3D Modeling of Complex and Detailed Cultural Heritage Using Multi-Resolution Data

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The article reports the interdisciplinary project of the virtualization of the Great Inscription of Gortyna, Crete, for 3D documentation, structural studies, and physical replica purposes. The digitization of the longest epigraphic text of the Greek civilization (6 m long and 1.75 m high, with approximately 2–3 mm-depth engraved letters) and its surrounding heritage area (around 30 × 30 m), required long planning and the construction of a dedicated acquisition system to speed up the surveying time, limited to few hours per day. Primarily, range sensors were employed in a multi-resolution way, digitizing detailed parts in high resolution and less smoothed areas with lower geometric resolution. Some selected areas were also modeled with our multiphoto geometrically constrained image matching approach to demonstrate that the same accuracy and details can be achieved using either scanners or photogrammetry. The derived 3D model of the heritage is now the basis for further archaeological studies on the incision techniques and a deeper structural analysis on the monument. The challenges of the work stay in the acquisition, processing, and integration of the multi-resolution data as well as their interactive visualization.

Categories and Subject Descriptors: I.3.7 [**Computer Graphics**]: Three-Dimensional Graphics and Realism; I.3.8 [**Computer Graphics**]: Applications

General Terms: Documentation

Additional Key Words and Phrases: 3D modeling, laser scanning, photogrammetry

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1. INTRODUCTION

According to UNESCO, a heritage can be seen as an arch between what we inherit and what we leave behind. In the last years, great efforts focused on what we inherit as cultural heritage and on their documentation, in particular for visual man-made or natural heritages, which received a lot of attention and benefits from sensor and imaging advances. A large number of projects, mainly led by research groups, have produced very good-quality digital models of visual cultural heritage [Levoy et al. 2000; Beraldin et al. 2002; Stumpfel et al. 2003; Gruen et al. 2005; El-Hakim et al. 2007; Guidi et al. 2008]. The actual technologies and methodologies for cultural heritage documentation allow the generation of very realistic 3D results (in terms of geometry and texture) used for many purposes like digital

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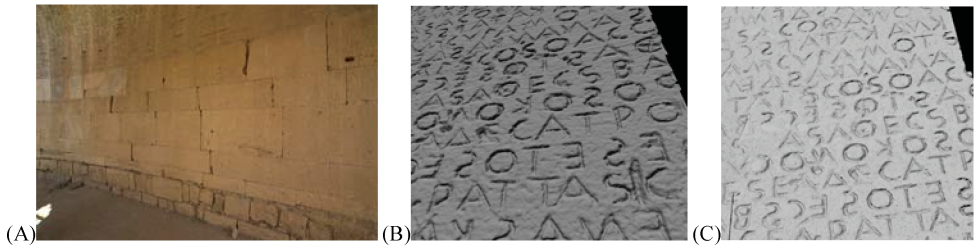

Fig. 1. The Great Inscription (A) of Gortyna, Crete, 5th century B.C. A detail of the image-based (B) and range-based (C) reconstructed surface model with its 3 mm-depth letters.

conservation, restoration purposes, VR/CG applications, 3D repositories and catalogs, Web geographic systems, etc. But despite all the possible applications, a systematic and well-judged use of 3D models in the cultural heritage field is still not yet generally employed as a default approach for the following reasons: (i) the high cost of 3D; (ii) the difficulties in achieving good 3D models; (iii) the consideration that it is an optional process of interpretation (an additional "aesthetic" factor) and documentation (2D is enough); and (iv) the difficulty in integrating 3D worlds with other, more standard 2D material. But the availability and use of 3D computer models of heritages opens a wide spectrum of further applications and permits new analyses, studies, and interpretations. Thus virtual heritages should be more and more frequently used due to the great advantages that digital technologies give to the heritage world.

The actual reality-based 3D technologies involve mainly optical active sensors [Blais 2004], passive sensors [Remondino and El-Hakim 2006], or an integration of the two [Guidi et al. 2008] as an effort to exploit the intrinsic potentialities of each technique. Surveying information and maps can also be combined for correct geo-referencing and scaling.

Nowadays in many projects, the integration of multiple sensors and a multi-resolution modeling approach, both in geometry and texture, is the state-of-the-art, to reconstruct in detail some particular features and with less geometric information some other areas.

Although hardware and software have shown tremendous improvements in the last years, still some difficulties remain in acquiring, processing, and visualizing huge dataset of complex and large sites or objects.

The article mainly touches these two stated problems, reporting the interdisciplinary project of the digital reconstruction of the Great Inscription of Gortyna, Crete, and its surrounding area (Figure 1 and Figure 2) for digital documentation, visualization, structural studies, and physical replica purposes. The work was designed to achieve a multi-resolution 3D model of the entire heritage area with a geometric resolution spanning from 0.3mm to 5cm. Primarily, range sensors were employed, although some detailed areas were modeled also using digital images and advanced matching algorithms. The project required long planning and the construction of a motorized scanning acquisition system (Figure 4). The range-data processing pipeline required to set up a cluster of PCs and large editing time to process the huge amount of data (around 500 million points).

In the successive sections we describe the heritage area and project objectives (Section 2), the multi-resolution modeling methodology (Section 3), the range-based modeling (Section 4), and the detailed image-based reconstruction (Section 5) using a multiphoto matching approach. Results of the multi-resolution 3D model and some final remarks will conclude the article.

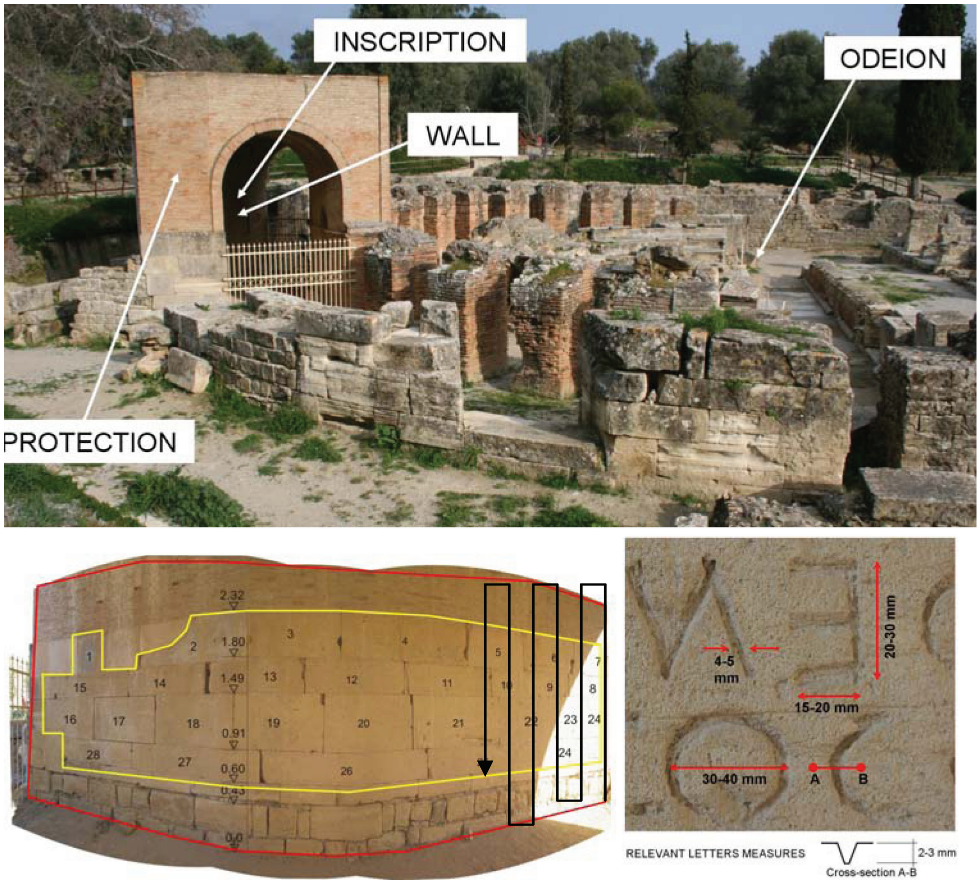

Fig. 2. The most important part of the heritage area in Gortyna, Crete, with the odeion, the brick protection, and on the internal wall the great inscription (above). The inscription subdivided in 12 columns and 30 blocks (lower left) and the relevant letters are measured on the inscription (lower right).

