Digitizing Pompeii's Forum

Gabriele Guidi,[1] Fabio Remondino,[2] Michele Russo,[1] Fabio Menna,[3] Alessandro Rizzi,[2] and Sebastiano Ercoli[1]

[1] Dept. INDACO, Politecnico of Milano. Italy.
[2] 3D Optical Metrology Group-Bruno Kessler Foundation (FBK). Trento, Italy.
[3] Dept. of Applied Sciences, Parthenope University. Naples, Italy.

Abstract

This paper presents a multi-resolution and multi-sensor approach developed for the accurate and detailed reality-based 3D modeling of the entire Roman Forum in Pompei, Italy. The Forum, approximately 150 x 80 m, contains more than 350 finds spread all over the area, as well as larger structural remains of buildings and temples. The interdisciplinary 3D modeling work consists of a multi-scale image- and range-based digital documentation method developed to fulfilll all the surveying and archaeological needs and to exploit all the intrinsic potentialities of the actual 3D modeling techniques. Data resolution ranges from a few decimeters down to a few millimeters. The results of the integration of the different 3D data in a seamlessly textured 3D model are presented and discussed.

Keywords: *3D modeling, multi-resolution, integration, image matching, laser scanning*

1 INTRODUCTION

The current generation of reality-based 3D models of objects and sites is usually made by means of images or active sensors (such as laser scanners or structured light projectors), depending on the surface characteristics, required accuracy, object dimensions and location, and the project's budget. Active sensors provide 3D data directly, and combined with color information, either from the sensor itself or from a digital camera, can capture relatively accurate geometric details.[1] Although Although
they are still costly, usually bulky, with limited flexibility, not easy to use everywhere or at every time, and affected by surface properties, active sensors have reached maturity; indeed, the range-based modeling pipeline[2] is now quite straightforward, although problems may arise with very large data sets.

On the other hand, image-based methods[3] require a mathematical formulation (perspective or projective geometry) to transform two-dimensional image measurements into 3D coordinates. Images contain all the useful information to derive geometry and texture for a 3D modeling application. But the reconstruction of detailed, accurate and photo-realistic 3D models from images is still a difficult task, particularly for large and complex sites or if uncalibrated or widely separated images are used.

Besides range- and image-data, surveying information and maps can also be combined for correct geo-referencing and scaling. Although many methodologies and sensors are available, to achieve a good and realistic 3D model containing the required level of detail the best approach is still the combination of different modeling techniques and sensors. A single technique is not yet able to give satisfactory results in all situations; high geometric accuracy, portability, automation, photo-realism and low costs, as well as flexibility and efficiency, image, and range data are generally combined in order to fully exploit the intrinsic potentialities of each approach.[4]

The continuous evolution and improvement of sensor technologies, data capture methodologies, and multi-resolution 3D representation can contribute important support to the refinement of information and to the

[1]François Blais, "A Review of 20 Years of Range Sensors Development," *Journal of Electronic Imaging* 13 (1) (2004): 231.

[2]Paolo Cignoni and Roberto Scopigno, "Sampled 3D Models for CH Applications: A Viable and Enabling New Medium or Just a Technological Exercise?" *ACM Journal on Computing and Cultural Heritage* 1 (1) (2008).

[3]Fabio Remondino and Sabry F. El-Hakim, "Image-based 3D Modeling: A Review," *Photogrammetric Record* 21 (115) (2006): 269.

[4]Gabriele Guidi et al., "Fusion of Range Camera and Photogrammetry: A Systematic Procedure for Improving 3-D Models' Metric Accuracy," *IEEE Transactions on Systems, Man, and Cybernetics*, Part B, (4) (2003): 667; Jessi Stumpfel et al., "Digital Reunification of the Parthenon and its Sculptures," *Virtual Reality, Archaeology and Cultural Heritage-VAST 2003*, 41 (2003); Sabry F. El-Hakim et al., "Detailed 3D Reconstruction of Large-scale Heritage Sites with Integrated Techniques," *IEEE Computer Graphics and Application*, 24 (3) (2004): 21.

Figure 1. *Part of the archaeological area of Pompeii seen in an oblique aerial view with the Forum (approximately 150 m long and 80 m wide) in the center* (top). *Details from the archaeological area* (bottom).

rowth of archaeological research. There is also an increasing need for digital documentation of archaeological sites at different scales and resolutions.

In this contribution we report our multi-resolution approach developed for the reality-based 3D modeling of the entire Roman Forum in Pompeii, Italy (fig. 1). The archaeological area is approximately 150 x 80 m and contains more than 350 finds spread all over the Forum as well as larger structures of previous buildings and temples. This type of project requires adequate planning before the field work, including: a systematic approach to identify the proper sensor technology and data capture methodology; an estimated time for scanning and imaging; definition of quality parameters; and avoidance of tourists. For our project, the fieldwork had to be completed within a specific time dictated by the availability of equipment and support personnel, access to the site, and project budget. Thus, it was important to assemble the right surveying methodology and an optimum working team on the site to handle all operations effectively.

The modeling methodology was developed to fulfilll all the surveying and archaeological needs and to exploit all the potentialities of the actual 3D modeling techniques. The completed 3D model will give to the Superintendency of Pompeii an instrument to control the complex conservation of the site, to educate the public, and to provide visitors to the site a means for understanding the complex stratigraphy of the Forum.

