A Multi-Resolution Methodology for the 3D Modeling of Large and Complex Archeological Areas

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This article reports on a multi-resolution and multi-sensor approach developed for the accurate and detailed 3D modeling of the entire Roman Forum in Pompei, Italy. The archaeological area, approximately 150 × 80 m, contains more than 350 finds spread all over the forum as well as larger mural structures of previous buildings and temples. The interdisciplinary 3D modeling work consists of a multi-scale image- and range-based digital documentation method developed to fulfill all the surveying and archaeological needs and exploit all the intrinsic potentialities of the actual 3D modeling techniques. The data resolution spans from a few decimeters down to few millimeters. The employed surveying methodologies have pros and cons which will be addressed and discussed. The results of the integration of the different 3D data in seamlessly textured 3D model are finally presented and discussed.

1. INTRODUCTION

The generation of reality-based 3D models of objects and sites is nowadays usually performed by means of images or active sensors (like laser scanner or structured light projectors), depending on the surface characteristics, required accuracy, object dimensions and location, project's budget, etc. Active sensors [1] provide directly 3D data and combined with color information, either from the sensor itself or from a digital camera, can capture relatively accurate geometric details. Although still costly, usually bulky, with limited flexibility, not easy to be use everywhere or at every time or affected by surface properties, active sensors have reached a maturity since some years and the range-based modeling pipeline [2] is nowadays quite straightforward although problems generally arise in case of huge data sets.

On the other hand, image-based methods [12] 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, nowadays 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. In fact, as a single technique is not yet able to give satisfactory results in all situations, concerning high geometric accuracy, portability, automation, photo-realism and low costs as well as flexibility and efficiency, image and range data are generally combined to fully exploit the intrinsic potentialities of each approach [7; 38; 4; 32].

The continuously evolving and improving of sensor technologies, data capture methodologies and multi-resolution 3D representation can contribute with an important support to the refinement of information and to the growth of the archaeological research. Furthermore there is an increasing requests and needs 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 (Figure 1). The archaeological area is approximately 150 × 80 m and contains more than 350 finds spread all over the Forum as well as larger structures of previous buildings and temples. In this kind of projects, adequate planning before the field work demands a systematic approach to identify the proper sensor technology and data capture methodology, estimate time for scanning and imaging, define quality parameters, avoid tourists, etc. In the project, the fieldwork had to be completed within a

◄ Figure 1. The Forum of Pompeii (approximately 150 m long and 80 m wide) seen in an oblique aerial view with highlighted the working area (A). Some of the finds spread all over the archaeological area and a detailed bas-relief.

specific time dictated by the availability of equipment and support personnel, allowed 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 fulfill all the surveying and archaeological needs and exploit all the potentialities of the actual 3D modeling techniques. The final 3D model will give to the Superintendence of Pompeii an instrument to control the complex conservation of the site, to educate and to provide to the common public a mean for understanding the stratified Forum's structure.

2. THE 3D MODELING PROJECT

The survey and 3D modeling of the Pompeii Forum 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 one produced the new SAP Information System, for the management of archaeological information (cataloguing resources and geographic data) related to the vast area around Mount Vesuvius. The second agreement, started in May 2007, consists of:

(i) the generation of a website for the communication to the broad public of studies and resources on Pompeii's heritage and

(ii) the developing 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 aimed at defining also some best practices for data acquisition and rendering of 3D models that will be realized in the future for the Superintendence of Pompeii. 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 the strict cooperation between archaeologists and engineers. In addition the final 3D results of the project will give to the local superintendence an up-to-date, digital and three-dimensional instrument for controlling the state of conservation of the heritage, planning future preservation actions as well as entertain the public with VR shows.

2.1. Historical Background

The Pompeii Forum was the main square of the ancient city, therefore the centre of the political, commercial and religious life. After an early architectural development during its first five centuries, in the second half of the II century B.C. the Forum was shaped as a rectangular square with a North/South axis, including the Capitolium (Temple of Zeus) in the shorter side and pointing at Mount Vesuvius, the Macellum, the Basilica, the Comitium and the so-called Porticus of Popidius along the East and South sides. During the Early Imperial Age, in the Roman period, the Forum changed again its aspect, the square was paved with travertine stone and new monuments were built along the East side: the Sanctuaries of Lares Publici (also called of the Imperial Cult), the Sanctuaries of the Geius of Augustus (or Temple of Vespasianus) and the Eumachia Building. The square was completed with the two monumental Arches placed on both sides 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 and covered with dust the entire city [15, 19].