2. THE CULTURAL HERITAGE AREA OF GORTYNA, CREETE

The main heritage area of Gortyna (Figure 2) contains a Basilica, a great Odeion (around 30 × 30m), a vaulted brick protection (around 8 × 5 × 4m), and on its internal limestone wall (approximately 8 × 3m) the Great Inscription (around 6 × 1.75 m) with its 2–3mm-depth engraved letters and symbols. The Great Inscription dates back to the middle/late 5th century B.C. and was discovered in 1884 by Federico Halbherr. Halbherr found inside a watercourse some limestone blocks incised with Greek alphabet letters and he reassembled them, forming the inscription. It is written in Doric dialect, read boustrophedon, and it is part of a law code of the Cretan city of Gortyna, the capital of the Roman province of Crete (near the actual village of Haghii Deka). The inscription has 2–3mm-depth (in the best case) engraved letters, is also called "The Queen of Inscriptions" [Willets 1967], and is the longest epigraphic text of the Greek civilization. The original setting of the Great Inscription is uncertain, but in the Roman period the incised blocks were reused as a part of an Odeion (a building intended for musical performances). After the discovery, the inscribed wall was covered with a vaulted brick roof originally designed with the aim to protect it but nowadays, causing damages to the inscription

Table I. Summary of the Acquired Multi-Resolution Range Data and the Derived Surface Model Characteristics

Area	Sensor	Dim [m]	Scans	Acquired pts [Mil]	Reduced pts [Mil]	Mesh Resolution [mm]	Final Numb Polygons [Mil]
Inscription	Shape Grabber SG1002	6 × 1.75	212	460	375	0.3	80
					176	0.5	65
					85	1	38
Wall	Leica ScanStation2	8 × 3	3	1.2	0.9	5	1.6
Protection (int+ext)		8 × 5 × 4	14	4.8	3.1	10	1.4
Odeion		30 × 30	15	55	31	50	3.1

itself. The importance of the Great Inscription is multiple: as a source for knowledge of ancient Cretan institutions and Doric dialect, as a monument, and as a legal text.

2.1 The Surveying and Modeling Work in Gortyna

The digital reconstruction of the entire heritage area with a detailed and high-resolution 3D model of the Great Inscription was mainly dictated by: (i) the need of a physical replica of the inscription, (ii) structural studies, and (iii) the visualization of the entire heritage. Indeed, the Great Inscription is not accessible and can be only seen from around a 4m distance behind a fence. Furthermore, Gortyna is not a typical tourist location, although amazing and containing the longest and oldest epigraphic text of the Greek civilization. Therefore a virtual tour is really sought and required. The structural studies are indeed mandatory, as the vaulted brick protection is greatly damaging the inscription due to its strong weight.

In the project, various sensors used at different geometric resolutions were integrated to produce a multi-resolution 3D model of the entire heritage area of Gortyna. Our approach is hierarchical by the data source and in the hierarchy; details and accuracy increase as we get closer to the Great Inscription. Thus data in one level overrides and replaces the overlapped data found in previous levels of resolution. The multi-resolution surveying approach has the advantages of adapting the level of information required by each piece of artwork and providing for data redundancy useful to identify possible metric errors.

In the project, active optical sensors were primarily used (see Table I), although we are aware of the potentialities of the image-based approach and its latest developments in automated and dense image matching. Nevertheless, the reliability of active sensors (and the related range-based modeling pipeline in certain projects) is still much higher, although time consuming and expensive. Therefore, mainly for research purposes and to close possible gaps in the range data, some areas of the inscription were modeled with an automated multiphoto matching approach [Remondino et al. 2008] and the 3D results afterwards compared with the range data.

The 3D modeling of the archaeological site and the detailed inscription with its 2–3mm engraved letters faced the following problems:

—planarity of the inscription's wall, raising problems in the alignment of single scans;

—dimension of the object compared to the small field of view of the triangulation-based scanner;

—limited working time for the data acquisition;

—preservation of the small geometric features of the inscription during the data processing phase;

—sun and light affecting the performances of the triangulation-based range sensor and the radiometric quality of the images;

—seamless merging of the data acquired at varying geometrical resolutions;

—texturing of the 3D models with uniform radiometry (the wall with the inscription was in shadow only ten minutes per day); and

—interactive visualization of the huge meshed 3D model.

3. THE GENERAL MODELING PROCEDURE FOR COMPLEX SITES

3.1 Reality-Based 3D Modeling

Nowadays, reality-based 3D modeling of objects and sites is generally performed by means of images (passive method) or active sensors (like a laser scanner or structured light projectors), depending on the surface characteristics, required accuracy, object dimensions and location, project's budget, etc.

Active optical sensors [Blais 2004] directly provide 3D range data and can capture relatively accurate geometric details, although they are still costly, usually bulky, not easy to use, requiring a stable platform, and are affected by surface properties. These sensors have limited flexibility, since a range sensor is intended for a specific range/volume and generally lacks good texture information. They can acquire millions of points, even on perfectly flat surfaces, often resulting in oversampling, but it is likely that corners and edges are not well captured. The range-based modeling pipeline [Bernardini and Rushmeier 2002; Scopigno and Cignoni 2005; Cignoni and Scopigno 2008] is nowadays quite straightforward but problems generally arise in case of huge datasets and complex objects.

On the other hand, image-based methods [Remondino and El-Hakim 2006] require a mathematical formulation (perspective or projective geometry) to transform 2D image observation into 3D information. Images contain all the useful information to derive 3D geometry and texture but recovering a complete, detailed, accurate, and realistic 3D textured model from images is still a difficult task, in particular for large and complex sites and if uncalibrated or widely separated images are used. Practical systems are still highly interactive if the 3D modeling aim is not only visualization but also a precise and reliable result. Indeed, current fully automated methods are still unproven in real applications and may not guarantee accurate results. Nevertheless, automated and dense image matching methods are promising [Brown et al. 2003; Goesele et al. 2007; Remondino et al. 2008].

Although many methodologies and sensors are available, to achieve an accurate and realistic 3D model of large and complex structures, containing all the required levels of detail, the better way is still to combine the previously mentioned modeling techniques (Figure 3). Indeed, as no single technique is able to give satisfactory results in all situations, concerning high geometric accuracy, portability, automation, photo-realism, and low cost, as well as flexibility and efficiency, image and range data are generally combined to fully exploit the intrinsic potentialities of each approach [Stumpfel et al. 2003; El-Hakim et al. 2004; Guarnieri et al. 2006; El-Hakim et al. 2007].

3.2 The Multi-Resolution Modeling Methodology

Multi-resolution data nowadays comprise the base of different geospatial databases and visualization repositories. Probably the best and most widely known examples are given by Google Earth or Microsoft Virtual Earth. Data span from hundreds of meters in resolution (both in geometry and texture) down to few decimeters (only in texture). The user can browse through the low-resolution geospatial information and get, when necessary, high-resolution and detailed imagery, often linked to other 2D/3D information (text, images, city models, etc).

The reader should distinguish within the multi-resolution concept between: (i) *geometric modeling* (3D shape acquisition, registration, and further processing) where multiple resolutions are combined to model features with the most adequate sampling step; and (ii) *appearance modeling* (texturing, blending, simplification, and rendering) where multiple resolutions are used to face 3D models' complexity during visualization and data transfer.