2 THE 3D MODELING PROJECT

The survey and 3D modeling of the Forum of Pompeii is part of a larger project regulated by two agreements among the company ARCUS, the Archeological Superintendence of Pompeii (SAP), and the Scuola

Normale Superiore of Pisa. The first collaboration produced the SAP Information System, designed for the management of archaeological information (e.g., cataloguing resources and geographic data) related to the vast area around Mount Vesuvius. The second, begun in May 2007, consists of (i) the generation of a website including resources for the study of Pompeii's heritage, and (ii) the development of a 3D model of the entire Forum. The modeling work is carried out by the INDACO Department of the Politecnico of Milan in collaboration with other scientific institutes and university departments. The 3D modeling project is also aimed at defining best practices for data acquisition and rendering of 3D models that will be undertaken for the Superintendency of Pompeii in the future. The main objective is to establish some core specifications for data acquisition and modeling, in order to guarantee the scientific quality of data and the interoperability of 3D models with the information system. Thus, the working methodology is centered on close cooperation between archaeologists and engineers. In addition, the final 3D results of the project will provide an up-to-date, digital, and three-dimensional instrument for controlling the state of conservation of the site, planning future preservation actions, and educating (and entertaining) the public with virtual reality shows.

2.1 Historical background

The Forum was the main square of ancient Pompeii, the center of political, commercial and religious life. Located in the middle of the so-called "Altstadt," the oldest part of the city (in the southwestern quadrant of the plan),[1] it is the key to interpretation of town-planning evolution from the seventh century B.C. to the final destruction of Pompeii by the eruption of Vesuvius in 79 A.D. The interpretation of the various building phases and the examination of the complex relationships among the walls of the monuments that are still visible in the Forum are therefore important topics in the archaeological investigation of the urban history of Pompeii. In its first configuration during the Samnite period, the Forum had a trapezoidal shape and was oriented on a northwest /southeast axis. This orientation was maintained at least until the second half of the second century B.C., when the Forum was transformed into a rectangular square with a north/south axis, including the Capitolium (Temple of Jupiter) on the shorter side, pointing toward Mount Vesuvius. The archaic Forum contained the main square, which was paved with pressed volcanic ashes, the Temple of Apollo, and some commercial buildings (*tabernae,* shops) found under the east Porticus. During the late Samnite period (second century B.C.), the appearance of the Forum changed completely: the square was paved, the Temple of Apollo was restored, and the Macellum was built. Other important buildings were added during the second half of the century: the Basilica, the Temple of Jupiter, and the Comitium, together with the so-called Porticus of Popidius along the east and south sides, defining the new orientation of the square. This ensemble of monuments has been interpreted by Dobbins as a whole and named the "Popidian Ensemble."[2] During the Early Imperial period, the Forum was altered again; the square was paved with travertine, which was also used for rebuilding the Porticus. New monuments were built along the east side of the Forum, which was completely transformed with a new complex of buildings dedicated to the Imperial cult: the sanctuaries of the *Lares Publici* (also called of the Imperial Cult), the sanctuaries of the *genius* of Augustus (or the Temple of Vespasian), and the Eumachia. The square was completed with the two monumental arches placed on each side of the Capitolium. In 62 A.D. a strong earthquake seriously damaged Pompeii and its monuments were still under restoration in 79 A.D., when the Vesuvius erupted. This chronology needs to be further refined on the basis of further archaeological data. Many researchers are currently investigating the history of the Forum and, through this, the evolution of the entire city of Pompeii. The continuously evolving sensor technologies and data capture methodologies, new techniques for data acquisition and rendering, and multi-resolution 3D representation can contribute important support to the refinement of information and to the growth of archaeological research.

2.2 Previous 3D surveys in Pompeii

Reality-based 3D reconstructions of single rooms, houses, or monuments of the UNESCO site of Pompeii have already been mentioned in the literature. The largest survey was conducted by Balzani et al., [3] using a TOF scanner, on the entire Forum, although the results were only presented in point cloud form. The Pompeii Project of the University of Virginia (USA) aims, with the help of photogrammetry, to provide the first systematic documentation of the architecture and decorations of the Forum, to interpret evidence as it pertains to Pompeii's urban history, and to make wider contributions to both the history of urbanism and

[1]Armin Von Gerkan, *Stadtplan von Pompeji*. Berlin, 1940; Hans Eschebach, *Die städtebauliche Entwicklung des antiken Pompeji*. Heidelberg: Die Baugeschichte der Stabianer Thermen, nach H. Sulze, RMErgH 17, 1970.

[2]John J. Dobbins and Larry F. Ball, "The Pompeii Forum Project," paper presented at the International Conference on Nuove ricerche archeologiche a Pompei ed Ercolano, Studi della Soprintendenza archeologica di Pompei 10, 2005.

[3]Marcello Balzani et al., "Laser Scanner 3D Survey in the Archaeological Field: The Forum of Pompeii," paper presented at the International Conference on Remote Sensing Archaeology, Beijing, China, October 2004; Gabriele Bitelli et al., "Photogrammetric Surveying of 'Nymphea,'" paper presented at the XVIII International Symposium of CIPA, Potsdam, Germany, 2001; Yoshiaki Hori et al., "Laser Scanning in Pompeian City Wall—A Comparative Study of the Accuracy of the Drawings from the 1930s to 1940s," *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 36 (5) (2007).

contemporary problems of urban design. Hypothetic reconstructions of the Forum, based on the integration of the real geometry of the relics with documents and philological reconstructions, date back to the seventeenth century;[1] these have been further developed in recent years with augmented and virtual reality technologies using handmade CAD models[2] or semi-automatically, using procedural models.[3]

The work presented here belongs to the first category (i.e. reality-based models) and its main goal is the proper integration of technologies for achieving the best tradeoff among (i) accuracy of geometrical and iconographic representation; (ii) acquisition and processing time; and (iii) size of the integrated model.