2.2. Previous Works

Reality-based 3D reconstructions of single rooms, houses or monuments of the UNESCO site of Pompeii were already mentioned in the literature [25; 22; 33]. The largest survey was conducted by Balzani et al. [23] with a ToF scanner on the entire Forum, although the results were only presented in point cloud form. The Pompeii Project of the Virginia University (USA) aims, with the help of photogrammetry, to provide the first systematic documentation of the architectures 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 contemporary problems of urban design [16]. Hypothetic reconstructions of the Forum, based on the integration of the real geometry of the relics with documents and philological reconstruction date back to the seventeenth century [20] and have been further developed in recent years with Augmented and Virtual Reality technologies using handmade CAD models [30; 11] or semi-automatically with procedural models [10].

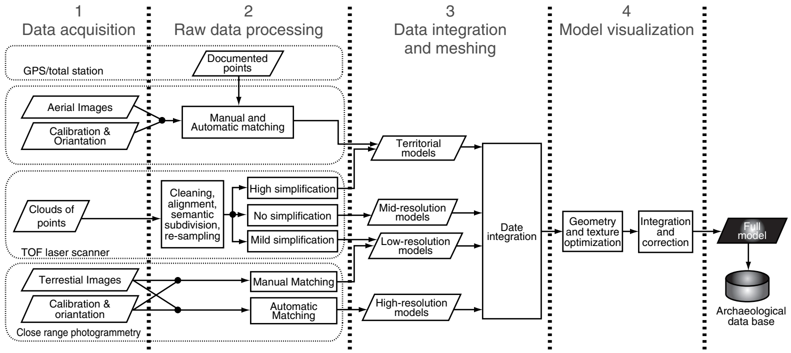
The work presented here belong to the first category (i.e. reality-based models) and its main goal is the proper integration of technologies for achieving the best tradeoff among (i) accuracy of geometrical and iconographic representation, (ii) acquisition and processing time and (iii) size of the integrated model. Furthermore the final 3D model will be for the Superintendence of Pompeii an instrument for controlling the complex conservation of the site and for scholars and common public a mean for understanding the stratified Forum structure.

3. THE MULTI-RESOLUTION MODELING METHODOLOGY

Multi-resolution data are nowadays the base of different geospatial databases and visualization repositories. Probably the best and most known examples are given by Google Earth or Microsoft Virtual Earth. Data span from hundreds meters 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).For the 3D archaeological survey of the Forum in Pompeii, a similar approach was selected. A top-bottom methodology was employed, which starts from traditional aerial images and reaches higher resolution geometric details through range data and terrestrial images. For large areas like the Forum, the documentation of both landscape and architectures requires data with very different resolution which must be afterwards carefully registered and integrated to produce seamless and realistic 3D results.

3.1. Related Works

The multi-resolution approach and the integration of different modeling technologies and methodologies (photogrammetry, active sensors, topographic surveying, etc) are nowadays providing the best modeling results. Indeed each LOD is showing only the necessary information while each technique is used where best suited to exploit its intrinsic modeling advantages. Since the nineties sensor fusion has been exploited with radars and infrared sensors as a mean for precisely estimate airplane trajectories in the military field [9] 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 [6]. Guidi et al. [31] 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. In order to give guidelines for the proper application of integrated survey technologies, Böhler and Marbs [26] made an exhaustive comparison between active and passive technologies both in the architectural and archaeological field. Gruen et al. [17] used a multi-resolution image-based



► Figure 2. Integration of multi-resolution data for 3D modeling the Pompeii Forum.

approach to document the entire valley of Bamiyan with its lost Buddha statues and produce an up-to-date GIS of the UNESCO area. Bonora et al. [27] fused multi-resolution range data to model the Rucellai chapel in Florence. El-Hakim et al. [3] integrated drawings, images, range data and GPS for the detailed modeling of castles and their surrounding landscapes.

4. 3D Modeling of the Forum

As demonstrated in the aforementioned literature, many contributions have been already proposed for illustrating how the integration of different technologies can help to optimize an archaeological survey. However these works have been generally carried on combining couples of different methods (e.g. radar/infrared sensors, TOF laser-scanner/photogrammetry, triangulation range cameras/close range photogrammetry). This paper attempt to demonstrate how the integration concept can be overstressed mixing up more technologies (i.e. GPS, topography, TOF laser scanning, aerial imaging, close range photogrammetry) in order to cover a full archaeological area with details ranging from the geographical level to a small a bas-relief and ending up in a 3D repository (Figure 2).

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

a) adapt the level of information associated to 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, photogrammetric dense matching for small detailed decorations);
b) introduce a level of redundancy useful to optimize the model accuracy and/or identify possible metric errors in the model.