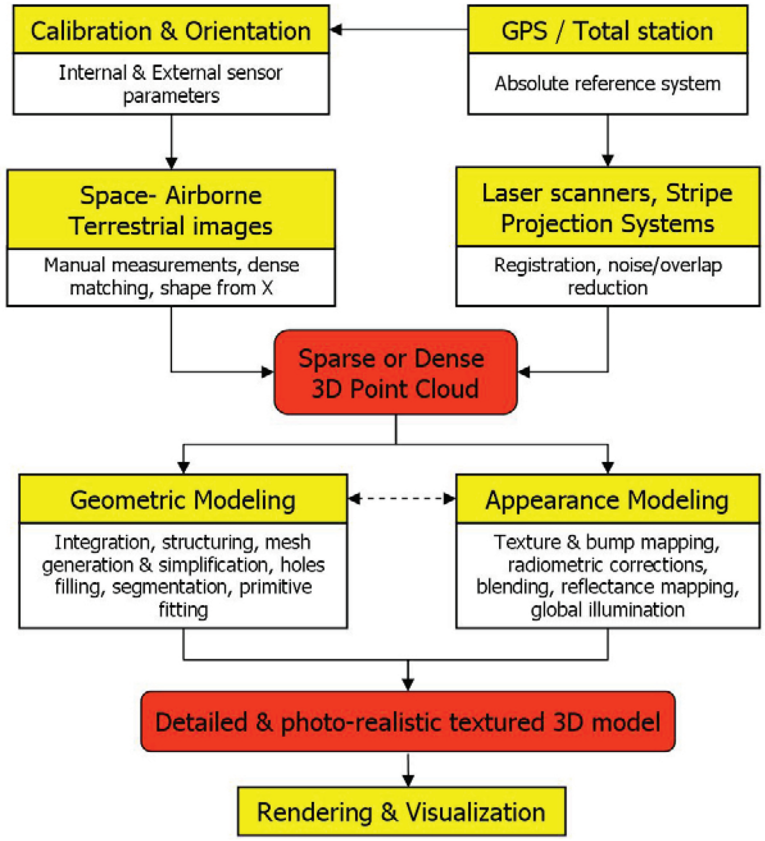

Fig. 3. General 3D modeling pipeline for the documentation and visualization of large and complex cultural heritage objects and sites using real data and measurements.

For the 3D documentation of large and complex sites, the state-of-the-art approach uses and integrates multiple sensors and technologies (photogrammetry, active sensors, topographic surveying, etc.) for the derivation of different geometric Levels Of Detail (LOD) of the scene under investigation. 3D modeling based on multiscale data and multisensors integration indeed provides the best 3D results in terms of appearance and geometric detail. Each LOD shows only the necessary information while each technique is used where best suited to exploit its intrinsic modeling advantages.

3.3 Related Works

The great challenge in geometric modeling using multiple sensors and multi-resolution data is the seamless integration and correct registration of information. Since the 1990's sensor fusion has been exploited, with radars and infrared sensors as a means for precisely estimating airplane trajectories in the military field [Hall and Llinas 1997], but with the end of that decade NRC Canada developed a Data Collection and Registration (DCR) system for integrating a 3D sensor with a set of 2D sensors for registration and texture mapping [El-Hakim et al. 1998]. Sensor and data fusion was then applied also in the cultural heritage domain, mainly at the terrestrial level but in some cases also with satellite, aerial, and ground information for a more complete survey. Beraldin et al. [2002] combined low-resolution photogrammetry and high-resolution range data for the 3D modeling of a Byzantine crypt. Guidi et al.

[2002] generated high-resolution 3D models of roman mosaic fragments with a pattern projection range camera, oriented them with photogrammetry, and integrated these data with TOF laser scanner. Gruen et al. [2005] used a multi-resolution image-based approach to document the entire valley of Bamiyan with its lost Buddha statues and produced an up-to-date GIS of the UNESCO area. From satellite to terrestrial amateur images, the geometric resolution of the project ranged from 5 m down to few mm. Beraldin et al. [2006] used a prototype multi-resolution scanner that allowed acquiring 3D data with a spatial resolution that improves with shorter standoffs. El-Hakim et al. [2008] integrated drawings and aerial, helicopter, and terrestrial images with range data and GPS measures for the detailed modeling of castles and their surrounding landscapes. Guidi et al. [2008] modeled the Pompeii's Forum merging a Digital Surface Model (DSM) derived from aerial images with TOF scanner data and high-resolution photogrammetrically derived 3D models.

On the other hand, appearance modeling renders a photo-realistic representation of the generated geometric model. Due to the data complexity, rendering of large 3D models is generally done with a multi-resolution approach, displaying the large meshes with different levels of detail and simplification approaches. Triangular meshes are nowadays very popular and intensively used in most of the projects [Botsch et al. 2008]. But the ability to easily interact with huge meshes is a continuing and increasingly difficult problem. Indeed, model sizes and resolutions (both geometry and texture), as well as demands for detailed models, are increasing at a faster rate than computer hardware advances. This limits the possibilities for interactive and real-time visualization of large 3D models. Therefore optimization, simplification, multi-resolution management, and LOD approaches are generally used to transmit and display big datasets and maintain seamless continuity between adjacent frames [Eppstein 2001; Luebke et al. 2002; Pajarola and DeCoro 2004; Cignoni et al. 2005; Borgeat et al. 2007; Dietrich et al. 2007].

Nevertheless, data simplification brings the problem of a loss of geometric accuracy of the generated 3D model and this poses the crucial question: Shall we really spend hours and hours of acquisition to collect millions of points to accurately describe the smallest element but then simplify and reduce all this information because we cannot interactively visualize it?

4. RANGE-BASED MODELING

4.1 Range-Data Acquisition

Due to the project requirements and the need of a physical replica, the data acquisition was divided in different parts (inscription, wall, protection, surrounding area) with different parameters and specifications. Following Beraldin et al. [2007], the scanning results are a function of:

—intrinsic characteristics of the instrument (calibration, measurement principle, etc.);

—characteristics of the scanned material in terms of reflection, light diffusion, and absorption (amplitude response);

—characteristics of the working environment;

—coherence of the backscattered light (phase randomization);

—dependence from the chromatic content of the scanned material (frequency response).

All the range sensors, in particular the triangulation-based systems, which aim at very high-resolution and accurate scans, should be calibrated before use. Furthermore, to verify the achieved calibration parameters, certified and NIST-traceable objects (e.g., balls bars, gauge blocks, etc.) should be used.

All these factors and precautions were taken under consideration in the project planning and instrument selection.

As the inscription contains carved symbols and letters with a depth of 2–3mm (Figure 2), a ShapeGrabber® laser scanner was employed, with a resolution of 0.3mm. The triangulation-based

Fig. 4. The employed range sensor mounted on the mobile motorized structure.

scanner, equipped with a SG1002 head, is mounted on a mechanical linear rail system (PLM600) which allows a 60cm horizontal translation of the sensor. The minimum acquisition distance (standoff) is 300 mm and the Depth of Field (DOF) is 900mm. The range camera is capable to acquire n = 1280 points for each vertical profile. The angle φ gcovered by the laser line is approximately 42° and the resolution along the horizontal x-axis is directly related to the camera-to-object distance d.

$$\Delta x \cong d \cdot \frac{\varphi}{n} \cdot \frac{\pi}{180^\circ}$$

According to the project requirements, the camera-to-object distance was set to 500 mm to achieve a resolution of 0.3mm. Due to strict project requirements, the scanner was precisely calibrated before each acquisition session. Furthermore, to speed up the acquisition of the entire wall, a mobile motorized structure was built (Figure 4) to quickly move the instrument vertically and on the ground.

For the interior and exterior vaulted brick protection (around 8 × 5 × 4m) as well as for the surrounding heritage area (around 30 × 30m), a Leica ScanStation2 Time of Flight (ToF) laser scanner was employed at different spatial resolutions (Table I). These data were used to contextualize the entire inscription and for visualization purposes.

4.2 Range-Data Processing

In the data processing of large sites, in particular for those digitized with active optical sensors, we should consider the following.

—The huge amount of range data makes very time consuming and difficult their processing at high resolution, yet processing at low resolution creates accuracy problems.