3 MULTI-RESOLUTION METHODOLOGY

Multi-resolution data are now the base of different geospatial databases and visualization repositories. Probably the best and most well-known examples are Google Earth and Microsoft Virtual Earth. Data resolution ranges from hundreds of meters (both in geometry and texture) down to a 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). For the 3D archaeological survey of the Forum in Pompeii, a similar approach was selected, combining data at different resolutions coming from different sensors and platforms. A top-to-bottom methodology was employed, which starts from traditional aerial images and reaches higher resolution geometric details through range data and terrestrial images. The great challenge of such an approach is the precise registration and seamless integration of the data for the realization of realistic reality-based 3D results.

3.1 RELATED WORKS ON MULTI-RESOLUTION 3D MODELING

The multi-resolution approach and the integration of different modeling technologies and methodologies (photogrammetry, active sensors, topographic surveying, etc.) provide the best modeling results. Each LOD shows only the necessary information, while each technique is used where best suited to exploit its intrinsic modeling advantages. During the 1990s, sensor fusion was exploited with radars and infrared sensors as a means for precisely estimating airplane trajectories in the military field,[4] but at the end of that decade NRC Canada developed a Data Collection and Registration system for integrating a 3D sensor with a set of 2D sensors for registration and texture mapping.[5] Guidi et al.[6] generated high resolution 3D models of Roman mosaic fragments with a pattern projection range camera, oriented them with photo-grammetry, and integrated these data with a TOF laser scanner. Böhler and Marbs[7] made a comparison between active and passive technologies in the architectural and archaeological field, in order to give guidelines for the proper application of integrated survey technologies. Gruen et al.[8] used a multi-resolution image-based approach to document the entire valley of Bamiyan with its lost Buddha statues and to produce an up-to-date GIS of the UNESCO area. Bonora et al.[9] fused multi-resolution range data to model the Rucellai chapel in Florence. Remondino et al.[10] integrated drawings, images, range data, and GPS for the detailed modeling of castles and surrounding areas.

[1]Carl Weichardt, *Pompei vor der Zerstörung. Reconstructionen der Tempel und ihrer Umgebung* (Leipzig: Karl Franz Koehler, 1898).

[2]Maurizio Forte et al., "DVR-Pompei: A 3D Information system for the House of the Vettii in OpenGL Environment," paper presented at the 1st International Symposium on Virtual Reality, Archaeology and Cultural Heritage, VAST, 2001; George Papagiannakis et al., "Mixing Virtual and Real Scenes in the Site of Ancient Pompeii," *Computer Animation and Virtual Worlds*, 16 (1) (2005): 11.

[3] Pascal Mueller et al., "Procedural Modeling of Buildings," *ACM Transactions on Graphics* 25 (3) (2006): 614.

[4]David L. Hall and James Llinas, "An Introduction to Multisensor Data Fusion," *Proceedings of the IEEE*, 85 (1) (1997): 6.

[5]Sabry F. El-Hakim et al., "A Multi-sensor Approach to Creating Accurate Virtual Environments," *ISPRS Journal for Photogrammetry and Remote Sensing* 53 (6) (1998): 379.

[6]Gabriele Guidi et al, "Multiscale Archaeological Survey Based on the Integration of 3D Scanning and Photogrammetry," paper presented at CIPA WG 6th International Workshop on Scanning for Cultural Heritage Recording, Korfu, Greece, 2002.

[7]Wolfgang Böhler and Andreas Marbs, "3D Scanning and Photogrammetry for Heritage Recording: A Comparison," paper presented at the 12th International Conference on Geoinformatics, Gävle, Sweden, 2004.

[8]Armin Gruen et al., "The Bamiyan Project: Multi-resolution Image-based Modeling," in *Recording, Modeling and Visualization of Cultural Heritage*, ed. by Emmanuel Baltsavias et al. (Balkema: Taylor & Francis, 2005) 45–54.

[9]Valentina Bonora et al., "3D Data Fusion and Multi-resolution Approach for a New Survey Aimed to a Complete Model of Rucellai's Chapel by Leon Battista Alberti in Florence," paper presented at CIPA XX International Symposium, Turin, Italy, 2005.

[10]Fabio Remondino et al., "3D Virtual Reconstruction and Visualization of Complex Architectures: The 3D-ARCH Project," *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 38 (2009).

	Sensors	Use	Quantity	Geometric resolution	Texture resolution
Aerial images	Zeiss RMK A 30/23	DSM of the site at low resolution	3 (scale 1:3500)	25 cm	5 cm
	Pictometry	Texturing	4	-	15 cm
Range sensors	Leica HDS3000	Modeling of entire Forum at middle resolution	21 scans (400 Mil pts)	5–20 mm	-
	Leica HDS6000		45 scans (800 Mil pts)	5–10 mm	-
Terrestrial images	Canon 10D (24 mm lens, 6 Mpixel) Canon 20D (20 mm lens, 8 Mpixel) Kodak DCS Pro (50 mm lens, 12 Mpixel)	Modeling of small finds, mural structures, ornaments	6000	0.5–10 mm	0.2–5 mm

Table 1. *The data employed for the multi-resolution 3D modeling of the Forum in Pompeii.*

