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# Multi-resolution modeling of complex and detailed Cultural Heritage

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**Abstract**

*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 ca 2-3 mm depth engraved letters) and its surrounding heritage area (ca 30 x 30 m), required a 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 multi-photo 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 visualization.*

## 1. INTRODUCTION

The actual technologies and methodologies for Cultural Heritage documentation and modeling allow the generation of very realistic 3D results (in terms of geometry and texture) used for many scopes like digital conservation, restoration purposes, VR/CG applications, 3D repositories and catalogs, web geographic systems. The actual 3D methodologies and technologies involve mainly active [Bla03] or passive sensors [RE06] or an integration of them, trying to exploit the intrinsic potentialities of each technique. 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 different reasons: (i) the high cost of 3D; (ii) the difficulties in achieving good 3D models by everyone; (iii) the consideration that it is an optional process of interpretation (an additional “aesthetic” factor) and documentation (2D is enough); (iv) the difficulty to integrate 3D worlds with other 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 the digital technologies are giving to the heritage world.
Although hardware and software have shown tremendous improvements in the last years, still many difficulties remain in acquiring, processing and visualizing huge data set of complex and large site. Furthermore the 3D documentation of different sites requires the integration of multiple sensors and a multi-resolution modeling approach, both in geometry and texture, to reconstruct in detail some particular features and with less geometric features some other areas.
The article touches these two problems, reporting the interdisciplinary project of the digital reconstruction of the Great Inscription in Gortyna (Figure 1) for documentation, structural studies and physical replica purposes. The work was designed to achieve a multi-resolution model of the heritage area with a geometric resolution spanning from 0.3 mm to 5 cm. Indeed the inscription contains engraved letters which are 3 mm depth (in the best case). The project required a long planning and the construction of a motorized scanning acquisition system (Figure 2). Primarily range sensors were employed although some detailed areas were modeled using digital images and advanced matching algorithms. The range-data processing pipeline required to set up a cluster of PCs and large editing time to process the huge amount of data (ca 500 million points). The entire heritage area of Gortyna and the Great Inscription were also textured for photo-realistic visualization and to produce a walk-thru movie.
In the successive sections, the project objectives, the range-based modeling and the detailed image-based reconstruction with a multi-photo matching approach are respectively described. Results of the multi-resolution 3D model and some final remarks will conclude the paper.

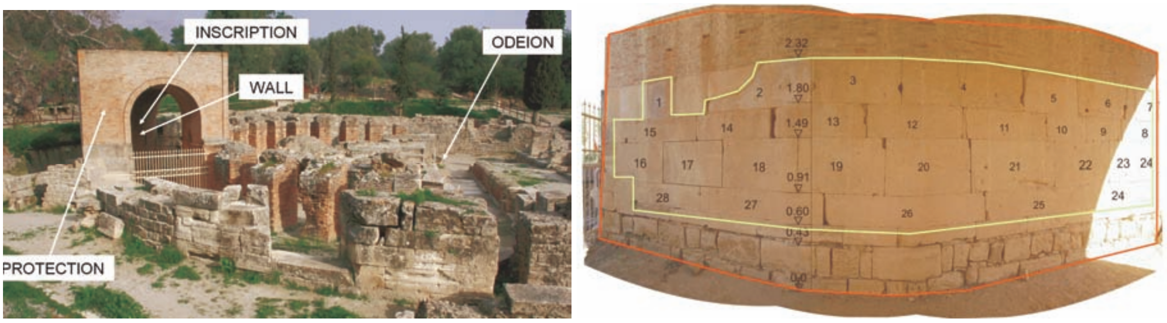


**Figure 1:** *The archaeological area of Gortyna with the parts of the site modeled at different geometric resolution (left). The internal wall in the brick protection containing the Great Inscription subdivided in 12 columns and 30 blocks (right).*

## 2. THE PROJECT

The heritage area of Gortyna (Figure 1) contains a great Odeion (ca 30 x 30 m), a vaulted brick protection (ca 8 x 5 x 4 m) and on its internal limestone wall (ca 8 x 3 m) there is the Great Inscription (ca 6 x 1.75 m) with 2-3 mm depth engraved letters and symbols (Figure 2).