—Combining data acquired with different sensors, at different resolutions and viewpoints can affect the overall accuracy of the entire 3D model if not properly considered.

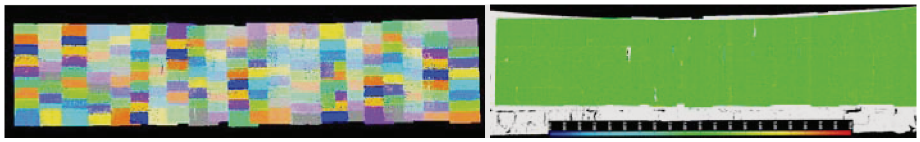

Fig. 5. The 212 scans of the inscription aligned and registered at 0.3mm (upper left). The successive alignment with the Leica TOF data (upper right) was performed to prevent deformations of the ShapeGrabber data and preserve the correct curvature of the inscription (final standard deviation of 0.68mm).

—Despite combining several sensors, some gaps and holes can still be present in the model, requiring filled and interpolated surface patches to prevent leaving them visible and unpleasant.

—The used sampled distance is rarely optimal for the entire site or object, producing undersampled regions where edges and high curvature surfaces are present and oversampled regions where flat areas exist.

Generally, the first operations performed on the acquired range data are error and outlier removal, noise reduction, and hole filling [Weyrich et al. 2004] while afterwards the aligning (or registration) of multiple scans is performed. The alignment phase is usually the most time consuming of the entire modeling pipeline. After a raw alignment, a more precise and robust registration technique like ICP [Salvi et al. 2007] or LS3D [Gruen and Akca 2005] is applied. Generally, the raw alignment requires some manual definition of tie points between scan-pairs (if targets are used, they can be automatically detected), although automated targetless methods have been proposed [Johnson and Hebert 1997; Vanden Wyngaerd and Van Gool 2002; Bendels et al. 2004; Fasano et al. 2005].

Once the scans are aligned, they are generally decimated to remove redundant points and then converted into a mesh, the typical standard for surface reconstruction and representation. The mesh generation and display also comprise a time-consuming process, therefore for faster visualization other methods (point-based techniques) were developed [Kobbelt and Botsch 2004]. If a mesh is generated, its triangular elements generally need some repairing to close holes and fix incorrect faces or nonmanifold parts. These errors are visually unpleasant and might cause lighting blemishes due to the incorrect normals, and the computer model will also be unsuitable for reverse engineering or replicas. Volumetric, surface-oriented, and surface-inpainting methods have been proposed in the literature to perform these operations [Davis et al. 2002; Liepa 2003; Bendels et al. 2005; Podolak and Rusinkiewicz 2005]. Finally, oversampled areas should be simplified while undersampled regions should be subdivided [Dey et al. 2001].

The available commercial packages (e.g., Polyworks, Geomagic, RapidForm, Reconstructor) are based on long years of experience and include a variety of optimizations and functionalities, although some inherent problems are still present, in particular for the handling and visualization of large meshes. Some research packages are also available to handle and process range data (e.g., MeshLab, VripPack).

In our project, as soon as a vertical scanning stripe was completed and before the motorized structure was located in the successive location, the range data were registered to check the complete coverage of the inscription.

After the scanning of all stripes, all 212 patches (around 460 million points) were globally aligned (Figures 5 and 6), that is achieving a final standard deviation of 0.27mm in agreement with the active sensor's specifications. This procedure required to set up a cluster of two 64-bit PCs with 8Gigabyte of RAM each. The final 3D surface model of the entire inscription at 0.3mm resolution was afterwards decimated and subsampled (0.5mm and 1mm) for further processing and visualization purposes (see Section 6.2).

For the surrounding area (wall, brick protection of the inscription, and Odeion) the range data acquired with the ToF scanner (Table I) were processed and registered following the same strategy

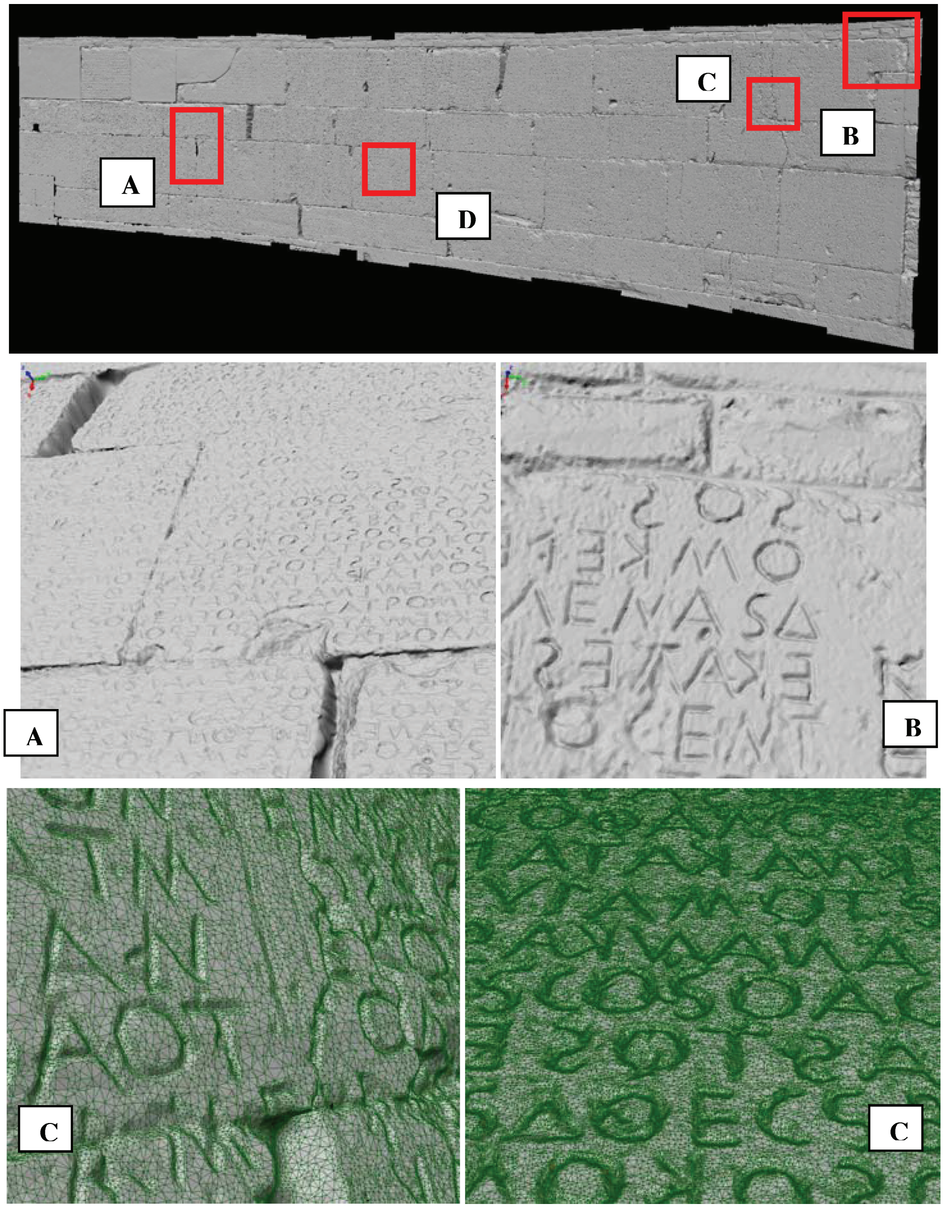

Fig. 6. The entire meshed 3D model of the Great Inscription (0.3mm sampling step), constituted of approximately 80 million polygons. Some closer views of the mesh are shown in shaded and wireframe mode.

previously described and used for the visualization of the entire heritage area of Gortyna (Figure 7). The meshes were also optimized and simplified, in particular in oversampled areas which were not presenting big discontinuities.