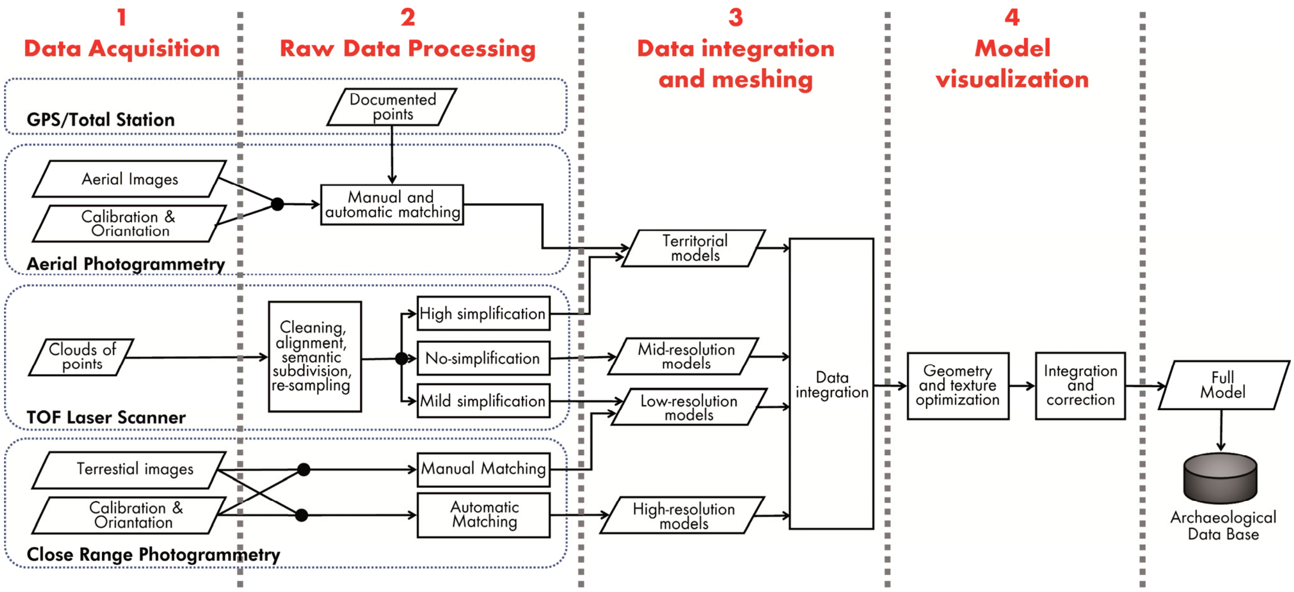

Figure. 2. *Multi-sensor and multi-resolution data integration for 3D digitization of Pompeii's Forum.*

4 DIGITIZATION OF THE FORUM

As demonstrated in the aforementioned literature, many proposals have already been made for illustrating how the integration of different technologies can help to optimize an archaeological survey. However, these have generally operated by combining pairs of different methods (e.g., radar/infrared sensors, TOF laser-scanner/photogrammetry, triangulation range cameras/ close range photogrammetry).

This paper attempts to demonstrate how the concept of integration can be overstressed, combining more technologies (i.e. GPS, topography, TOF laser scanning, aerial imaging, and close range photogrammetry) in order to cover a full archaeological area with details ranging from the geographical level to a small bas-relief and ending up in a 3D repository (fig. 2).

In this project, the reason for adopting an integrated methodology was twofold:

a) to adapt the level of information associated with each artifact contained in the area to the proposed instrument (e.g., conventional photogrammetry for large flat walls, laser scanning for irregular or partially broken wall structures, or photogrammetric dense matching for small detailed decorations);
b) to introduce a level of redundancy useful to optimize the model accuracy and/or identify possible metric errors in the model.

4.1 MULTI-SENSOR DATA ACQUISITION

For the 3D documentation of the large archaeological area, the following data were employed (Table 1):

1. classical aerial images acquired for a previous mapping project (scale 1:3500);
2. oblique aerial views acquired for texturing purposes;
3. range-data acquired from the ground with two TOF Leica scanners;
4. terrestrial images to (i) fill gaps, (ii) document small finds in higher resolution by means of dense image matching, and (iii) reconstruct simple structures with fewer geometric details.

The geometric resolution of the data ranges from 25 cm to a few mm in geometry and from 15 cm down to a few mm in texture. The use of oblique images (coming from Pictometry technology) was dictated by the fact that the available vertical aerial images were dated to 1987 and the actual situation of the Forum is slightly different.

4.2 DATA PROCESSING

The available triplet of aerial images (1:3500 image scale) was oriented with a standard photogrammetric bundle block adjustment, using some control points available from the local cartographic network (fig. 3). For the Digital Surface Model (DSM) generation, the ETH multi-photo matcher SAT-PP was employed.[1] The matcher derived a dense point cloud of ca. 18 million points (the area is approximately 1 x 0.8 km).

The range data (ca. 1.2 billion points) were processed inside Cyclone (Leica Geosystems AG, Switzerland) and PolyWorks (Innovmetric, Canada). The scans' alignment (surface-based) and data editing (cleaning, layer generation, sampling, and semantic subdivision of different structures) required about six months of work. After cleaning, simplification, and overlap reduction, 36 million points were used for the buildings (walls of 14 structures plus a boundary wall) and the terrain model, while 64 million points were needed for roughly describing the geometry of 377 archaeological finds all around the Forum. A total of 100 MPoints were therefore useful for describing all the geometries in the Forum from 1.2 GPoints of raw data acquired (approximately a 1:10 ratio).

For reducing the number of polygons in the final mesh, the IMCompress software was used. It is part of the Polyworks package and is based on a sequential optimization process that iteratively removes triangulation vertices, minimizing the 3D distance between the reduced triangulation and the original one. The process stops when the maximum 3D distance between the current triangulation and the original model exceeds a tolerance level. In this way the software removed redundant vertices in over-sampled areas while keeping the reduced model as close as possible to the original one.

The terrestrial images (ca. 6000) were used to (i) model all the mural structures surrounding the Forum area; (ii) reconstruct the 377 finds; and (iii) derive detailed and high-resolution geometric models of some decorations. Most of the processing, which was applied to well-conserved (flat) structures and to the pieces scattered around the Forum, such as parts of columns, trabeations and pedestals, was achieved with standard close-range photogrammetry software (PhotoModeler). For detailed surfaces (ornaments, reliefs, etc.) the multi-photo geometrically constrained software CLORAMA[2] was used.