The digital reconstruction of the entire heritage area with a detailed and high-resolution 3D model of the Great Inscription was mainly dictated by the need of a physical replica of the inscription but also structural studies and a virtual visualization of the entire heritage. Indeed the Great Inscription is not accessible and can be only seen from ca 4 m distance behind a fence. Furthermore Gortyna is not a typical touristic location, although amazing and containing the longest and oldest epigraphic text of the Greek civilization. Therefore a virtual visit and tour is really seek and required.

In the project, various sensors used at different geometric resolution 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 to adapt the level of information required by each piece of artwork and to provide for data redundancy useful to identify possible metric errors.

In the project range sensors were primarily used (see Table 1) although aware of the potentialities of the image-based approach and its latest developments in automated and dense image matching [BBM03; GSC07; REG08]. Nevertheless the reliability of active sensors and the related range-based modeling pipeline [BR02] in certain projects is still much higher, although time consuming and expensive. Therefore, also for research purposes, only some areas of the inscription were modeled with our automated multi-photo matching approach [REG08] and the 3D results afterwards compared with the range data.

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

- planarity of the inscription's wall, rising problems in the alignment of the single scans;
- dimension of the object compared to the small field of view of the scanner;
- limited working time for the data acquisition;
- 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 resolution;
- texturing of the 3D models with uniform radiometry (the wall with the inscription was in shadow only ten minutes per day).

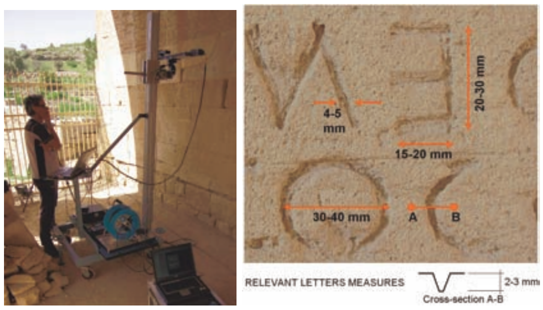


**Figure 2:** *The triangulation-based range sensor mounted on a mobile motorized structure (left) and the relevant letters measures on the Great Inscription (right).*

### 2.1 Historical background

The Great Inscription, ca 6 m long and 1.75 m high, dates back to the middle/late 5$^{th}$ century BC and was discovered in 1884 by Federico Halbherr. Halbherr found inside a watercourse some limestone blocks incised with of the Greek alphabet letters and he reassembled them forming the inscription. The inscription 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 0.3 cm depth (in the best case) engraved letters, is also called "The Queen of Inscriptions" [Wil67]) 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 aiming to protect it but nowadays causing damages to the inscription 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.

| Area | Sensor | Dim [m] | Scans | Acquired pts [Mil] | Reduced pts [Mil] | Mesh resolution [mm] | Final numb polygons [Mil] |
|---|---|---|---|---|---|---|---|
| **Inscription** | ShapeGrabber SG1002 | 6 x 1.75 | 212 | 460 | 375 | 0.3 | 85 |
| | | | | | 176 | 0.5 | 65 |
| | | | | | 85 | 1 | 38 |
| **Wall** | Leica ScanStation2 | 8 x 3 | 3 | 1.2 | 0.9 | 5 | 1.6 |
| **Protection** | | 8 x 5 x 4 | 14 | 4.8 | 3.1 | 10 | 1.4 |
| **Odeion** | | 30 x 30 | 15 | 55 | 31 | 50 | 3.1 |

**Table 1**: *The acquired multi-resolution range data and the derived surface model characteristics.*

## 2.2 Related works

The multi-resolution concept should be distinguished between (i) geometric modeling (3D shape and texture acquisition, registration and further processing) and (ii) appearance modeling and visualization (texturing, blending and rendering of the 3D results).