The internal wall, acquired at 5mm resolution, was used to check the correct alignment and curvature of the registered ShapeGrabber data (Figure 5). Indeed, to prevent deformations during the registration of the single patches and to avoid a wrong curvature of the Great Inscription, the high-resolution

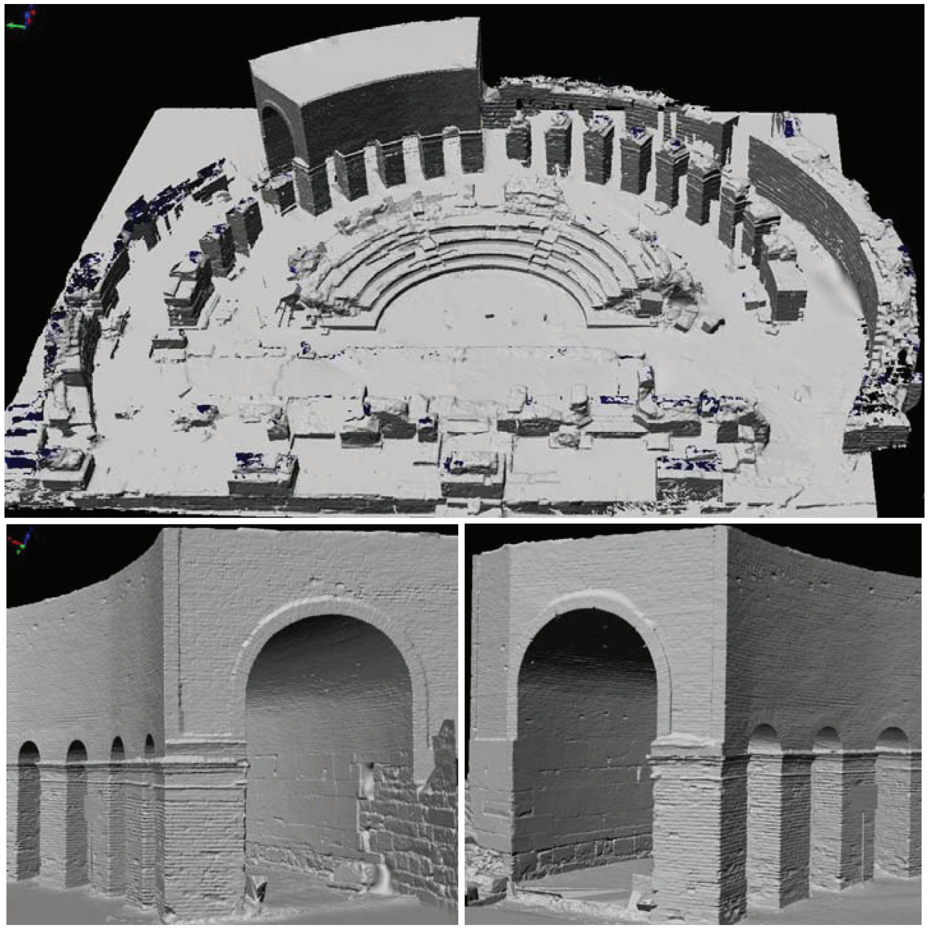

Fig. 7. The Odeion of Gortyna (around 30 × 30m) surveyed and modeled with the TOF sensor (above). The meshed model of the brick protection containing the Great Inscription (below).

ShapeGrabber scans were also aligned with the lower-resolution Leica ToF data, providing a measure of the absolute registration error. The curvature of the wall, a parameter useful for the physical replica, was also computed.

4.3 3D Data Texturing

In the cultural heritage domain, 3D models generally also need a precise color mapping and not only an accurate shape reconstruction. The generation of a photo-realistic result essentially requires that there is no difference between a view rendered from the model and a photograph taken from the same viewpoint. The texture mapping process is generally intended as the mapping of RGB information onto 3D data, in the form of points or triangles (mesh). The texturing of 3D point clouds (point-based techniques [Kobbelt and Botsch 2004]) allows a faster visualization but for certain 3D models this is not an appropriate method. In case of meshed data, homologous points between the 3D mesh and the 2D image to be mapped should be identified. This is the bottleneck of the texturing phase, as it is still an interactive procedure (no automated and reliable approaches have yet been proposed). Indeed, the identification of homologous points between 2D and 3D data is a hard task, much more complex than image-to-image or geometry-to-geometry registration. Moreover, a fully automated approach should be also able to select which image should be mapped, therefore a visibility analysis is required [Hanusch 2008]. If the image to be mapped covers the entire 3D model, the silhouette of the model can be used as the matching feature [Lensch et al. 2000]. Pulli et al. [1997] proposed to fix the camera onto the active sensor so that the relative position between the two sensors is known. In the general case, the classical DLT approach is used to compute the intrinsic and extrinsic camera parameters and then to map the color information on the surface polygons using a color-vertex encoding or a mesh parameterization.

The texture mapping phase goes much further than simply projecting one or more static images over the 3D geometry. Problems arise firstly from the time-consuming image-to-geometry registration and then because of variations in lighting, surface specularity, and camera settings. Generally, the images are exposed with the illumination at imaging time but this may need to be replaced by illumination consistent with the rendering point of view and the reflectance properties (BRDF) of the object [Lensch et al. 2003]. High Dynamic Range (HDR) images might also be acquired to recover all scene details [Reinhard et al. 2005]. Methods to reduce color discontinuities and aliasing effects, as well as to render seamless textured surfaces, have been presented in [Debevec et al. 2004; Umeda et al. 2005; and Callieri et al. 2008].

The Great Inscription model (around 80 million polygons) and the surrounding areas (around 5 million polygons) were textured using 13.5 Mpixel Kodak DSC-Pro digital images, acquired with 18mm and 50 mm objectives. The assisted procedure employed 58 digital images and obtained the seamless textured model displayed in Figures 8 and 11.

5. IMAGE-BASED MODELING

3D modeling from images provides sparse or dense point clouds according to the employed measurement methodology (manual or automated), project requirements, and aims. For simple structures (e.g., buildings) interactive approaches are satisfactory, but for complex and detailed surfaces we need automated measurement approaches. An automated, precise, and reliable commercial image matching system, adaptable to different terrestrial image sets and scene contents, is not available, in particular for outdoor, convergent, and wide baseline images. In the computer vision community a great effort was devoted to the recovery of 3D structure from photo streams [Nister 2001; Pollefeys et al. 2004; Vergauwen and Van Gool L. 2006], although in most practical situations, occlusions, illumination, or scale changes and low texture limit this kind of approach. Wide baselines were also faced in various works [Furukawa and Ponce 2007; Goesele et al. 2007] but practical systems are still interactive. A successful image matcher should use: (1) images with strong geometric configuration, (2) local and global image information, (3) constraints to restrict the search space, (4) an estimated shape of the object as a priori information, and (5) strategies to monitor the matching results. In light of these considerations, Remondino et al. [2008] developed an advance multiphoto geometrically constrained image matching approach able to accurately reconstruct in high resolution details visible in multiple convergent images and to retrieve dense and precise 3D point clouds, similar to range sensors. The algorithm combines multiple matching primitives (feature and grid points together with edges) and various area-based matching techniques to exploit all the content information of the images. The matching can also cope with depth discontinuities, wide baselines, repeated patterns, flat surfaces, occlusions, and illumination changes by using several advancements over standard stereo matching techniques [Brown et al. 2003].

In the project, some areas of the Great Inscription were digitally reconstructed also using the dense image matching previously described. Images were acquired with a calibrated 13.5 Mpixel SRL Kodak DCS-Pro digital camera, equipped with 50 and 35mm lenses, providing a footprint spanning from 0.09 to

Fig. 8. The Great Inscription textured with 36 high-resolution images (above) and its brick protection (below).

0.15mm. The images were oriented with a bundle adjustment and afterwards the multiphoto matching retrieved accurate and dense surface models of the areas of interest (Figures 9 and 10). The derived 3D surface models were afterward compared to the range data (Section 6.1) to check the accuracy of the image-based results and the potentiality of the photogrammetric method.

