Virtualizing a Byzantine Crypt by Combining High-resolution Textures with Laser Scanner 3D Data

J-A Beraldin(1), M. Picard(1), S.F. El-Hakim(1), G. Godin(1), V. Valzano(2), A. Bandiera(2), and C. Latouche(3)

(1) *Institute for Information Technology, National Research Council Canada, Canada*
(2) *SIBA Coordination, University of Lecce, Lecce, Italy*
(3) *Depart. of Electrical and Computer Engineering, Université Laval, Canada*
angelo.beraldin@nrc.ca
siba@siba2.unile.it

Abstract

In recent years, high-resolution recording of heritage sites has stimulated a lot of research in fields like photogrammetry, computer vision, and computer graphics. Numerous algorithms and methodologies have been proposed in the literature for heritage recording from photogrammetry and laser scanner 3D data. In practice, what a 3D photographer needs for photo-realistic 3D model building is a commercially available solution to this so-called as-built documentation. In this paper, we present such a solution. It is applied to the virtualization of a Byzantine Crypt where geometrically correct texture mapping is essential to render the environment accurately in order to produce virtual visits and apply virtual restoration techniques. A video animation has been created to show the results.

1 Introduction

The capacity to create, display, manipulate, archive and share a digital representation of the shape and appearance of an existing object (as-built) finds a most challenging class of applications in high-resolution recording of heritage-related objects and sites. When combined with immersive technologies, a virtual 3D visit can become a quite appealing way to study or to promote a cultural site. However, beyond photo-realistic rendering, a 3D model contains a wealth of information that can be analyzed and enhanced. Features that are small or only visible from a distance can be interactively examined, thus, allowing the study of fine details such as tool marks or surface texture. Furthermore, sites that must be closed for conservation reasons can still be studied and visited once a 3D model has been created. Computer-based visual enhancement and analysis techniques can be applied to the digital model in all of these situations. One such application is found in virtual restoration of an historical site. As opposed to "traditional" restoration that is performed on the physical object or site, virtual restoration is applied directly onto the digital copy. For instance, it allows the optimization of the legibility of textual and artistic informative data, without turning to interventions often traumatic for the original copy. Besides, virtual restoration is always reversible unlike the traditional one. A digital 3D model is editable in both shape and surface appearance properties. For instance, architectural elements that have been added over the years can be removed and the digital 3D model of the site can then be viewed in the correct historical context. Finally, virtual restoration can help with an in-depth study on possible interventions of traditional restoration.

As a way to demonstrate the proposed method for photo-realistic 3D model building, we selected a Byzantine Crypt (see Fig.1) that is not part of a typical tourist itinerary in Italy, i.e., the Crypt of Santa Cristina located in Carpignano, Apulia [1]. The Crypt was excavated (rupestrian site) around the 9^{th} century c.e. It measures about 16.5 m × 10 m × 2.5 m and is characterized by two entrances. One leads to the area that served as a cemetery and the other, as the church. The church portion is divided into two naves according to a structure that is typical of the period. The Crypt is characterized by a number of well-preserved frescoes on the walls. One of them, Christ and the Annunciation, is dated at 959c.e. and is signed by Theophylact. During the course of history, a Baroque altar was added along with three pillars that replaced one that collapsed.

a) b)

Figure 1. Byzantine Crypt, a) the two outside entrances, b) view of the interior located underground.

Notwithstanding its size, this 1000-year old crypt presented many challenges from the technical and historical point of view. In order to model a complete site like this Crypt, a 3D photographer would have to be skilled in a number of 3D modeling procedures. The 3D photographer could be a specialist that does this type of work on contract basis. Or, in cases where the property of data is of concern, it can even be a technician directly link to the agency requesting the work. Furthermore, he or she might be faced with the fact that the acquisition of the 3D shape could have been done before the acquisition of the texture images or that no high-resolution texture information is available from the 3D laser scanner. The combination of range data and texture information was examined from a user point of view. Numerous papers have dealt with this issue, but *one problem remains* to be addressed i.e. *the availability of commercial tools* for high-resolution texture mapping onto dense 3D models generated from range images. Very few solutions exist on the market addressing this issue. We report on an effective approach based on commercial software tools to this problem. Section 2 presents an overview of the processing pipeline and section 3 describes the elements in the processing pipeline used for the Byzantine Crypt. Section 4 surveys some large projects pertaining to object and site modeling and then shows how the challenges were addressed for the Byzantine Crypt. Section 5 discusses some practical aspects in such a project. Finally, concluding remarks appear in section 6.

2 General overview of the processing pipeline

Environment or site modeling is more difficult than object modeling because of the size and complexity involved. Several methods and a variety of sensors exist, however, given the application requirements, selecting and implementing the most efficient method for data collection and modeling is not a trivial task. Applications include virtual museums, historical site documentation, mapping of hazardous sites, as-built modeling of industrial and power plants, and virtual production for the entertainment industry. Many aspects of sensing and modeling must be understood. All these factors combine to give a non-expert a formidable obstacle in producing a complete 3D documentation of a site. The typical processing pipeline used for 3D modeling includes calibration/verification, geometric modeling, and appearance modeling. The sequence of steps required is well documented [2,3]. We summarize some of the steps for the reconstruction of a fully textured 3D model.

2.1 Calibration/Verification

The *calibration* of a range camera is concerned with the extraction of the internal parameters of the 3D camera [4]. The manufacturer should include with their 3D camera a test object to verify the accuracy (*verification*). For 2D cameras, different calibration methods exist spanning from the simple pin-hole model to the complete photogrammetric solution.