For 3D documentation of large and complex sites, the state-of-the-art approach is the use and integration of 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. Furthermore 3D modeling based on multi-scale data and multi-sensors is providing the best 3D results in terms of appearance and geometric detail. Indeed each LOD is showing only the necessary information while each technique is used where best suited to exploit its intrinsic modeling advantages. [BPE02] combined low-resolution photogrammetry and high-resolution range data for the 3D modeling of a Byzantine crypt. [STY03] used laser scanners, structured light systems, photogrammetry and photometric stereo for the digital reunification of all the Parthenon's structures. [GRZ05] used a multi-resolution image-based approach to document the entire valley of Bamiyan with its lost Buddha statues and produce 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. [BBC06] used a prototype multi-resolution scanner that allowed acquiring 3D data with a spatial resolution that improves with shorter standoffs. [ERV08] integrated drawings, aerial, helicopter and terrestrial images, range data and GPS measures for the detailed modeling of castles and their surrounding landscapes. The great challenge in the geometric modeling with multi-resolution data is their integration and registration.

On the other hand, appearance modeling seeks a photo-realistic representation of the generated geometric model, using reflectance properties (BRDF) of the object [LKG03] or HDR images [RWP05]. Finally the rendering of large 3D models is done with a multi-resolution approach displaying the large meshes with different levels of detail. Triangular meshes are nowadays very popular and intensively used in most of the projects [BPK08]. But the ability to easily interact with huge meshes is a continuing and increasing problem. Indeed model sizes and resolutions (both geometry and texture) as well as the demands for detailed models are increasing at faster rate than computer hardware advances and this limits the possibilities for interactive and real-time visualization of large 3D models. Therefore optimization, simplification and LOD approaches are generally used to transmit and display big data sets and maintain seamless continuity between adjacent frames [Epp01; LRC02; PD04; CGG05; BGM07; DGY07].

## 2.3 Range-based modeling

As the inscription contains carved symbols and letters with a depth of 2-3 mm (Figure 2), it was digitized with a ShapeGrabber® laser scanner at 0.3 mm lateral resolution. The triangulation-based scanner is equipped with a SG1002 head mounted on a mechanical linear rail system (PLM600) which allows a 60 cm horizontal translation of the sensor. The minimum acquisition distance (standoff) is 300 mm and the Depth of Field (DOF) is 900 mm. The range camera is capable to acquire n=1280 points for each vertical profile. The angle covered by the laser line is ca 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 lateral resolution of 0.3 mm. Due to the 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 2) to quickly move vertically and horizontally the instrument in front of the inscription.

During the data acquisition, as soon as a vertical scanning stripe was completed and before the motorized structure was located in the successive location, the range data were inspected and pre-registered using Polyworks® to check the quality of the data and guaranty sufficient overlap for proper registration and complete coverage of the inscription. After the scanning of all the vertical stripes, the 212 patches (ca 460 million points) were globally aligned and a final standard deviation of 0.27 mm was achieved, in agreement with the sensor's specifications. This procedure required to set up a cluster of two 64 bits PCs with 8 Gigabyte of RAM each. The final 3D surface model of the entire inscription optimized and sampled at 0.3 mm resolution was afterwards decimated and sub-sampled for further texturing and visualization purposes.

For the surrounding area (wall, protection of the Great Inscription and Odeion) the range data acquired with the ToF scanner (Table 1) were processed and registered following the same strategy previously described and afterwards used for the visualization of the entire heritage area of Gortyna. After some holes filling and further editing, the meshed models were textured using

TextCapture and Kodak DCS Pro digital images with 12 Mpixel (18 mm and 50 mm objectives).

### 2.4 Image-based modeling

3D modeling from images is providing sparse or dense point clouds according to the employed measurement methodology (manual or automated). An automated, precise and reliable commercial matching system, adaptable to different image sets and scene contents is not available, in particular for outdoor, convergent and wide baseline images. 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. Following these considerations, [REG08] developed an advance multi-photo geometrically constrained image matching approach able to accurately model in high-resolution details visible in multiple convergent images and retrieve dense and precise 3D point clouds similar to range sensors. The algorithm combines multiple matching primitives and various area-based matching techniques to exploit all the content information of the images. It 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.