6. RESULTS AND CONSIDERATIONS

The processing of all the range data (Section 4) required about 2 months of work of 2 persons. The main problems came from the employed hardware and software, which could not easily stand the huge amount of data. All the generated 3D models (around 85 million polygons) were merged together to produce a unique multi-resolution virtual model of the heritage area. Low-resolution data (5cm) describe the surrounding Odeion while the geometric resolution increases (down to 0.3mm) the closer we get to the small letters of the Great Inscription. In the visualization, higher-resolution data in one level of detail

Fig. 9. Part of the inscription (about 30 × 40cm) modeled using 3 images with a ground sample distance of 0.09mm (above left). The generated surface model (around 990 000 points) with a resolution of 0.3mm shown in color-code and shaded modes.

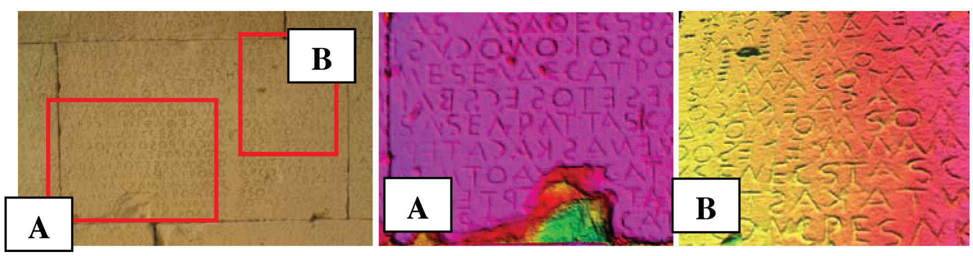

Fig. 10. A block of the inscription (around 1.2 × 0.6m) modeled using 5 images with a ground sample distance of about 0.15mm (left). Two views of the recovered surface model (approximately 2.2 million points at 0.5mm geometric resolution) shown in color-code mode to highlight the recovered depth differences.

override and replace the overlapping lower-resolution data found in previous levels. The closer we get to a certain detail, the more higher-resolution data are loaded, both in geometry and texture (down to 0.25 mm). Different commercial software and research packages were evaluated for the interactive visualization of the multi-resolution 3D data. Walk-through videos were also produced for educational and communication purposes.

6.1 Comparison of 3D Modeling Methodologies

The surface models derived using the multi-photo matching method (Figures 8 and 10) were aligned and compared with the triangulation-based range data. The comparison of the meshes was performed

Fig. 11. The internal wall of the brick protection and some closer views of the textured 3D model of the Great Inscription of Gortyna, Crete, modeled at 0.3mm geometric resolution for physical replica purposes.

in Polyworks/IMInspect. The achieved standard deviation of the differences between the triangular faces resulted 0.36mm in the case of meshes at 0.5 mm and 0.14mm between the meshes interpolated at 0.3mm.

These results confirm that we can model detailed areas with range sensors or images, achieving the same results in terms of accuracy and modeled details. Nevertheless, the obtained surface statistical values do not indicate which surface model (or modeling methodology) is better. They simply provide an indicator of the very small discrepancy between the two surface models. A standard methodology for the performance evaluation of surface reconstruction methods is needed, like those available for the traditional surveying or CMM methods.

Further geometric comparisons are presented in Remondino et al. [2008] while Strecha et al. [2008] proposed some benchmark data to compare range- and image-based surface models. Cignoni et al.

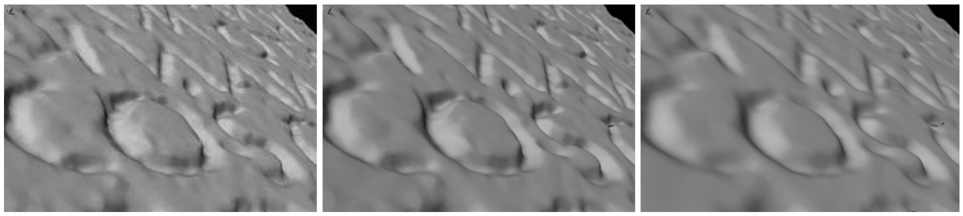

Fig. 12. A detail of the high-resolution mesh (A) and the two reduced versions (B = 0.5mm; C = 1mm). The simplification at 1mm smoothed most of the details.

Table II. Numerical Evaluation of the Loss of Geometric Accuracy and Error Introduced in Down-Sampling the Mesh

Mesh Comparison	Max Deviation	Min Deviation
0.3 mm versus 0.5 mm	+0.407 mm	−0.268 mm
0.3 mm versus 1 mm	+0.916 mm	−0.745 mm

[1998], Roy et al. [2004], and Silva et al. [2005] presented research about the development of mesh comparison tools.

6.2 Mesh Simplification and Geometric Evaluation

Besides the high-resolution mesh with a regular sample of 0.3mm realized for the physical replica, further models at lower resolution were also produced for faster handling and visualization. This required a subsampling of the data and therefore a loss of the geometric accuracy. Therefore an evaluation was conducted to prove the possible loss of geometric accuracy and to confirm the correct sampling step (0.3mm) employed to survey and model the Great Inscription.

Figure 12 shows a visual comparison of a part of the surface model optimized and then regularized at 0.3, 0.5, and 1mm resolution, respectively. The clear smoothing effect in producing the lower-resolution meshes has been also numerically evaluated comparing different profiles and cross-sections on the entire inscription at the three different geometric resolutions. Table II reports the maximal and minimal deviations between the high-resolution and resampled meshes. As also visible in Figure 13, the mesh at 1mm (38 million polygons) clearly smoothes out areas with large discontinuities while the mesh at 0.5mm (65 million polygons) still keeps most of the details, despite its 20% mesh reduction. Although for faster handling and visualization purposes the simplification might be very useful, given the project objectives and requirements, it was not acceptable.

6.3 Archaeological and Structural Studies

Following the project of the virtualization of the Great Inscription described in the previous sections, it is interest of the involved institutions to continue, using the recovered digital 3D model, with a study of the techniques of incision and with a deep analysis of the evidence of "suffering" of the monument. Indeed, after its discovery, the inscribed wall was covered with a vaulted brick roof which is probably causing damages to the wall itself. Different signs of the heavy weight on the engraved stones are also clearly visible simply by looking at the inscription. Civil engineers can employ the detailed 3D model for structural studies and to decide preservation policies. Indeed, in comparing the old evidence of the inscription (photographs, drawings, etc.) with the newly generated 3D data, there is a good possibility of identifying critical points in order to develop a new project intended to prevent future structural problems and avoid further damages.

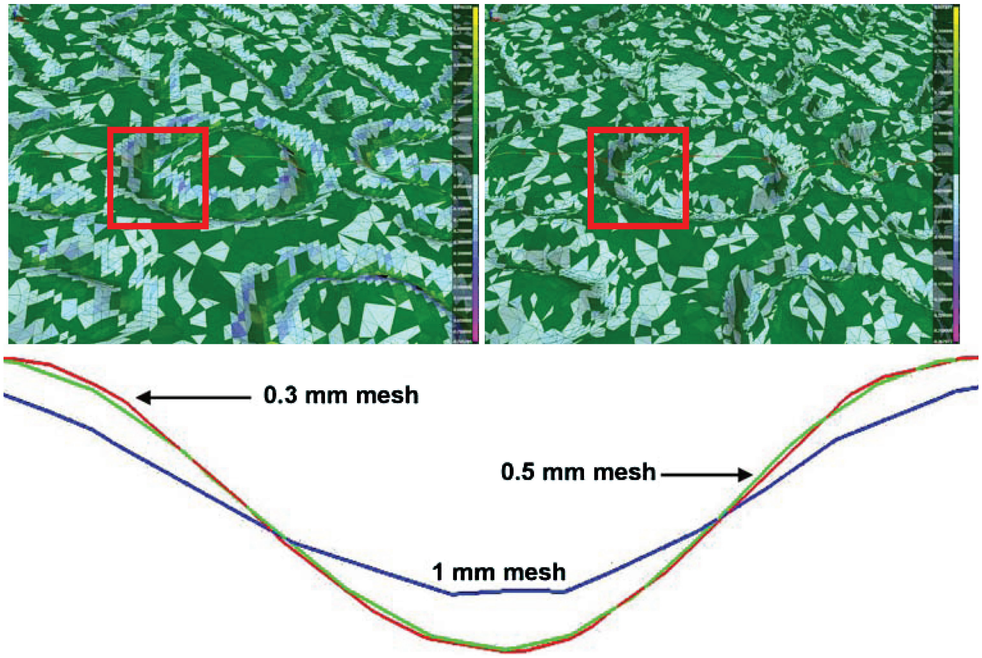

Fig. 13. A closer view of the mesh comparision results (left: 0.3mm vs. 0.5mm; right: 0.3mm vs. 1mm). The derived profile of the highlighted boxed area shows the large smoothing effect of the mesh at 1mm.