2.2 Geometric Modeling

A model is a digital representation of the object or site on which one can perform operations. Of course, this broad definition emphasizes the task-oriented nature of the model. If the only goal is the generation of photorealistic images for visualization, then purely image-based rendering techniques offer a general solution. However, if the goal is to analyze the works, to preserve and share a record of their geometry and appearance, then explicit shape information must be acquired and stored in an adequate representation that also includes some form of appearance modeling. Acquiring dense 3D data of surfaces has been a hot topic of research in the last 20 years. Traditional applications have been in industrial inspection, robotics and heritage. Though not as mature as photography, 3D imaging is seeing new applications emerging every year. Numerous commercial systems are available to measure dense 3D data. Some supply a color texture in registration with the 3D image but in most cases with very limited visual image quality. Apart from these systems, Rioux [5] presents a system that uses a color laser to measure both 3D and reflectance information of objects and that, at high resolution.

Geometric modeling is essential to recreate realistic models. In most cases, the creation of a 3D model will rely on multiple scans (range images), taken at various locations all around an object or inside a site, that need to be registered. This demands accurate integration (geometry and color) and representation, and adequate compression [6]. A few techniques have been devised for this problem. One method combines photogrammetry and laser range-imaging techniques. Targets or spheres are placed on the surface of the object and/or laid around it. These features are matched in the different views in order to recreate the complete surface [7]. Another method uses only the surface data from the multiple views [8,9]. The views must have enough overlap between them to find the registration and to merge them together. One important feature of this approach is that neither the camera positions nor targets are needed for the construction of a complete model. In fact, the geometric details of the surface of the object itself are used to register the views together. Obviously, quasi-planar or spherical surfaces should be avoided with this latter technique and for those cases, the former method.

2.3 Appearance

Appearance modeling includes methods like image perspective techniques (IPT) [7,10,11,12,13] which are concerned with direct mapping of photographs onto a 3D model and reflectance modeling. This last process is used to extract from the measured color and shape those physical properties of an object that are intrinsic to it and that determine its appearance when viewed with artificial lighting on a computer screen. The true appearance of an object is the result of the interaction of light with material. Many mathematical models to describe this phenomenon have been proposed in the literature. The knowledge of such a model is important in order to reproduce hypothetical lighting conditions under varying observation points. A method developed by Baribeau et al. [14], allows for the recovery of a small number of parameters for each surface element. These parameters relate to the color reflectance of the material and to local specular characteristics. The method is based on a careful calibration of the brightness images produced by a camera equipped with an RGB laser. Bernardini et al. [3] focus on methods to construct accurate digital models of scanned objects by integrating high-quality texture and normal maps with geometric data. Their contributions include new techniques for processing range, reflectance, and surface normal data, for image-based registration of scans, and for reconstructing high-quality textures for the output digital object. Techniques that map real-scene images onto the geometric model, also known as IPT have gained a lot of interest. High-resolution color 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 accurately computing lens distortions, estimating 2D camera to 3D-model pose, dealing with hidden surfaces and incomplete views [3,7]. We will review a few of these challenges.

When standard lenses are used with 2D cameras, lens distortion parameters have to be applied. If not, 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. Furthermore, on the practical side, it is difficult to find a commercial package that does accurate real scene image (texture) mapping onto general cloud points or onto polygonal 3D models. Those that don't possess the complete processing pipeline 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 [15]. Orthophotographs are used a lot in terrain mapping (Orthophoto maps) or in architecture because of the high distance camera-object, perspective and tilt effects can be minimized [16].

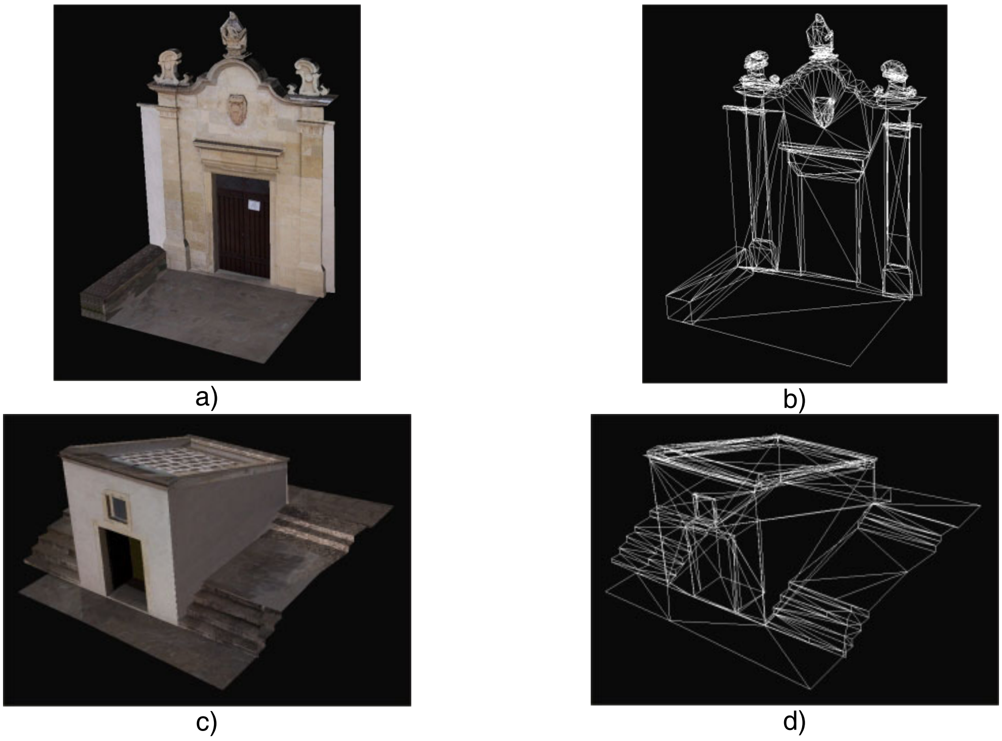


Figure 2. Models of the Crypt two entrances built with photogrammetry, a) main entrance model with texture, b) wire frame model, c) secondary entrance model with texture, d) wire frame model.