4.3 DATA REGISTRATION AND INTEGRATION

In order to register the whole dataset in a geo-referenced coordinate system, a set of starting topographic points given by the Pompeii Superintendency was used and enriched with a dedicated topographic campaign. The laser scanning campaign was primarily devoted to creating a geometrical framework on which to orient each photogrammetric model. For this reason, the two starting scans were acquired from two documented topographic points and all the other point clouds were aligned on these. The final range model was afterwards roto-translated through the other documented points with a spatial similarity transformation (with the scale constrained to 1). The resulting point cloud (fig. 4) was afterwards employed to align each single photogrammetric model and, thanks to redundancy, to check for possible dimensional errors.

5 RESULTS

The three aerial images provided a dense DSM (ca. 18 million points), which was then interpolated at 25 cm to produce a surface model of the entire archaeological area. The model was afterwards textured with the relative orthophoto. This constitutes the first low-resolution level of detail of the entire 3D model of the Forum in Pompeii. Despite the fact that the 25 cm DSM slightly smoothed out small architectural features (like walls or columns), it is a good start for a fly-over and as an initial visualization of the site. The range data, primarily used to orient all the terrestrial photogrammetric models, resulted in a cloud of ca. 100 million points (fig. 4). Some areas of particular archaeological interest were also meshed, and high resolution models, textured with the acquired digital images, were produced.

The photogrammetric processing of all the 6000 terrestrial images produced 3D models of simple structures (arches, walls, columns) or larger complexes such as temples. Detailed decoration or reliefs, modeled in high resolution with an advanced multi-photo matching approach (fig. 6), were afterwards integrated with the other low-resolution data. Special care was given to model optimization. Indeed, the models generated using the range data were initially extremely detailed and heavy, due to the high point density. In order to optimize the successive visualization steps, the

[1] Li Zhang, *Automatic Digital Surface Model (DSM) Generation from Linear Array Images* (Ph.D. diss., Technische Wissenschaften ETH Zurich, 2005); 4DiXplorer AG, www.4dixplorer.com/.

[2] Fabio Remondino et al., "Turning Images into 3-D Models—Development and Performance Analysis of Image Matching for Detailed Surface Reconstruction of Heritage Objects," *IEEE Signal Processing Magazine* 25 (4) (2008): 56.

models were then selectively simplified, leaving few polygons in flat areas and a high geometrical resolution only in areas designated by the archaeological team involved in the project. The level of texture resolution was also considered independently by the geometric resolution for maximizing the level of information associated with any specific artifact. In this way, low geometric resolution and high texture mapping resolution was used for flat walls with interesting *opus reticulatum* sections, while high geometric resolution with low texture mapping resolution was used for complex shapes made with uniform and not particularly interesting materials.

6 VISUALIZATION

The final visualization of such kinds of models, possibly in a virtual reality (VR) environment, is typically a critical step. Several visualization tools for effective display of polygonal models have been developed in the last few years. Starting from the QSplat software[1] to the most recent achievements,[2] the base concept was the possibility of using several different levels of detail (LODs), simplifying the mesh off-line at different levels and generating a single multi-resolution file including all the LODs, similar to what happens in 2D with pyramidal images. On the other hand, several virtual reality visualization packages are currently available on the market or in the Open Source domain for application in the Industrial Design area (e.g., Autodesk Alias Showcase, RTT Deltagen, Autodesk Opticore) or environmental simulation (e.g., Paradigm Multigen, Open Scene Graph, Ultramundum, mental images RealityServer). These systems have been developed mainly for visualizing CAD models represented by a set of mathematical surfaces such as NURBS or B-Splines, tessellated at the visualization stage at the optimal level (the lowest possible number of polygons for the best visual effect), and enriched in real-time with ray tracing features such as texture mapping, bump mapping, transparencies, reflections, etc., to achieve a more realistic rendering.

The advantage of this kind of software is that stereoscopy is also easily managed, since the package is specifically designed for virtual theaters. In addition, any 3D entity can be considered as a node of a hierarchical network and each node can be connected to a database for linking the model to different kinds of information (text, images, or other 3D models), useful in specific applications. The main disadvantage is that their architecture is not oriented to virtually unlimited LODs and the model is often simply preloaded into the Computer RAM before navigation.

Therefore, although the latter kind of system seems suitable only for smooth CAD models (with synthetic procedural textures), we attemped to use it on our reality-based 3D model made with a texturized mesh originated by irregular acquired data. The large 3D model of the Forum of Pompeii (ca. 600K polygons) was forced to fit the requirements of one of these commercial packages (RTT Deltagen), in order to evaluate its performance and to prepare an engineered ready-to-use version for virtual reality, suitable for a museum or a public institution (fig. 7). The model texture was simplified to ¼ of the original in order to fill up the on-board memory on the specific PC used (8 GB), including geometry and texture. Real-time rendering visits have been tested with a smooth navigation into the digital version of the Forum in Pompeii, with a frame rate between 10 and 15 frames per second, in a virtual theater equipped with active stereoscopy.

7 CONCLUSIONS

In this paper, the reality-based 3D modeling project of the Forum in Pompeii has been presented. The first results of the modeling and integration are promising, although practical and reliable solutions for the visualization of the entire 3D multi-resolution model are still under investigation. The final and complete 3D model should also be linked to the existing SAP Information System, for the management and the query of archaeological information in three dimensions. The integration of multiple modeling methodologies has allowed us to exploit the intrinsic advantages of each technique and to use each one where best suited. Therefore, flat mural surfaces were reconstructed with few points while ornaments and details were modeled with laser scanner or dense image matching. This approach also helped in the generation of the level of details of the final 3D model of the large site. Our approach was planned to be hierarchical by the data source, and in the hierarchy, details, precision, and reliability increase as we get closer to a find or to an item of particular archaeological interest.