7. CONCLUSIONS

The continuous evolution and improvement of sensor technologies, data capture methodologies, and multi-resolution 3D representation can contribute important support to the collection of historic information and the growth of archaeological research. The potential of actual reality-based 3D modeling techniques offers promising applications in the cultural heritage field. Although the actual standard during documentation campaigns is generally a 2D survey, 3D models will probably be the norm in the near future in most of the work related to cultural heritage.

As demonstrated in this article, in the virtualization of the Great Inscription of Gortyna, Crete, and its surrounding heritage area, a high degree of realism can be achieved. The big challenges of the project were the dimensions and richness of detail of the scene, handling the huge meshes and their seamless integration, preservation of the small letter details, and the interactive visualization of the entire virtual area. A 80-million polygon mesh at 0.3mm resolution was produced for the physical replica of the inscription. Studies on the mesh simplification (optimization and further regularization) showed that the reduction of the mesh to 1mm, although useful for faster visualization and handling, would have removed most of the letter details. The final 3D model of the entire area is sufficiently multiscaled and multi-resolution in the acquired data, going from 0.3mm to 5cm geometric resolution.

The image-based modeling approach applied on different parts of the inscription gave satisfactory results in terms of reconstructed details, and the numerical comparison with the range data confirms this. The performed comparisons show how photogrammetry can achieve very high-resolution and accurate results, similar to range sensors.

The virtual model of the Great Inscription now provides a new source of documentation which can be used for a variety of conservation, research, and display applications. The model will firstly be used to build a physical replica of the epigraphic text. Furthermore, it is in the best interests of the involved institutions to continue, using the recovered 3D model, with a study of the techniques of incision and with a deep analysis of the evidence of suffering of the inscription.

REFERENCES

Bendels, G. H., Degener, P., Wahl, R., Körtgen, M., and Andklein, R. 2004. Image-based registration of 3D-range data using feature surface elements. In *Proceedings of the 5th International Symposium on Virtual Reality, Archaeology and Cultural Heritage (VAST'04)*. 115–124.

Bendels, G. H., Schnabel, R., and Klein, R. 2005. Detail-preserving surface inpainting. In *Proceedings of the 6th International Symposium on Virtual Reality, Archaeology and Cultural Heritage (VAST'06)*. 41–48.

Beraldin, J.-A., Picard, M., El-Hakim, S. F., Godin, G., Valzano, V., Bandiera, A., and Latouche, D. 2002. Virtualizing a Byzantine crypt by combining high-resolution textures with laser scanner 3D data. In *Proceedings of the International Conference on Virtual Systems and Multi-Media (VSMM'02)*. 3–14.

Beraldin, J.-A., Blais, F., Cournoyer, L., Picard, M., Gamache, D., Valzano, V., Bandiera, A., and Gorgoglione, M. 2006. Multi-resolution digital 3D imaging system applied to the recording of grotto sites: The case of the Grotta dei Cervi. In *Proceedings of the 7th International Symposium on Virtual Reality, Archaeology and Cultural Heritage* (VAST).

Beraldin, J.-A., Rioux, M., Cournoyer, L., Blais, F., Picard, M., and Pekelsky, J. 2007. Traceable 3D imaging metrology. In *Proceedings of the SPIE: Videometrics IX 6491*, B.1–B.11.

Bernardini, F. and Rushmeier, H. 2002. The 3D model acquisition pipeline. *Comput. Graph. For. 21,* 2, 149–172.

Blais, F. 2004. A review of 20 years of range sensors development. *J. Electron. Imag. 13*, 1, 231–240.

Borgeat, L., Godin, G., Massicotte, P., Poirier, G., Blais, F., and Beraldin, J.-A. 2007. Visualizing and analyzing the Mona Lisa. *Comput. Graph. Appl. 27*,6, 60–68.

Botsch, M., Pauly, M., Kobbelt, L., Allienz, P., and Levy, B. 2008. Geometric modeling-based on polygonal meshes. *Eurographics Tutorial.*

Brown, M. Z., Burschka, D., and Hager, G. D. 2003. Advance in computational stereo. *IEEE Trans. Patt. Anal. Mach. Intel. 25,* 8, 993–1008.

Callieri, M., Cignoni, P., Corsini, M., and Scopigno, R. 2008. Masked photo blending: Mapping dense photographic dataset on high-resolution sampled 3D models. *Comput. Graph. 32*, 4, 464–473.

Cignoni, P., Rocchini, C., Scopigno, R. 1998. Metro: Measuring error on simplified surfaces. *Comput. Graph. For. 17*, 2,167–174.

Cignoni, P., Ganovelli, F., Gobbetti, E., Marton, F., Ponchio, F., and Scopigno, R. 2005. Batched multi-triangulation. In *Proceedings of the IEEE Visualization Conference*. 207–214.

Cignoni, P. and Scopigno, R. 2008. Sampled 3D models for CH applications: A viable and enabling new medium or just a technological exercise? *ACM J. Comput. Cult. Herit.* 1, 1, article 2.

Davis, J., Marshner, S., Garr, M., and Levoy, M. 2002. Filling holes in complex surfaces using volumetric diffusion. In *Proceedings of the 1st International Symposium on 3D Data Processing, Visualization and Transmission (3DPVT'02)*. IEEE Computer Society, 428–438.

Debevec, P., Tchou, C., Gardner, A., Hawkins, T., Poullis, C., Stumpfel, J., Jones, A., Yun, N., Einarsson, P., Lundgren, T., Fajardo, M., and Martinez, P. 2004. Digitizing the Parthenon: Estimating surface reflectance properties of a complex scene under captured natural illumination. In *Proceedings of the Visim, Modeling and Visulization Conference (VMV04)*.

Dey, T. K., Giesen, J., Goswami, S., Hudson, J., Wenger, R., and Zhao, W. 2001. Undersampling and oversampling in sample-based shape-modelling. In *Proceedings of the IEEE Visualization Conference*. 83–90.

Dietrich, A., Gobbetti, E., and Yoon, S.-E. 2007. Massive-model rendering techniques: A tutorial. *Comput. Graph. Appl. 27*, 6, 20–34.

El-Hakim, S. F., Brenner, C., and Roth, G. 1998. A multi-sensor approach to creating accurate virtual environments. *ISPRS J. Photogram. Remote Sensing* 53, 6, 379–391.

El-Hakim, S. F., Beraldin, J. A., Picard, M., and Godin, G. 2004. Detailed 3D reconstruction of large-scale heritage sites with integrated techniques. *IEEE Comput. Graph. Appl.* 24, 3, 21–29

El-Hakim, S., Gonzo, L., Voltolini, F., Girardi, S., Rizzi, A., Remondino, F., and Whiting, E. 2007. Detailed 3D modeling of castles. *Int. J. Archit. Comput.* 5, 2, 199–220.