3 Elements in the processing pipeline used for the Byzantine Crypt

To model the Byzantine Crypt (Fig.1), we chose for the outside (i.e. main and secondary entrances located above the Crypt) a photogrammetric technique and for the inside (the actual Crypt) a laser range scanner that provided un-organized clouds of points. The laser scanner came equipped with a verification object and modeling software that performed 3D-image registration based on spheres. However, since no useful texture is derived from the scanner, it had to be acquired separately with a high-resolution digital camera.

3.1 2D imaging for IPT and geometric measurements

Current CCD technology is supplying sensors that pack more than 5 Mega-pixels in commercially available products. Access to high quality texture images is now within reach of everyone. Two-dimensional imaging is not only used to record appearance but also to perform geometric measurements, i.e. photogrammetry. Proper camera calibration and bundle adjustment algorithms combine to give accurate feature coordinates and reliable pose estimations. More and more people use digital photogrammetry as a means for obtaining accurate measurements and building 3D textured models from digital photographs [17]. Many commercial packages perform this task quite nicely [18,19,20]. The resulting 3D models for the Crypt's entrances are shown on Figure 2.

We selected a lens-interchangeable SLR-type digital camera, the Nikon D1x, for the texture acquisition. The CCD sensor has a resolution of 3008 x 1960 pixels. Proper texturing of the 3D model requires special lighting fixtures in order to control illumination. Good uniformity of the illumination is essential in order to ease the virtual restoration tasks. The main problems with lighting are the amount of heat generated by high power lamps and UV content. These must be kept to a minimum to avoid damage to the frescoes. Xe flashtubes with a color temperature of about 5600 K were used to acquire textures. The tubes are UV coated and the stored energy is about 500Ws (stability at ±1%) with duration of 1/700 sec. All of the images were acquired with a fixed focal length to ease calibration of intrinsic parameters and an f/22 aperture to produce a large depth of field.

Table 1. SOISIC™ 2000 laser range scanner specifications

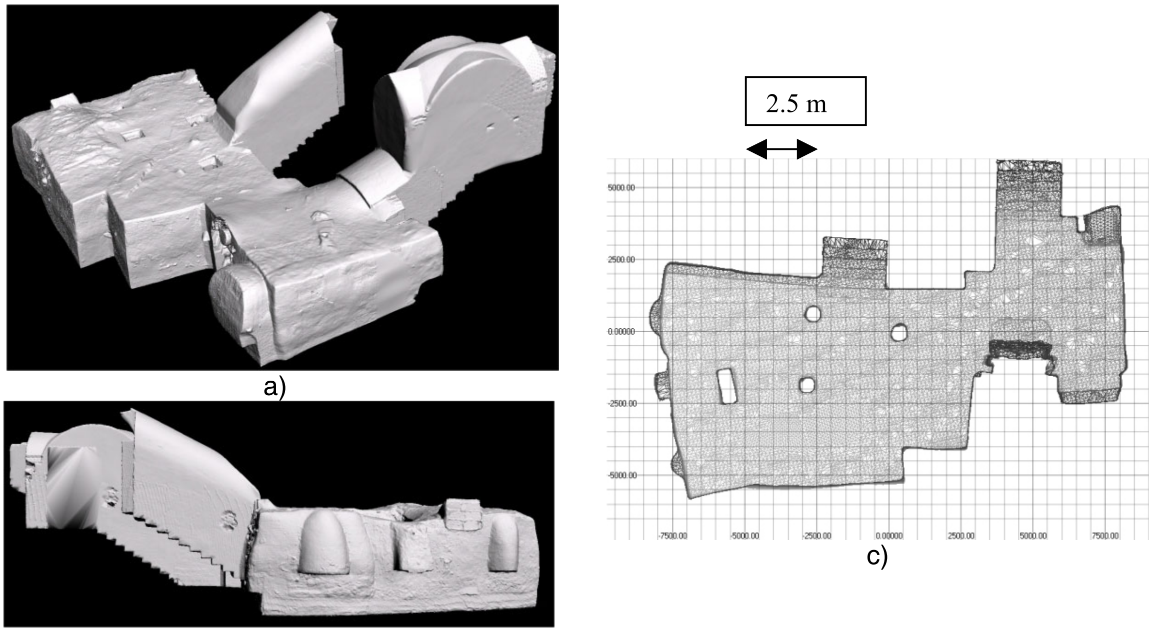
SPECIFICATION	VALUE
Field of View	46° × 320°
Standoff (mm)	800
Maximum range (mm)	10 000
Resolution (X) minimum mesh size	0.1 mm per meter of range
Z measurement Uncertainty-1 σ (mm) Cooperative surface	0.3 @ 800 mm 0.4 @ 2500 mm 0.6 @ 4000 mm
Data Rate (Hz)	100
Scanner size (cm^3)	73 × 21 × 28
Scanner weight (Kg)	16.3

3.2 3D imaging

In order to create a dense 3D model of the Byzantine Crypt, a MENSI SOISIC™-2000 SD model was used. This laser scanner can acquire 3D images at a minimal distance of 0.8 m and at up to 10 m. Table 1 summarizes the specifications of this laser range scanner. The Byzantine Crypt is relatively large (16.5 m by 10 m by 2.5 m) and we wanted to model it with a fairly high spatial resolution. For these kinds of environments (distances between 2 m and 6 m), there are not a lot of range cameras on the market that could provide us with the desired level of spatial resolution and measurement uncertainty. This range of distances represents the transition between optical triangulation and time of flight technologies.