In the project, some areas of the Great Inscription were digitally reconstructed using dense image matching. Images were acquired with a calibrated 12 Mpixel SRL Kodak DCS Pro digital camera, equipped with a 50 and 35 mm lenses, providing a footprint spanning from 0.09 to 0.15 mm. After the bundle adjustment step to compute the exterior orientation parameters, the multi-photo matching retrieved accurate and dense surface models. The derived 3D models (Figure 6 and 7) were afterward compared to the range data (Section 3.1).

## 3. RESULTS AND CONSIDERATIONS

The processing of all the range data required ca 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. The triangulation-based range data of the inscription (212 scan, ca 460 million points) were aligned and modeled (a regular sample step was required) at 0.3 mm for the replica purpose (Figure 3). To prevent deformations during the registration of the single patches and avoid a wrong curvature of the Great Inscription, the high-resolution ShapeGrabber scans were also aligned with the Leica ToF data (5 mm sampling distance), providing a measure of the absolute registration error. The curvature of the wall, parameter useful for the physical replica, was also computed. All the meshes were optimized and simplified, in particular in over-sampled areas which were not presenting big discontinuities. The generated 3D models were afterwards merged together to produce a unique multi-resolution virtual model of the heritage area. The interactive visualization of the entire model is currently in progress. Walk-through videos were instead produced for educational purposes and communication. In the visualization, higher resolution data in one level of detail overrides and replaces the overlapping lower resolution data found in previous levels. The closer we get to a certain detail, the higher resolution data are loaded, both in geometry (down to 0.3 mm) and texture (down to 0.25 mm).

The achieved 3D models of the Odeion and the brick protection are shown in Figure 4 and 5.

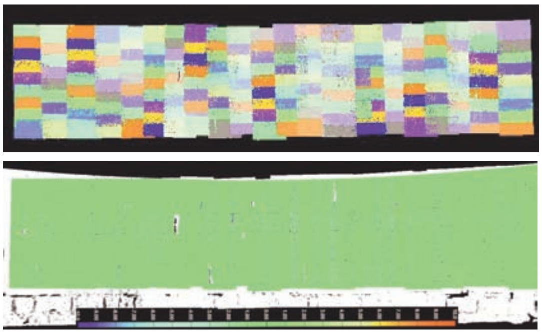

**Figure 3:** *The 212 scans of the inscription aligned and registered at 0.3 mm (above). The successive alignment with the Leica data (final standard deviation of 0.68 mm) performed to prevent deformations of the ShapeGrabber data and preserve the correct curvature of the inscription (below).*

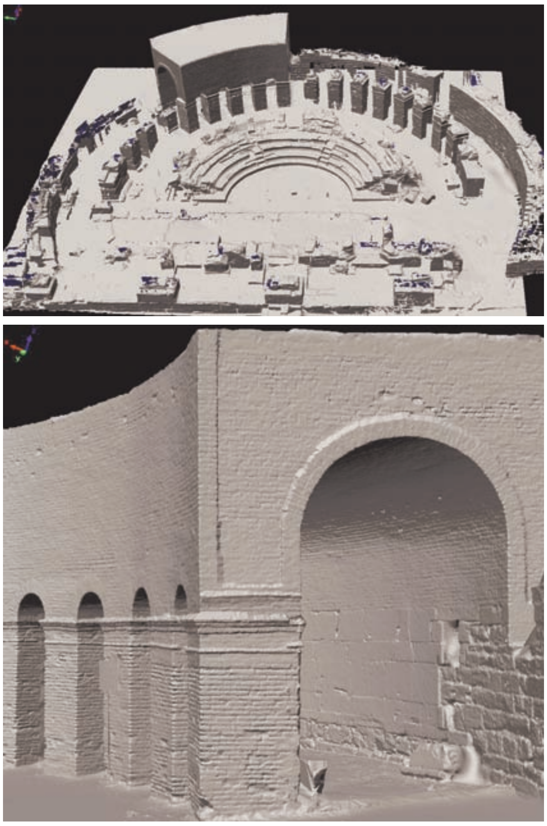

**Figure 4:** *The Odeion of Gortyna modeled with the TOF sensor (above). The brick protection containing the Great Inscription (below).*