Since it is geo-referenced, the entire 3D model can be easily linked to existing archaeological databases using the spatial coordinate as query. We plan to implement the database model relationship in two ways: (i) from the geometrical model to the connected data, for explaining historical and conservation details of a specific artifact in the Forum, and (ii) from a specific document or philological detail to the corresponding location in the 3D space. This tool is intended as an instrument to enhance the complex conservation activity of the Pompeii Superintendency, the general archaeological study of the area, and the explanation of the Forum's ruins to the public.

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[1] Szymon Rusinkiewicz and Marc Levoy, "QSplat: A Multiresolution Point Rendering System for Large Meshes," paper presented at *ACM SIGGRAPH 2000*: 343.

[2] Louis Borgeat et al., "GoLD: Interactive Display of Huge Colored and Textured Models," *ACM Transactions on Graphics*, 24 (3) (2005): 869; Paolo Cignoni et al., "Batched Multi Triangulation," paper presented at IEEE Visualization, Minneapolis, MN, USA, October 23–28, 2005.

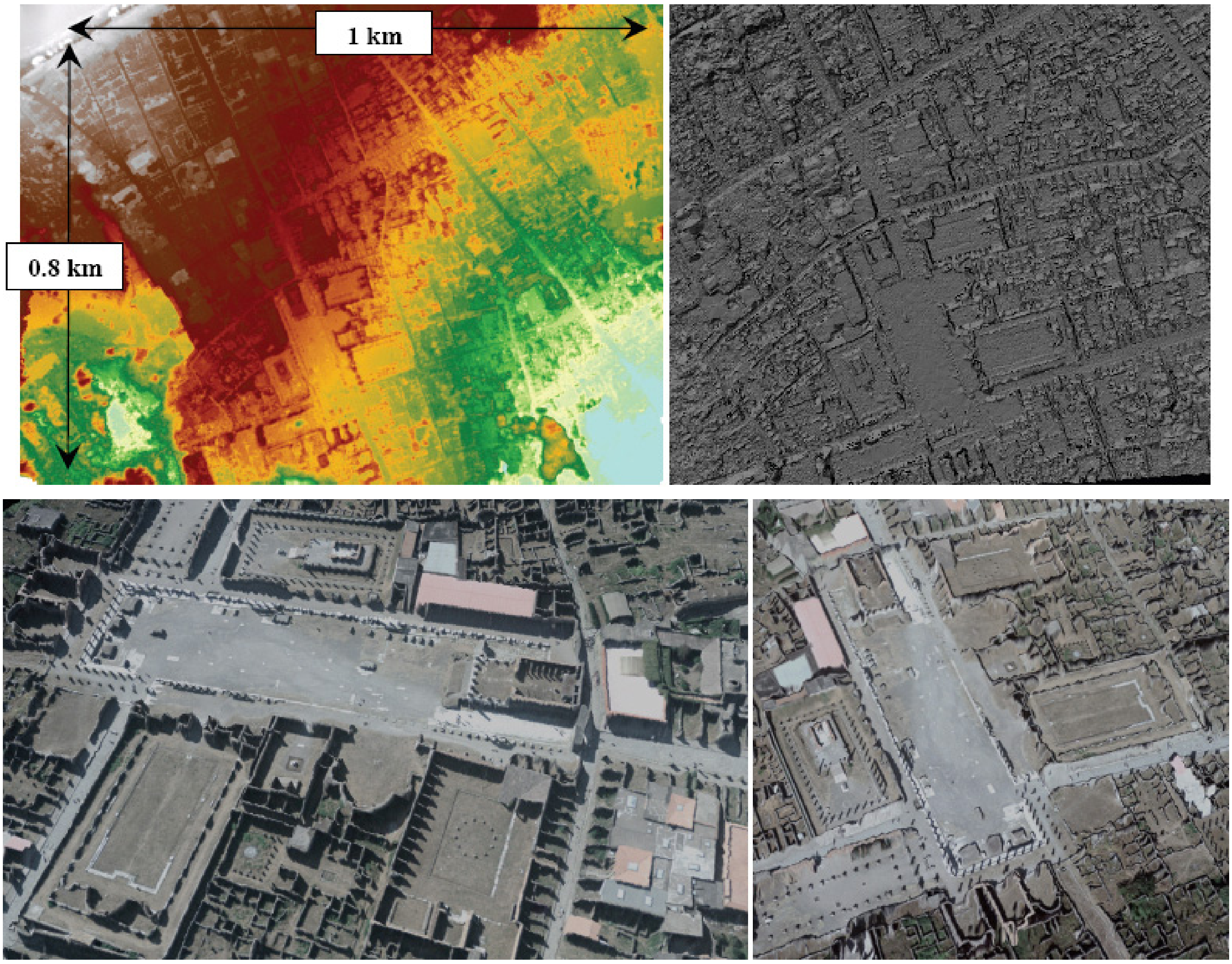

Figure 3: *DSM of the archaeological area generated from three aerial images, in color-coded and shaded mode* (top). *Surface model, interpolated at 25 cm and textured with the generated orthophoto* (bottom).