To minimize the amount of time spent in the Crypt, a strategy for scanning was defined well before starting the work. In order to keep a quasi-constant spatial sampling on the surface of the walls, 3D vertical scans were used to build the 3D model. The automatic focusing used in that scanner which gives 0.1 milli-radians of angular resolution sets the lower limit for the mesh. For instance at a distance of 2.5 m (standoff distance selected), this angular resolution corresponds to a spatial resolution of about 0.25 mm. And for that distance, the depth uncertainty on a cooperative surface is about 0.4 mm (1 sigma). In practice, this type of spatial resolution would have required long scanning sessions and therefore in cooperation with the historian it was decided to increase the sampling step to 5 mm. This gave an average scan time per 3D image of about 80 minutes. Also, one has to keep in mind that in order for the modeling phase to be practical (limiting acquisition time by reducing the number of images), a large field of view has to be used. Therefore, with a large field of view, surface details like small tool marks won't be measured well by that system but the overall shape of the Crypt will be excellent. Figure 3 a) and b) present the complete 3D model (without color information) that would appear if one could see through the ground. From this model, a floor plan was created and is shown on Figure 3 c).

Finally, the actual measurement uncertainty was about twice the value given for cooperative surfaces. In fact, the generation of the models was done with both the camera manufacturer's software 3Dipsos™ and Polyworks™ software from Innovmetric. The Polyworks™ software gives the standard deviation of the alignment error after each alignment. For properly calibrated 3D data, this value is useful to determine the range measurement uncertainty. The software 3Dipsos™ provides the errors only between matching spheres present in the scene in order to align two 3D scans. Both methods were extensively tested and experimented with.



a)

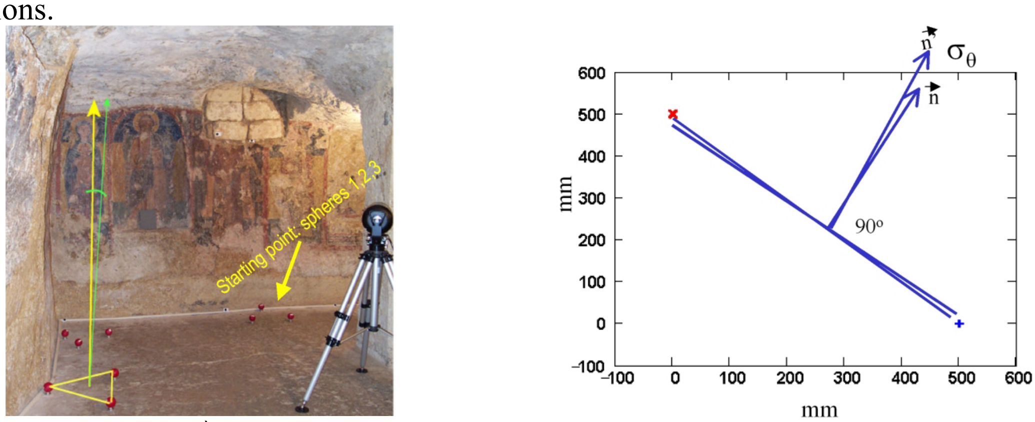
b)

c)

Figure 3. Complete 3D model of the Byzantine Crypt, a) view from outside shown with synthetic shading, b) a particular view of the stairs leading to the Crypt, c) floor plan generated from an orthographic view of the 3D model of the Crypt showing the dimensions.

3.3 Comparison of two alignment methods for 3D images

We tested two techniques to align the 3D images, the first based upon spheres positioned strategically in the scene and data-driven alignment (ICP-based) followed by a global alignment. For the spheres method, we had to determine an average distance between three spheres that would fit the camera's field of view and where the angular uncertainty of the normal of the triangle formed by those three spheres would be lower than 1 mRad. This error corresponds to an error of 2.5 mm at a height of 2.5 m i.e., the distance floor-ceiling (see Figure 4a). The computations were performed through a Monte Carlo simulation. This gave an average distance between the spheres of 0.75 m (see Figure 4). Model building using common spheres present in adjacent 3D images where pair wise alignment is not followed by a global alignment yields an inaccurate model. For instance, in the model of the Crypt, this procedure was tested and it was found that between the first and last 3D image the closure of the model was 16.87 mm with *sphere #1*, 16.37 mm with *sphere #2* and 18.15 mm with *sphere #3*. This is about 1:1000 of the total dimensions of the Crypt. These results are fairly good considering that many things can affect the result, e.g., systematic errors caused by calibration, choice of distance between spheres, and/or vibrations.



a)

b)

Figure 4. Sphere-based alignment, a) image showing the grouping of the spheres, b) estimate of angular uncertainty for a given triangular base structure used to align images.