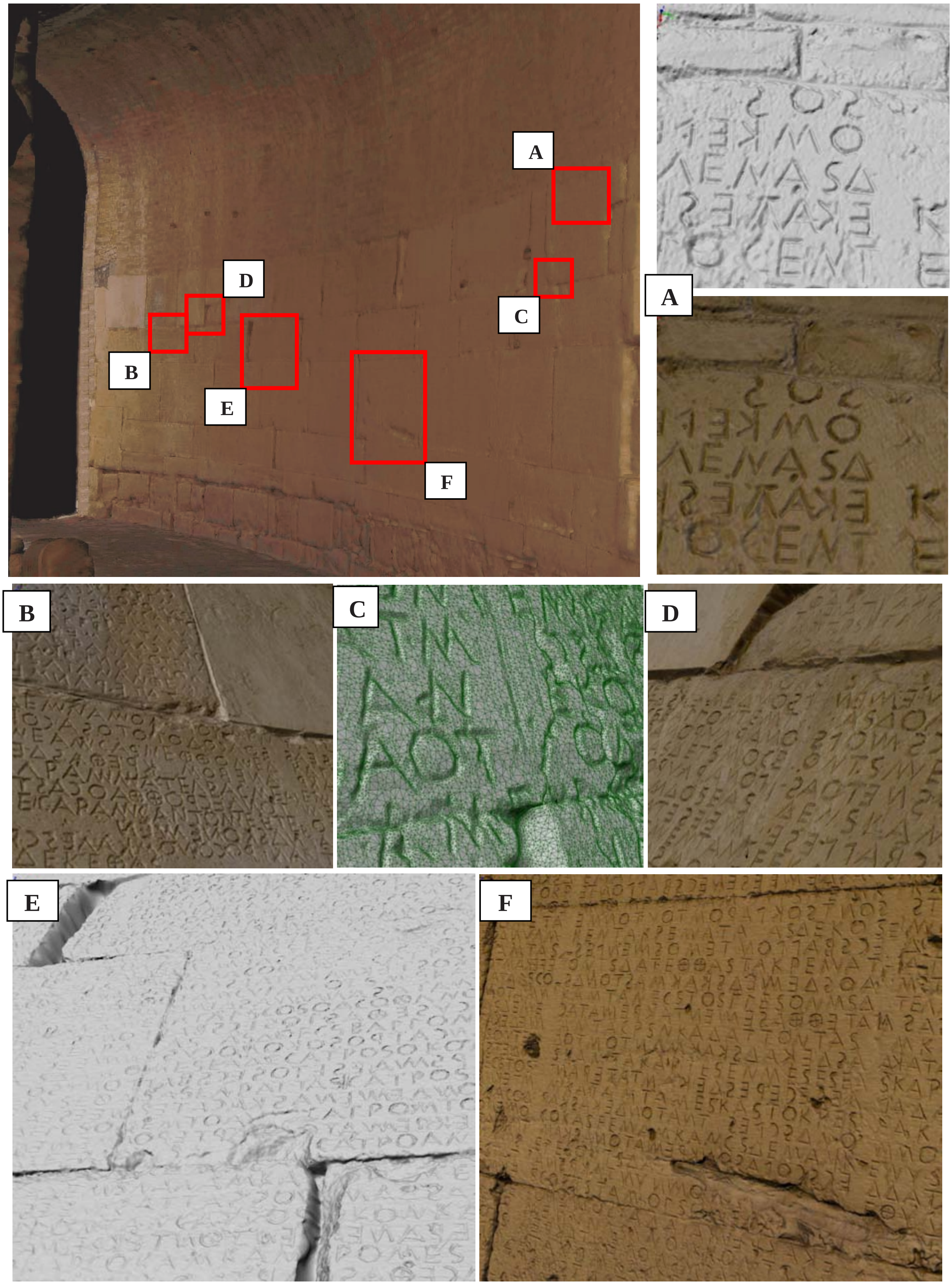


**Figure 5:** *The textured 3D model of the protection and the Great Inscription modeled at 0.3 mm (above left). Some closer views of the wireframe, shaded and textured 3D model.*