4.1. Sensors and 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 precedent mapping project (scale 1:3500);

	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, 8Mpixel) Kodak DCS Pro (50 mm lens, 12 Mpixel)	Modeling of small finds, mural architectural structures, ornaments	3200	0.5-10 mm	0.2-5 mm

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

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 less geometric details.

The geometric resolution of the data spans from 25 cm to few mm in geometry and from 15 cm down to few mm in texture. The use of oblique images (coming from Pictometry technology) was dictated by the fact that the available vertical aerial images dated back 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. For the Digital Surface Model (DSM) generation, the ETH multi-photo matcher SAT-PP was employed [21; 13]. The matcher derived a dense point cloud of ca 18 millions points (the area is approximately 1×0.8 km).

The range data (ca 1.2 billions points) were processed inside Cyclone (Leica Geosystems AG, Switzerland) and Polyworks (Innovmetric, Canada). The scans alignment (surface-based) and data editing (cleaning, layers generation, sampling and semantic subdivision of different structures) required ca 6 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 where therefore useful for describing all the geometries in the Forum after 1.2 GPoints of raw data acquired (approx 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 maintaining the reduced model as close as possible to the original one.

The terrestrial images (ca 3200) were employed 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 ornaments. Most of the processing, applied to well conserved (flat) structures and to the pieces scattered around the Forum, such as pieces of columns, trabeations and pedestals, was achieved with standard close-range photogrammetry software (PhotoModeler), while for detailed surfaces (ornaments, reliefs, etc) the multi-photo geometrically constrained ETH matcher CLORAMA [13] was used.

4.3. Data Registration and Integration

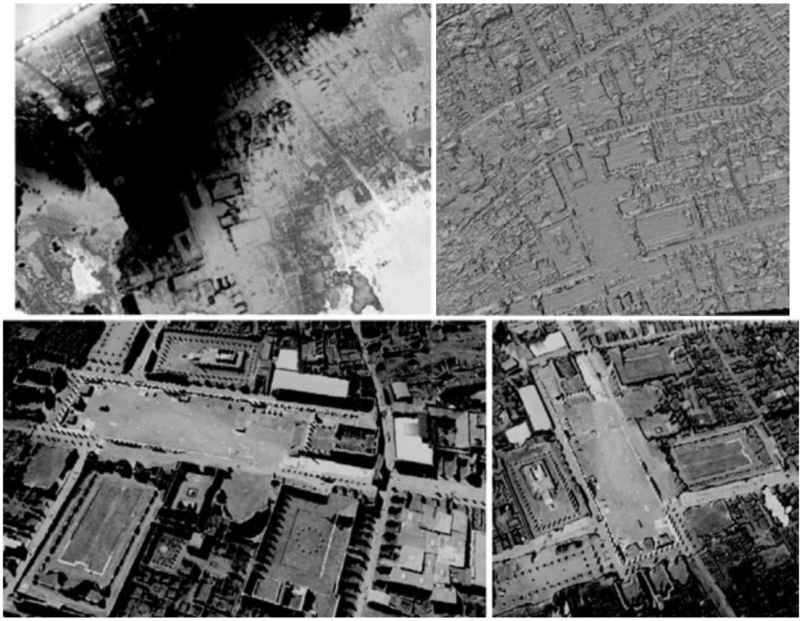
In order to register the whole dataset in a geo-referenced coordinate system, a set of starting topographic points given by the Pompeii Superintendence was used and enriched with a dedicated topographic campaign.

The laser scanning campaign was primarily devoted to create a geometrical framework on which orient each photogrammetric model. For this reason, the two starting scans were acquired from two documented topographic points and all the other clouds of point where 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 (Figure 4) was afterwards employed to align each single photogrammetric model and, thanks to redundancy, for checking possible dimensional errors.