The alignment was improved by using the actual 3D data (without the spheres) for the alignment (based on ICP), which was completed with a global alignment procedure. In fact, Polyworks™ gave an alignment error in the order of the actual scanner measurement uncertainty, i.e. 0.8 mm. A procedure based on spheres would give good results in situations where the model cannot be closed or too many planar surfaces are present in the environment. This is not the case with the Byzantine Crypt. It has a lot of surface relief. In general, both methods ought to be understood and used in the right situation.

4 Putting it all together: IPT mapping onto 3D

Many projects aimed at the construction of large 3D models of objects or environments with or without appearance modeling are briefly reviewed here. We then present our solution to building a photo-realistic 3D model of the Byzantine Crypt.

4.1 Survey of some 3D projects

At Altamira in Spain and Lascaux in France, one could once admire the caves of our Paleolithic ancestors. Unfortunately, it was found the carbon dioxide that visitors exhaled was making the atmosphere inside the caves more acidic, dissolving the surfaces of the limestone walls and loosening the paintings [21]. Furthermore, all the tourists at Altamira were raising the temperature inside the caves to the point where bacteria began growing on the artwork. In order to protect these ancient illustrations, wide-scale access to cave galleries was stopped about 25 years ago. Hence, close-up experience is no longer available. Efforts in replicating those caves began in the 1980s with Lascaux in France, for which two of the cave's galleries were reproduced using manual measurements and photogrammetry. In Spain, Spanish agencies selected in 1988 a Madrid-based replication specialist to create a facsimile of Altamira [21]. Here, environment modeling and replication was aimed at recreating the experience one would have inside those caves.

After nearly 100 years of displaying the world's first triceratops skeleton, the Smithsonian National Museum of Natural History (NMNH) was forced to disassemble its specimen and replace it with a cast replica to protect the fragile bones from further atmospheric wear and tear. The NMNH scientists also rewrote history by using 3D scanning and stereo-lithography to correct scientific inaccuracies in the original 1905 mounted skeleton. By digitizing its triceratops skeleton with a 3D laser scanner, the Smithsonian was able not only to build a precise physical replica, but also to create an accurate animation of the dinosaur's movements to better understand how it behaved [22]. Here environment modeling and replication targeted both scientific and tourism purposes.

The digital reconstruction of Olympia and 3D Zeus was presented as an exhibition at the Powerhouse Museum, Sydney in 2000. Entitled "1000 Years of the Olympic Games: treasures from ancient Greece", the exhibit offered a unique opportunity to supplement the traditional experience of the visitor by the introduction of virtual reality components. The 54 rare antiquities, which travelled from Greece for the first time, were enhanced using a full-scale digital reconstruction of Ancient Olympia, and a 3D model of the statue of Zeus from Artemision [23]. Here a mixture of virtual and virtualized environment and object modeling were used to recreate a site which no longer exists.

A team of 30 faculty, staff, and students from Stanford University and the University of Washington spent the 1998-99 academic year in Italy scanning the sculptures of Michelangelo. As a side project, they also scanned 1,163 fragments of the Forma Urbis Romae, a giant marble map of ancient Rome. Their goal is to produce a set of 3D computer models - one for each statue, architectural setting, and map fragment they scanned - and to make these models available to scholars worldwide [24]. Bernardini et al. [25,26] published a good survey of other projects along with their Michelangelo's Pietà project. Miyazaki, D. et al. [27] describe the Great Buddha project. Gaiani et al. [16] present their work on the Coliseum in Rome. Each project tries to optimize some part or all of the modeling phases using custom and commercial tools. Both virtualization of existing sites and recreation of virtual sites (when they no longer exist) are modeled.

4.2 Byzantine Crypt: challenges and solutions

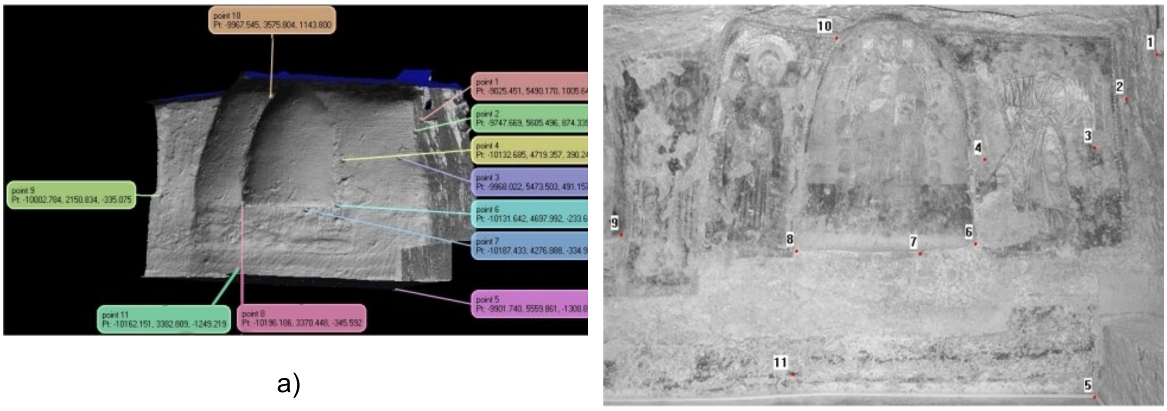
The 3D model was created with the technique implemented in the commercially available software Polyworks^{TM} [9]. Regarding texture mapping, though the Mensi provides 2D images from its internal video camera, the resolution and color quality is not acceptable for our application. Furthermore, the laser intensity at each 3D point is not supplied by the scanner and hence can't be used to register 2D images taken with a separate camera. Therefore, what we had to deal with is a 3D model that *did not have intensity data attached to it*. Below we will explain how the synthetically shaded images created from the 3D scans were used to register our high-resolution 2D images.