El-Hakim, S., Remondino, F., and Voltolini, F. 2008. Integrating techniques for detailed and photorealistic 3D modelling of castles. *GIM Int. 22*, 3, 21–25

Eppstein, D. 2001. Global optimization of mesh quality. In *Proceedings of the the 10th International Meshing Roundtable*. (Tutorial)

FASANO, A., PINGI, P., CIGNONI, P., MONTANI, C., AND SCOPIGNO, R. 2005. Automatic coarse registration of range maps. *IEEE Trans. Visual. Comput. Graph.*

FURUKAWA, Y. AND PONCE, J. 2007. Accurate, dense and robust multi-view stereopsis. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition (CVPR07)*.

GOESELE, M., SNAVELY, N., CURLESS, B., HOPPE, H., AND SEITZ, S. M. 2007. Multi-view stereo for community photo collections. In *Proceedings of the International Conference on Computer Vision (ICCV'07)*.

GRUEN, A., REMONDINO, F., AND ZHANG, L. 2005. The Bamiyan project: Multi-resolution image-based modeling. In *Recording, Modeling and Visualization of Cultural Heritage*, E.Baltsavias et al., Eds. 45–54.

GRUEN, A. AND AKCA, D. 2005. Least squares 3D surface and curve matching. *ISPRS J. Photogram. Remote Sensing* 59, 3, 151–174.

GUARNIERI, A., REMONDINO, F., AND VETTORE, A. 2006. Digital photogrammetry and TLS data fusion applied to cultural heritage 3D modeling. *Int. Archives Photogram. Remote Sensing Spatial Inf. Sci. 36*, 5, on CD-Rom.

GUIDI, G., TUCCI, G., BERALDIN, J-A., CIOFI, S., DAMATO, V., OSTUNI, D., COSTANTINO, F., AND EL HAKIM, S. F. 2002. Multiscale archaeological survey-based on the integration of 3D scanning and photogrammetry. In *Proceedings of the CIPA WG 6 International Workshop on Scanning for Cultural Heritage Recording*. 58–64.

GUIDI, G., REMONDINO, F., RUSSO, M., MENNA, F., RIZZI, A. 2008. 3D modeling of large and complex site using multi-sensor integration and multi-resolution data. In *Proceedings of the 9th International Symposium on Virtual Reality, Archaeology and Cultural Heritage (VAST'08)*. 85–92.

HALL, D. L. AND LLIMAS, J. 1997. An introduction to multi-sensor data fusion. *Proc. IEEE* 85, 1, 6–23.

HANUSCH, T. 2008. A new texture mapping algorithm for photorealistic reconstruction of 3D objects. *Int. Archives Photogram. Remote Sensing Spatial Inf. Sci.* 37, 5.

KOBBELT, L. AND BOTSCH, M. 2004. A survey of point-based techniques in computer graphics. *Comput. Graph.* 28, 6, 801–814.

JOHNSON, A. E. AND HEBERT, M. 1997. Surface registration by matching oriented points. In *Proceedings of the International Conference on 3D Imaging and Modeling (3DIM)*.

LENSCH, H., HEIDRICH, W., AND SEIDEL, H. 2000. Automated texture registration and stitching for real world models. In *Proceedings of the 8th Pacific Graphics Conference on Computer Graphics and Applications*. 317–327.

LENSCH, H. P. A., KAUTZ, J., GOESELE, M., HEIDRICH, W., AND SEIDEL, H.-P. 2003. Image-based reconstruction of spatial appearance and geometric detail. *ACM Trans. Graph.* 22, 2, 234–257.

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. 2000. The digital Michelangelo project: 3D scanning of large statues. In *Proceedings of the SIGGRAPH Computer Graphics Conference*. 131–144.

LIEPA, P. 2003. Filling holes in meshes. In *Proceedings of the EG/ACM Symposium on Geometry Processing (SGP'03)*. 200–206.

LUEBKE, D., REDDY, M., COHNE, J., VARSHNEY, A., WATSON, B., AND HUEBNER, R. 2002. *Level of Detail for 3D Graphics*. Morgan-Kaufmann.

NISTER, D. 2001. Automatic dense reconstruction from uncalibrated video sequences. Ph.D. thesis, Computational Vision and Active Perception Lab, NADA-KHT, Stockholm.

PAJAROLA, R. AND DECORO, C. 2004. Efficient implementation of real-time view-dependent multi-resolution meshing. *IEEE Trans. Visualiz. Comput. Graph. 10*, 3, 353– 368.

PODOLAK, J. AND RUSINKIEWICZ, S. 2005. Atomic volumes for mesh completion. In *Proceedings of the EG/ACM Symposium on Geometry Processing (SGP'05)*. 33–41.

POLLEFEYS, M., VAN GOOL, L., VERGAUWEN, M., VERBIEST, F., CORNELIS, K., TOPS, J., AND KOCH, R. 2004. Visual modeling with a hand-held camera. *Int. J. Comput. Vision* 59, 3, 207–232.

PULLI, K., COHEN, M., DUCHAMP, T., HOPPE, H., SHAPIRO, L., STUETZLE, W. 1997. View-based rendering: Visualizing real objects from scanned range and color data. In *Proceedings of the Eurographics Rendering Workshop*. 23–34.

REINHARD, E., WARD, G., PATTANAIK, S., AND DEBEVEC, P. 2005. *High Dynamic Range Imaging: Acquisition, Display and Image-Based Lighting*. Morgan Kaufmann.

REMONDINO, F. AND EL-HAKIM, S. 2006. Image-based 3D modelling: A review. *The Photogram. Rec.* 21, 115, 269–291.

REMONDINO, F., EL-HAKIM, S., GRUEN, A., AND ZHANG, L. 2008. Development and performance analysis of image matching for detailed surface reconstruction of heritage objects. *IEEE Signal Process. Mag.* 25, 4, 56–65.

ROY, M., FOUFOU, S., AND TRUCHETET, F. 2004. Mesh comparison using attribute deviation metric. *Int. J. Image Graph.* 4, 1, 127–140.

SALVI, J., MATABOSCH, C., FOFI, D., AND FOREST, J. 2007. A review of recent range image registration methods with accuracy evaluation. *Image and Vision Comput. 25*, 5, 578–596.

SCOPIGNO, R. AND CIGNONI, P. 2005. Processing huge scanned data sets: Issues and solutions. In *Proceedings of the Recording, Modeling and Visualization of Cultural Heritage Conference*, E. Baltsavias et al., Eds. Taylor & Francis / Balkema.

SILVA, S., MADEIRA, J., AND SANTOS, B. S. 2005. PolyMeCo - A polygonal mesh comparison tool. In *Proceedings of the 9th IEEE International Conference on Information Visualization*. 842–847.

STRECHA, C., VON HANSEN, W., VAN GOOL, L., FUA, P., AND THOENNESSEN, U. 2008. On benchmarking camera calibration and multi-view stereo for high-resolution imagery. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition (CVPR'08)*.

STUMPFEL. J., TCHOU, C., YUN, N., MARTINEZ, P., HAWKINS, T., JONES, A., EMERSON, B., AND DEBEVEC, P. 2003. Digital reunification of the Parthenon and its sculptures. In *Proceedings of the Conference on Virtual Reality, Archaeology and Cultural Heritage (VAST)*. 41–50.

UMEDA, K., SHINOZAKI, M., GODIN, G., AND RIOUX, M. 2005. Correction of color information of a 3D model using a range intensity image. In *Proceedings of the 5th International Conference on 3D Digital Imaging and Modeling (3DIM'05)*. 229–236.

VANDEN WYNGAERD, J. AND VAN GOOL, L. 2002. Automatic crude patch registration: Toward automatic 3D model building. *Comput. Vision Image Understand. 86,* 2, 8–26.

VERGAUWEN, M. AND VAN GOOL, L. 2006. Web-based 3D reconstruction service. *Mach. Vision Appl. 17*, 6, 411–426.

WEYRICH, T., PAULY, M., KEISER, R., HEINZLE, S., SCANDELLA, S., AND GROSS, M. 2004. Postprocessing of scanned 3D surface data. In *Proceedings of the Eurographics Symposium on Point-Based Graph.*, 85– 94.

WILLETS, R. F. 1967. *The Law Code of Gortyn*. de Guyter, Berlin.

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