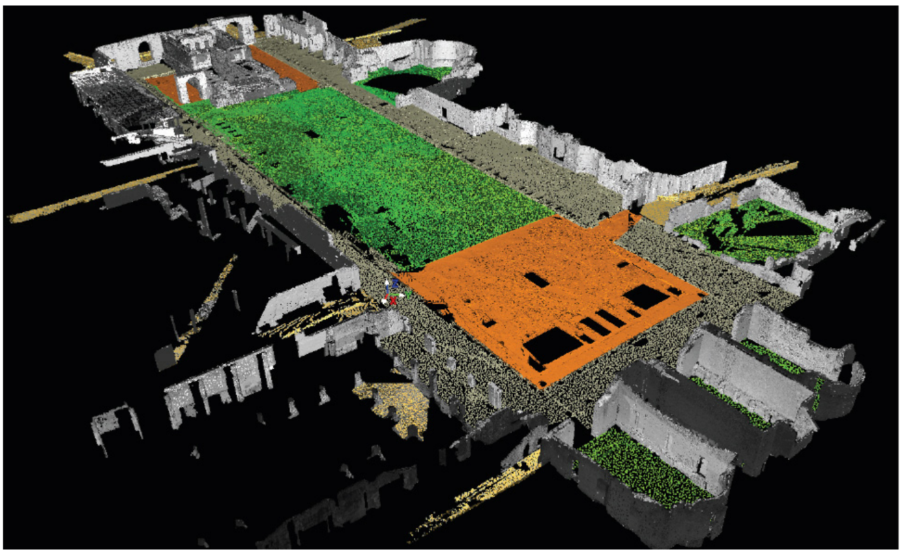

Figure 4. *The acquired range data of the main mural structures of the Forum. Those data were the basis for the alignment of all the photogrammetric 3D model.*

Figure 5. *Range models of archeologically significant structures.*

Figure 6. *Detailed and accurate 3D models of columns, arches or finds generated using photogrammetry***.**

Figure 7. *Detailed ornament* (above) *and bas-relief* (below) *modeled by means of dense image matching. The derived surface models are shown in color-coded, shaded, and textured mode.*

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BIBLIOGRAPHY

Balzani, Marcello, Nicola Santopuoli, Alessandro Grieco, and Nicola Zaltron. "Laser Scanner 3D Survey in the Archaeological Field: The Forum of Pompeii," paper presented at the International Conference on Remote Sensing Archaeology, Beijing, China, October 18–21, 2004.

Bitelli, Gabriele, Andrea Capra, and Antonio Zanutta. "Photogrammetric Surveying of 'Nymphea'," paper presented at the XVIII International Symposium of CIPA (Comité International de Photogrammétrie Architecturale), Potsdam, Germany, 2001: 236–242.

Blais, François. "A Review of 20 Years of Range Sensors Development," *Journal of Electronic Imaging* 13 (1) (2004): 231–240.

Böhler, Wolfgang, and Andreas Marbs. "3D Scanning and Photogrammetry for Heritage Recording: A Comparison," paper presented at the 12th International Conference on Geoinformatics, Gävle, Sweden, 2004: 291–298.

Bonora, Valentina, Grazia Tucci, and Vincenzo Vaccaro. "3D Data Fusion and Multi-resolution Approach for a New Survey Aimed to a Complete Model of Rucellai's Chapel by Leon Battista Alberti in Florence," paper presented at the XX International Symposium of CIPA (Comité International de Photogrammétrie Architecturale), Turin, Italy, 2005.

Borgeat, Louis, Guy Godin, François Blais, Philippe Massicotte, and Christian Lahanier. "GoLD: Interactive Display of Huge Colored and Textured Models." *ACM Transactions on Graphics* 24 (3) (2005): 869–877.

Cignoni, Paolo, Fabio Ganovelli, Enrico Gobbetti, Fabio Marton, Federico Ponchio, and Roberto Scopigno. "Batched Multi Triangulation," paper presented at IEEE (Institute of Electrical and Electronics Engineers) Visualization 2005, Minneapolis, MN, USA, October 23–28, 2005.

Cignoni, Paolo, and Roberto Scopigno. "Sampled 3D Models for CH Applications: A Viable and Enabling New Medium or Just a Technological Exercise?" *ACM Journal on Computing and Cultural Heritage* 1 (1) (2008).

Dias, Paulo, Victor Sequeira, Francisco Vaz, and Joao G. M. Gonçalves. "Registration and Fusion of Intensity and Range Data for 3D Modeling of Real World Scenes," paper presented at the 4th IEEE (Institute of Electrical and Electronics Engineers) International Conference on Recent Advances in 3D Digital Imaging and Modeling (3DIM '03), Banff, Canada, 2003.

Dobbins, John J., and L. F. Ball. "The Pompeii Forum Project," paper presented at the International Conference "Nuove ricerche archeologiche a Pompei ed Ercolano." *Studi della Soprintendenza archeologica di Pompei* 10 (Napoli, 2005): 60–72.

El-Hakim, Sabry F., Claus Brenner, and Gerhard Roth. "A Multi-sensor Approach to Creating Accurate Virtual Environments," *ISPRS Journal for Photogrammetry and Remote Sensing* 53 (6) (1998): 379–391.

El-Hakim, Sabry F., J.-Angelo Beraldin, Michel Picard, and Guy Godin. "Detailed 3D Reconstruction of Large-Scale Heritage Sites with Integrated Techniques," *IEEE Computer Graphics and Application* 24 (3) (2004): 21–29.

Eschebach, Hans. *Die städtebauliche Entwicklung des antiken Pompeji*. Heidelberg: Die Baugeschichte der Stabianer Thermen, nach H. Sulze, *RMErgH* 17, 1970.

Forte, Maurizio, Eva Pietroni, Claudio Rufa, Angela Bizzarro, and Stefano Tilia. "DVR-Pompei: A 3D Information System for the House of the Vettii in OpenGL Environment," paper presented at the 1st International Symposium on Virtual Reality, Archaeology and Cultural Heritage-VAST, 2001: 307–314.