### 3.1 Comparison of 3D modeling methodologies

The surface models derived using the multi-photo matching method (Figure 6 and Figure 7) were registered and compared with the triangulation-based range data. The comparison of the meshes was performed in Polyworks/IMInspect. The achieved standard deviation of the differences between the triangular faces resulted 0.36 mm in the case of meshes at 0.5 mm and 0.14 mm between the meshes interpolated at 0.3 mm. These results confirmed that we can model detailed areas with range sensors or images, achieving the same results in terms of accuracy and modeled details. Nevertheless the statistical values are not indicating which surface model (or modeling methodology) is better. They simply provide an indicator of the very small discrepancy between the two models. A standard methodology for the performance evaluation of surface reconstruction methods is needed, like those available for the traditional surveying or CMM. Research works presenting mesh comparison tools have been presented in [CRS98; RFT04; SMS05].

**Figure 6:** *Part of the inscription (ca 30 x 40 cm) modeled using 3 images with a ground sample distance of 0.09 mm (above left). The generated surface model (ca 990 000 points) with a resolution of 0.3 mm shown in colour-code and shaded mode.*

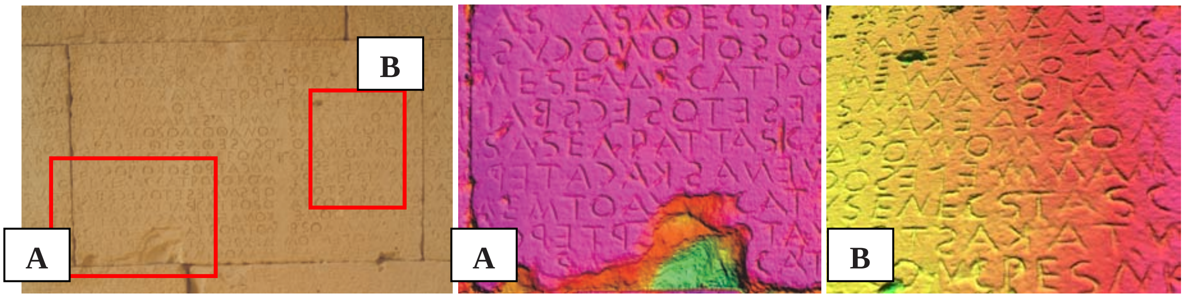


**Figure 7:** *Part of the inscription (ca 1.2 x 0.6 m) modeled using 5 images with a ground sample distance of ca 0.15 mm (left). Two views of the recovered surface model (2.2 million points at 0.5 mm geometric resolution) derived using the multi-photo matching approach [REG08] and shown in colour-code mode.*

### 3.2 Mesh simplification and geometric evaluation

Beside the high-resolution mesh realized for the physical replica with a regular sample of 0.3 mm, further models at lower resolution were also produced, for faster handling and visualization. This required a sub-sampling of the data and therefore a loss of the geometric accuracy.

Figure **8** shows a visual comparison of a part of the surface model optimized and then regularized at 0.3, 0.5 and 1 mm resolution respectively. The clear smoothing effect in producing the lower resolution meshes has been numerically evaluated comparing different profiles and cross-sections on the entire wall. Table 2 reports the maximal and minimal deviations between the high-resolution and resampled meshes. The mesh at 1 mm (38 Mil polygons) is clearly smoothing out areas with large discontinuities while the mesh at 0.5 mm (65 Mil polygons) is still keeping the details despite its 20% mesh reduction. Although for faster handling and visualization purposes the simplification might be very useful and not visible, given the project objectives and requirements, it was not acceptable.

