinates with a 2D customized texture image. Such tools enable the development of a 3D surface either in its entirety, in case of a simple object, or in parts, whenever the object of interest is rather complex. Another significant aspect of this process is the density of the mesh to be used. A mesh comprising of 700K tiny triangles, such as the one in this case, would be almost impossible to process. This is mainly because the editing of the 3D to 2D data grouping and mapping is done manually. Also, the form of the model in question is highly complex as the surface is highly curved and comprises 3 handles. The quality of a texture map and, consequently, of the final 3D model, depends heavily on the form of the 3D surface, the parts that are grouped and developed in the 2D space, the relative size of surface units, the selected resolution, the quality of the original data etc. In this case, it was desired that the final model would be small enough so as to enable easy internet access and a high degree of interaction, but the texture colour should be as accurate as possible. In this respect, it was selected, instead of working with the full 700K 3D surface mesh to construct and work on a significantly lighter constrained mesh. A constrained mesh is a collection of quads that is usually manually designed onto a 3D mesh using GSI of Geometric Systems Inc. It resembles the contour layout of a NURBS surface, but the difference is that all quads are planar. In this respect a constrained mesh was designed for the monument of Zalongon. The constrained mesh was broken into 5 pieces and processed in DeepUV, a low cost UV mapping software. In Figure 6 a part of the constrained mesh is illustrated through the UV mapping software.

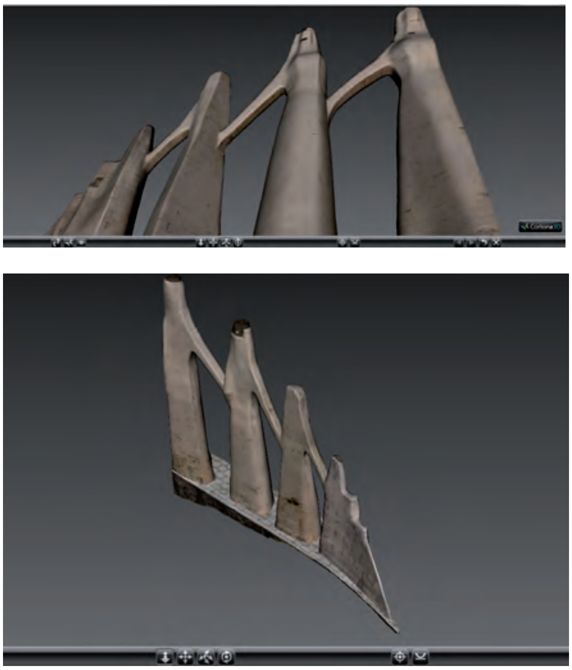

Figure 8: Views of the 3D textured model of the Zalongon monument through the Cortona 3D viewer

By breaking the constrained mesh into 5 pieces (4 pieces for the 4 figures and 1 piece for the floor) it was possible to efficiently achieve the even distribution of the nodes on the UV level, ensure almost uniform scale and go for higher resolution as each piece was associated with a 4K texture map. Based on these UV mappings, the color of the individual .objs was projected onto the related texture maps. This resulted to a series of texture maps that later on were combined into a single texture map for each piece. During this step, care was taken so that adjacent parts were textured from the same images so that no seams are visible and for each texture image all parts were properly adjusted and corrected for tone, brightness and contrast differences. The final 4 texture maps that were created for the monument are presented in Figure 7.

By exporting the 3D model in a VRML format and the associated texture maps in JPEG format, the total file size is no more than 10MB and by installing a free plugin such as the Cortona 3D viewer in an internet browser, any user can easily interact with the model. The tree dimensional model of Zalongon combines unique texture quality and high user interaction. The user can freely handle the model in space and view the model from every imaginable aspect. In Figure 8 two snapshots of the model in the Corton viewer are illustrated. In the first image the viewpoint is selected as if the user is actually standing in front of the monument. The second image is captured form an elevated point rendering a view that would be impossible for the actual visitor.

In Figure 9, an example of the actual resolution of the 3D textured model is given. By employing the same methods and by modifying parts of the process, the authors actually created two 3D textured models for the Zalongon monument. The first illustrated the original status of the monument, while the second model was created so as to present the current form of the monument, i.e. after all of the restoration work has been completed. The two models are available for display on the internet and a small HD movie has been produced by the authors for dissemination purposes. To this end an environment that resembles the actual surroundings of the monument has been created virtually, including the anaglyph of the greater area and the sky was simulated, given the orientation of the monument and its geographical position. The movie presents the monument in full texture, beginning with the original state and later on transforming to the new, restored form. In Figure 10, 4 scenes created for the movie sequence are presented.

Although quite laborious and complicated, the process described in the above resulted to the creation of texture maps that are unique for their high resolution and accuracy given the size of the object. The selected format and 3Dviewer allow for the completely free, unconstrained user interaction, enabling customized selection of the point of view, walk-through, flying mode and free zoom in for full resolution display.


Figure 9: Detail of the final 3D textured model captured through the Cortona 3D viewer in order to give an example for the quality and resolution of the textured maps created by the proposed methods

Figure 10: Scenes of the image sequence created for the production of an HD movie for the dissemination of the monument

## 4. CONCLUSIONS

The examples presented in this paper prove the potential of photogrammetric texture mapping. The integration of photogrammetric processes into the 3D model texture mapping workflow introduces several benefits such as: accurate image to 3D surface registration when the original color is poor or non-existent, uniform and generally higher resolutions, exploitation of a significantly larger amount of image data and elimination of poorly textured model areas. It may be argued that existing methods could yield similar results but in most cases it remains a challenge to work with large objects and sites at high resolutions. In this area, photogrammetry can be the key for highly interactive and real-life textured models. The output of the process is unique regarding the quality of the final texture maps but also light enough for exploitation in various applications such as: movies, games, Google-earth applications, 3D GIS etc. For all of the above mentioned applications, light weight models with rich realistic texture would be valuable assets that could increase their appeal, potentially draw new users and inspire new functionalities. Regarding future work, the authors will be working on optimizing the photogrammetric texturing module so as to include texture blending and further automate various parts of the process.

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