The goal of the procedure, shown below, is to take either a cloud points of un-registered 3D data or a 3D model, texture map high resolution 2D images that are un-registered between themselves and with the 3D data, and, create a geometrically correct visually realistic and highly detailed 3D model. The methodology proposed is very flexible and within reach to many people. Therefore, people that are worried about copyright or data ownership can do the work themselves without relying on external help. It uses commercially available software to give the complete realistically looking and geometrically correct 3D textured model. The 2D camera does not have to be rigidly mounted on the 3D camera and therefore 2D images created from digital cameras can be mapped onto the 3D model (see Figure 7a for 2D camera setup). These 2D images can be taken specifically for texturing purposes or obtained by other means, e.g., tourist photos, postcard, infrared or ultraviolet images, or even historical photos.

The 3D model is first segmented into mutually exclusive regions (like in Figure 5a). Each region is mapped onto a region (entirely comprised) that is a subset of one of the 2D images. Then, features are located on a shaded version of the 3D image using Polyworks IMinspect (see Figure 6a) and an ASCII file is created that contains those 3D points. The same features are located in the 2D image, and the relative position between 2D and 3D cameras is found using the photogrammetirc software, ShapeCapture^{TM} (ShapeQuest Inc.) (see Figure 6b). The last step required here is a simple mapping that assigns the texture coordinates to each vertex of the 3D model. We assumed that the 2D camera has already been calibrated and that the 3D points generated by Polyworks were imported as control points in ShapeCapture. Pose estimation uses the distortion parameters of the lens computed from the camera calibration. We used a 6-parameter lens distortion model. The calibration can be performed once, before taking the 2D images or if the camera is no longer available, then, 3D data points found on the 3D model can be used for the lens calibration. Other methods based on constraint equations (e.g. perpendicularity or parallelism amongst features) are available [20].

a) b)

Figure 5. A section of the Crypt, a) synthetic shading replaces one of the colour images, b) the proper colour image mapped with the technique proposed in this paper.



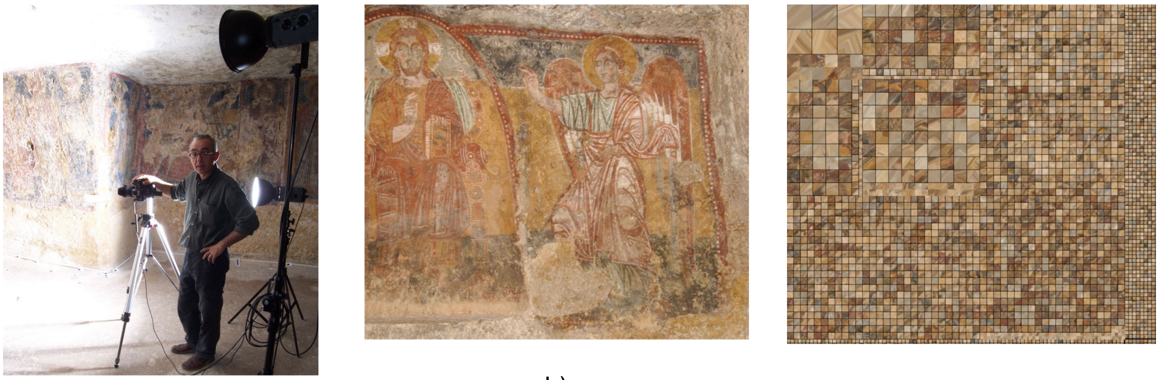
a)

b)

Figure 6. Pose calculation, a) 3D points selection in Polyworks using the shaded images, b) selection of homologous points in 2D image with ShapeCapture.

We have experimented with two approaches for the construction of a texture-mapped simplified model, again with the goal of maximizing the use of commercially available software tools. The *first method* prepares the data so that it can be entered into the model compression and texture mapping process available in Polyworks. This technique requires a triangulated geometric model with a color value assigned to each vertex. The original high-resolution model is compressed into a simplified model through a vertex removal process. The appearance of the original model is approximated by computing a texture patch for each triangle of the simplified model that approximate the appearance of the area represented by the removed vertices. As part of the geometric compression, the removed vertices are projected onto the larger triangles. When the desired level of compression is reached, a texture image is created. It is a tessellated image where each triangle of the simplified model is mapped onto a color patch integrating the information from the removed vertices. More details are found in [28]. The method was designed for arbitrary topologies, and possibly incorrect or incomplete models. Thus, it does not attempt to create a piecewise parameterization of adjacent triangles on the model that would be maintained in the texture image. Rather, each triangle is mapped independently (or by adjacent pairs), and after affine transformation of the triangle into an isosceles right angle triangle for efficient packing. Figure 7c illustrates the results. In order to apply this method, the color information contained in the 2D images must be attached to vertices of the geometric model. For the Crypt, the surface sampling of the original 2D images is denser than the geometric sampling (by 25 times). In order to incorporate the color information in the model, triangles are subdivided to accommodate the new points. The over-sampled model is then fed into the pipeline. One advantage of using this method is that all the texture is embedded in a single, efficiently occupied texture map, and that the algorithm easily allows the generation of maps of different sizes. The major inconvenient of this approach is the requirement to process an excessively large model. But another one is in the usability of the texture map obtained (Figure 7c): if there are requirements to modify the images, only global corrections (e.g. contrast, brightness) can be easily applied to the texture. If, in the course of virtual restoration, the original images need to be modified, then the entire compression/texture mapping process must be applied again.