Hori, Yoshiaki, Osamu Ajioka, and Asami Hanghai. "Laser Scanning in Pompeian City Wall: A Comparative Study of Accuracy of the Drawings from the 1930s to 1940s," *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences* 36 (5) (2007). www.isprs.org/commission5/3darch07/pdf/hori_etal.pdf.

Kadobayashi, Rieko, Nobuo Kochi, Hitoshi Otani, and Ryo Furukawa. "Comparison and Evaluation of Laser Scanning and Photogrammetry and Their Combined Use for Digital Recording of Cultural Heritage," *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 35(5) (2004): 401–406. http://www.isprs.org/congresses/istanbul2004/comm5/papers/586.pdf.

Iorio, Vincenza, Satoshi Sakai, Hirofumi Chikatsu, and Tatsuya Ohdake. "Archaeological Investigation of the Fountains in Pompeii and Creating Virtual Environments," *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences* 36 (5) (2007). www.isprs.org/commission5/3darch07/pdf/iorio_etal.pdf.

Gruen, Armin, Fabio Remondino, and Li Zhang. "The Bamiyan Project: Multi-resolution Image-based Modeling," in *Recording, Modeling and Visualization of Cultural Heritage*, edited by Emmanuel Baltsavias, Armin Gruen, LucVan Gool, and Maria Pateraki, 45–54, Balkema: Taylor & Francis, 2005.

Guidi, Gabriele, Grazia Tucci, J.-Angelo Beraldin, Stefano Ciofi, Valentina Damato, Daniele Ostuni, Fabrizio Costantino, and Sabry F. El Hakim. "Multiscale Archaeological Survey Based on the Integration of 3D Scanning and Photogrammetry," paper presented at CIPA (Comité International de Photogrammétrie Architecturale) Work Group 6; International Workshop on Scanning for Cultural Heritage Recording, Korfu, Greece, 2002: 58–64.

Guidi, Gabriele, J.-Angelo Beraldin, Stefano Ciofi, and Carlo Atzeni. "Fusion of Range Camera and Photogrammetry: A Systematic Procedure for Improving 3-D Models' Metric Accuracy," *IEEE Transactions on Systems, Man, and Cybernetics*, *Part B* 33 (4) (2003): 667–676.

Guidi, Gabriele, J.-Angelo Beraldin, and Carlo Atzeni. "High Accuracy 3D Modeling of Cultural Heritage: The Digitizing of Donatello's 'Maddalena'," *IEEE Transactions on Image Processing* 13 (3) (2004): 370–380.

Hall, David L., and James Llinas. "An Introduction to Multisensor Data Fusion," *Proceedings of the IEEE* 85 (1) (1997): 6–23.

MacLean, Steve G., Marc Rioux, François Blais, Julius J. Grodski, Paul Milgram, H.F.L. Pinkney, and B. A. Aikenhead. "Vision System Development in a Space Simulation Laboratory," paper presented at Close-Range Photogrammetry Meets Machine Vision, Society of Photo-Optical Instrumentation Engineers, 1394, 1990: 8–15.

Mueller, Pascal, Peter Wonka, Simon Haegler, Andreas Ulmer, and Luc Van Gool. "Procedural Modeling of Buildings," Paper presented at ACM SIGGRAPH 2006/*ACM Transactions on Graphics* 25 (3) (2006): 614–623.

Papagiannakis, George, Sebastien Schertenleib, Brian O'Kennedy, Marlene Arevalo-Poizat, Nadia Magnenat-Thalmann, Andrew Stoddart, and Daniel Thalmann. "Mixing Virtual and Real Scenes in the Site of Ancient Pompeii," *Computer Animation and Virtual Worlds* 16 (1) (2005): 11–24.

Remondino, Fabio, and Sabry F. El-Hakim. "Image-based 3D Modeling: A Review," *Photogrammetric Record* 21 (2006): 269–291.

Remondino, Fabio, Sabry F. El-Hakim, Armin Gruen, and Li Zhang. "Turning Images into 3-D models-Development and Performance Analysis of Image Matching for Detailed Surface Reconstruction of Heritage Objects," *IEEE Signal Processing Magazine* 25 (4) (2008): 56–65.

Remondino, Fabio, Sabry F. El-Hakim, Stefano Girardi, Alessandro Rizzi, Stefano Benedetti, and Lorenzo Gonzo. "3D Virtual Reconstruction and Visualization of Complex Architectures-The 3D-ARCH Project," *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 38 (5) (2009). www.isprs.org/commission5/3darch09/pdf/remondino_etal.pdf.

Rusinkiewicz, Szymon, and Marc Levoy. "QSplat: A Multiresolution Point Rendering System for Large Meshes," paper presented at ACM SIGGRAPH 2000: 343–352.

Stumpfel, Jessi, Christopher Tchou, Nathan Yun, Philippe Martinez, Timothy Hawkins, Andrew Jones, Brian Emerson, and Paul Debevec. "Digital Reunification of the Parthenon and its Sculptures," paper presented at Virtual Reality, Archaeology and Cultural Heritage-VAST 2003, 41–50.

Von Gerkan, Armin. *Stadtplan von Pompeji*. Berlin, 1940.

Weichardt, Carl. *Pompei vor der Zerstörung. Reconstructionen der Tempel und ihrer Umgebung.* Leipzig: Karl Franz Koehler, 1898.

Zhang, Li. *Automatic Digital Surface Model (DSM) Generation from Linear Array Images.* Ph.D. diss., Technische Wissenschaften ETH Zurich, 2005.