## 4. CONCLUSIONS

The potentiality of actual reality-based 3D modeling techniques opens really promising applications in the Cultural Heritage field. As demonstrated in this contribution with the virtualization of the Great Inscription of Gortyna 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 details of the scene, the handling of the huge meshes, their seamless integration, the preservation of the small letters details and the interactive visualization of the entire virtual area. A 80 millions polygons mesh at 0.3 mm resolution was produced for the physical replica of the inscription. Studies on the mesh simplification (optimization and further regularization) showed that, although useful for faster visualization and handling, the reduction of the mesh at 1 mm would have removed most of the letters. The final 3D model of the entire area is multi-scale and multi-resolution already in the acquired data, going from 0.3 mm to 5 cm 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 confirm 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 interest 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. Indeed, after the discovery, the inscribed wall was covered with a vaulted brick roof which is probably causing damages to the wall itself. Comparing the old evidence of the inscription (photographs, drawings etc.) and the actual 3D model there is a good possibility to identify the critical points in order to develop a new project intended to prevent future structural problems.

(A)

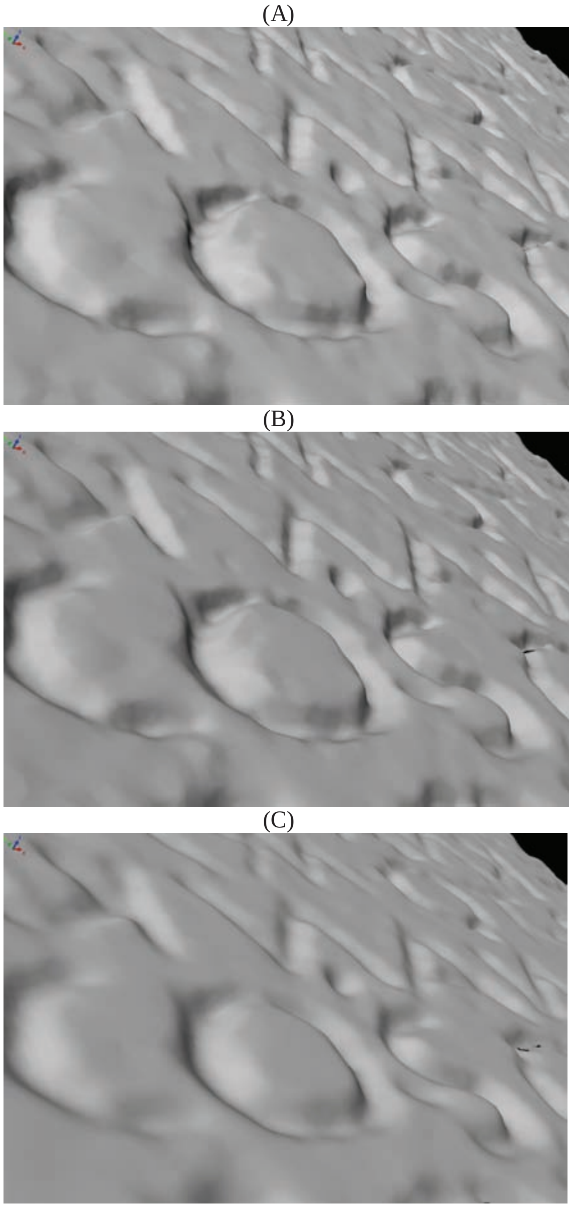


**Figure 8**: *A detail of the high-resolution mesh (A) and the two reduced versions (B = 0.5 mm; C = 1 mm). The simplification at 1 mm smoothed most of the details.*

| **Mesh comparison** | **Max deviation** | **Min deviation** |
|---|---|---|
| 0.3 versus 0.5 mm | +0.407 mm | -0.268 mm |
| 0.3 versus 1 mm | +0.916 mm | -0.745 mm |

**Table 2**: *Numerical evaluation of the loss of geometric accuracy in down-sampling and regularizing the mesh.*

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