The *second method*, which we ultimately adopted, simply uses the manually assigned pairings between subsets of 3D triangles and individual 2D images. Because the triangles are relatively small, no perspective correction was applied to the mapped texture triangles. With this method, the original high-resolution 2D images (Figure 7b) are always available for processing. Once modified for a given task, e.g., like virtual restoration, a simple reload of the VRML file in the viewer updates the model. There is no need to re-compute the projection or go through the modeling procedure.



a) b) c)

Figure 7. Texture mapping, a) setup used to acquire 2D texture images, b) the preferred method maps those texture images onto the 3D model hence are easier to use for possible virtual restorations, c) texture map for the color per vertex method.

The realistic looking nature of the model comes from the fact that a calibration of the 2D camera guarantees the geometric quality of the mapping; the mapping uses all the texture data present in the 2D image, and a dense 3D model. Therefore, a user can select the level of resolution for an application and then map the texture on a high-resolution 3D model or a compressed version of it. Though full automation may seam a legitimate goal as a way to reduce the time to create a model, experience shows that some involvement by the user can make a huge difference in the final quality or realism of the digital model. For example, automatic hole filling in a 3D model might imply modifying the intentions of the creator of the work of art. Therefore, proper knowledge by the user can assist a semi-automatic hole-filler in cases like these. The matching between 2D and 3D data is performed interactively. We could include in the features detection part of the solution a module that does segmentation and matching between 2D and 3D imagery [11]. We don't rely on automatic best view computations at this point. If 3D points are occluded then at this point we don't remove the texture mapping around that point. Presently we rely on the ability of the user to take the 2D snapshots and to pick the best point of views when segmenting the 3D model. However, all of these features can be added. Figure 8 presents a view of the Crypt taken from the final model.

a) b)

Figure 8. Texture mapping result, a) portion of the Crypt shown with synthetic shading, b) same portion after texture mapping showing a higher level of realism.

5 *Practical aspects*

Realistic estimate of the time to acquire the range images, build a 3D model and the determination of the required quality of model is very critical for such a project. The starting point is usually general information found about the site. The procedure outlined in [29] allows one to estimate with good certainty the time it takes to acquire and model an object starting from the scan time of a single 3D image. For this site, the estimate is fairly close to that for an object. With an average scan time of 80 minutes per 3D image, a total of

92 hours were spent in the Crypt. During that time, fifty 3D images were acquired for the Crypt along with thirty 3D images for the altar. The total modeling time is significantly affected by the scanning time. A total of 6.3 million 3D points (excluding the altar) were acquired. The spatial resolution on the wall is about 5 mm and on the ceiling and floor, 15 mm. The range uncertainty was estimated at 0.8 mm. The 3D model was created over a period of one month. That time was also used to test and verify the data-driven and the spheres-based registration methods. The acquisition of the texture took 3 days and the actual mapping was done in 4 days. A number of models with different levels of complexity were created from the original data. We are currently working with 3 models: one 4.6 million-polygonal un-textured model (10 mm resolution) of the complete Crypt, a 12.8 million-polygon fully textured model (5 mm resolution) of the section of the Crypt that contains the two apses, and, a lighter textured model with 0.4 million polygons. A movie showing a fly through of the Byzantine Crypt was prepared. Finally, periodic verification of the accuracy of the scanner using the stadia provided by the manufacturer gave an average uncertainty of 0.85 mm and a bias of 1.5 mm (0.2%). There is either a scale error, the stadia has a different length, or fitting routine problems! The fitting routines were verified with metric standards, and results were very good. We are verifying with the scanner manufacturer if there is an actual scale error in the data or the stadia. The stadia could be the source of the scale error because it did not come with a certification that is traceable to a National Standard.

6 Conclusions and Future Work

The potential of modeling *as-built reality* in heritage opens-up applications such as virtual restoration (see Figure 9) or as an input to virtualized reality tours. It was demonstrated with a Byzantine Crypt. A high degree of realism can be attained by those techniques and the context in which the artifacts were discovered or were used can be recreated. Real world acquisition and modeling is now possible. Technological advances are such that difficulties are more of a logistical nature than technological per se. Many techniques exist to digitize small objects with both a high-resolution 3D surface and a view independent surface texture with perfect registration between them. Models of large objects, structures and environments are possible but as demonstrated here require the combination a number of techniques. Many papers in the literature explore both modeling and texture mapping onto dense 3D models but the results are not necessarily accessible to everyone interested in applying this technology. The problem we addressed in this paper is the creation of tools and methods that work with commercial devices and software.

a) b)

Figure 9. Example of a simple virtual restoration, a) current state of some of the writings, b) enhanced version with some modifications brought to the texture image.

Acknowledgements

Contributors: E. Bandiera, F. Bergamo, M.C. Catamo, Sac. G. Colavero, D. Lucarella, R. Ingrosso, A. Marra, F. Melcarne, S. Nuccio, P. Pulli, A. Van Den Troost, U. Parrini, M. Biliotti, C. Sempi, V. Blasi, R. De

Rinaldis and M. L. Blasi. Co-financing was provided by the Ministero dell'Istruzione, dell'Università e della Ricerca and the European Union (F.E.S.R.) for initiative 18 of the Piano Coordinato delle Università di Catania e Lecce.

References

[1] Bandiera E. 1980. Carpignano Salentino: Centro, Frazione, Casali, Ed. Lorenzo Capone, Cavallino.
[2] Soucy, M. Godin, G. Baribeau, R. Blais, F. and Rioux, M. 1996. Sensors and algorithms for the construction of digital 3-D colour models of real objects, *Proc. of the IEEE ICIP*, Lausanne, Suisse. Sept. 16-19, Vol. II. 409-412.
[3] 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.
[4] Beraldin, J.-A., Cournoyer, L., Rioux, M., Blais, F., El-Hakim, S.F., and Godin, G. 1997. Object model creation from multiple range images: Acquisition, calibration, model building and verification. In *Intern. Conf. on Recent Advances in 3D Dig. Imaging and Modeling*, Ottawa, Canada, 326-333.
[5] Rioux, M. 1997. Colour 3-D electronic imaging of the surface of the human body. *Optics and Lasers in Eng.*, 28, 119-135.
[6] 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.
[7] El-Hakim S.F., Brenner C., and Roth G. 1998. A multi-sensor approach to creating accurate virtual environments, *ISPRS Journal of Photogrammetry & Remote Sensing*, 53, 379–391.
[8] Bergevin, R., Soucy, M., Gagnon, H., and Laurendeau, D. 1996. Towards a general multi-view registration technique. *IEEE Trans. Pattern Anal. Mach. Intell.*, 18, 5, 540–547.
[9] Soucy, M. and Laurendeau, D. 1995. A General Surface Approach to the Integration of a Set of Range Views, In *IEEE PAMI*, 17, 4, 344-358.
[10] Weinhaus M. and Devarjan V. 1997. Texture mapping 3D models of real-world scenes, *ACM Computing Survey*, 29 4, 325-365.
[11] Neugebauer P.J. and Klein K. 1999. Texturing 3D Models of Real World Objects from Multiple Unregistered Photographic Views, In *Eurographics '99 Conference proceedings*, 245-256.
[12] Sequiera, V., Ng, K., Wolfart, E., Goncalves, J. and Hogg, D. 1999. Automated reconstruction of 3D models from real environments. *ISPRS Journal of Photogrammetry & Remote Sensing*, 54, 1-22.
[13] Stamos I. and Allen P.K. 2000. 3-D model construction using range and image data. *Proceedings IEEE Conference on Computer Vision and Pattern Recognition. CVPR 2000*, 1, 531-536.
[14] Baribeau, R., Rioux, M., and Godin, G. 1992. Color reflectance modeling using a polychromatic laser range sensor, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 14 2, 263-269.
[15] Cortelazzo G.M. and Lucchese L. 1999. A New Method of Image Mosaicking and Its Application to Cultural Heritage Representation, *Eurographics '99 Conference proceedings*, Sept., 265-276.
[16] Gaiani, M., Balzani, and M., Uccelli, F. 2000. Reshaping the Coliseum in Rome: an integrated data capture and modeling method at heritage sites, *Eurographics 2000*, M. Gross and F.R.A. Hopgood, 19, 3.
[17] Triggs, W., McLauchlan, P., Hartley, R., and Fitzgibbon, A. 2000. Bundle Adjustment for Structure from Motion, in *Vision Algorithms: Theory and Practice*, Springer-Verlag.
[18] Vit Web Site: http://www.vit.iit.nrc.ca/
[19] Debevec, P. E., Taylor, C. J. and Malik, J. 1996. Modeling and rendering architecture from photographs: A hybrid geometry-based and image-based approach. In Proc. of ACM Siggraph 1996, ACM Press/ACM.
[20] El-Hakim S.F. 2001. Three-dimensional modeling of complex environments. *SPIE Proceedings vol. 4309, Videometrics and Optical Methods for 3D Shape Measurement*, San Jose, Jan 20-26.
[21] Donelan J. 2002. Making Prehistory. Computer Graphics World, March, 32-33.
[22] Moltenbrey, K. 2001. No Bones About it. Computer Graphics World, Feb., 24-30.
[23] Virtual Olympia 2000 http://www.virtualheritage.net
[24] Levoy M., Pulli K., Curless B., Rusinkiewicz S., Koller D., Pereira L., Ginzton M., Anderson S., Davis J., Ginsberg J., Shade J., and Fulk D. The Digital Michelangelo Project: 3D scanning of large statues. In Proc. of ACM Siggraph 2000, ACM Press/ACM SIGGRAPH, New York. E. Fiume, Ed., Computer Graphics Proceedings, Annual Conf. Series, ACM.
[25] Bernardini, F. and Rushmeier, H. 2000. The 3D model acquisition pipeline. *Eurographics 2000 State of the Art Report (STAR)*.
[26] Bernardini, F. et al. 2002. Building a digital model of Michelangelo's Pietà. *IEEE Computer Graphics and Applications,* Jan/Feb, 59-67.
[27] Miyazaki, D. et al. 2000. The Great Buddha project : Modelling cultural heritage through observation. *Proc. of the sixth Intern. Conf. On Virtual Systems and Multi-media (VSMM 2000),*Gifu, Japan, 138-145.
[28] Soucy, M., Godin, G., and Rioux, M. 1996. A texture-mapping approach for the compression of colored 3D triangulations, *The Visual Computer*, 12, 503-514.
[29] Beraldin, J.-A., Blais, F., Cournoyer, L., Rioux, M., El-Hakim, S.F., Rodella, R., Bernier, F., and Harrison, N. 1999. Digital 3-D imaging system for rapid response on remote sites, *Proc. of the Second Intern. Conf. on 3-D Digital Imaging and Modeling*, Ottawa, Ontario, 34-43.