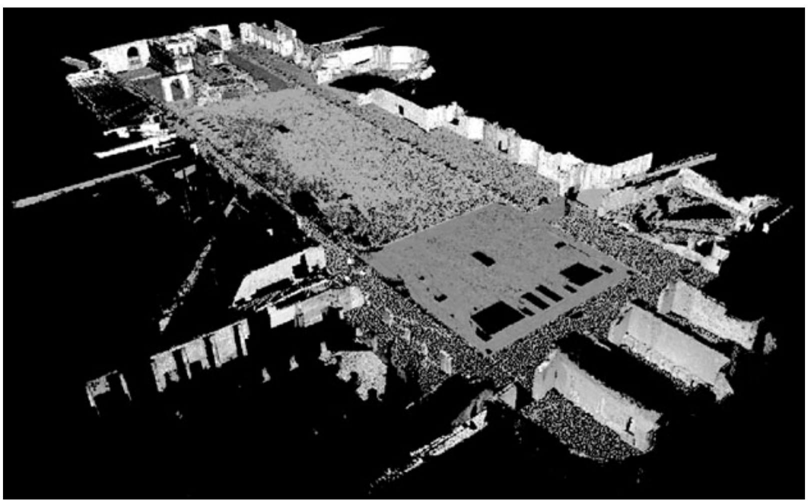
5. RESULTS

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 (Figure 3). 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 smoothed slightly out small architectural features (like walls or columns) it is a good starting for a flight-over and as initial visualization of the heritage.

The range data, primarily used to orient all the terrestrial photogrammetric models, resulted in a cloud of ca 100 million points (Figure 4). Some areas of particular archaeological interests were also



◀ Figure 3. The DSM of the archaeological area generated from three aerial images, shown in colour-code and shaded mode (above). Two views of the surface model, interpolated at 25 cm and textured with the generated orthophoto (below).



◀ Figure 4. The acquired range data of the main mural structures of the Forum.

meshed and high resolution models, textured with the acquired digital images, were produced (Figure 5).

The photogrammetric processing of all the 3200 terrestrial images produced 3D models of simple structures (arches, walls, columns) or larger complexes (e.g. temples). Detailed ornaments or relief, modeled in high resolution with an advanced multi-photo matching approach (Figure 6) [13] 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

► Figure 5. Range models of archeologically interesting large structures (a) and terrestrial photogrammetric models of columns, arches or finds (b).

point density. In order to optimize the successive visualization step, the models were then selectively simplified leaving few polygons in flat areas and a high geometrical resolution only in the areas indicated 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, or, high geometric resolution with low texture mapping resolution for complex shapes made with uniform and not particularly interesting materials.

6. INTERACTIVE VISUALIZATION

The final visualization of such kind of models, possibly in a Virtual Reality (VR) environment, is typically a critical step.

Several visualization tools for effectively display of polygonal models have been developed in the last years. Starting from the QSplat software [37] to the most recent achievements [5; 28], the base concept was the possibility to

◀ Figure 6. Detailed ornament modeled by means of dense image matching. The derived surface model is shown in colour-code mode.

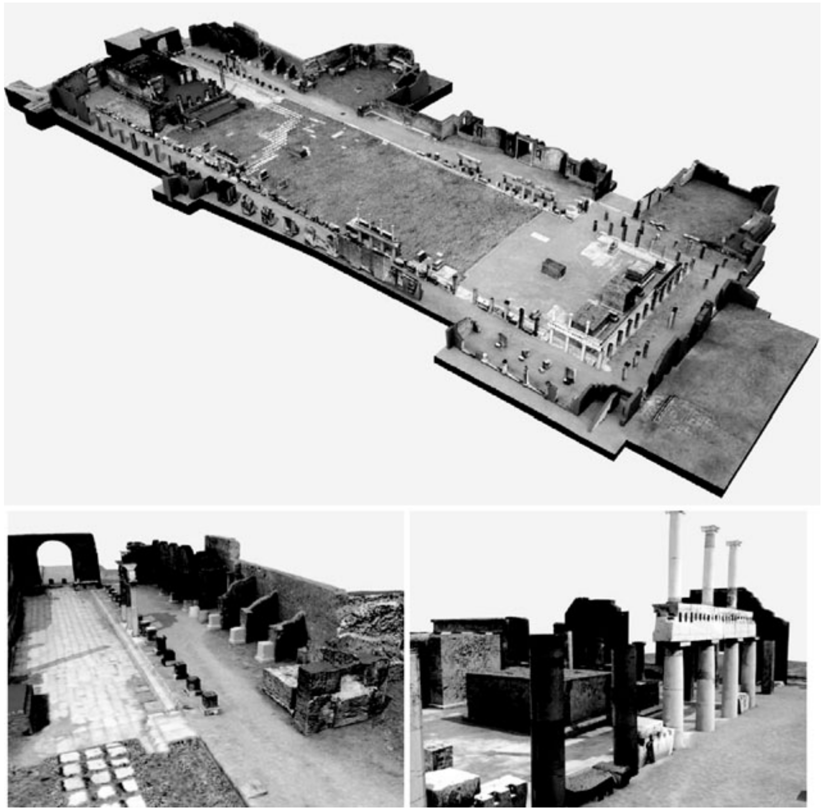
use several different Levels Of Detail (LODs), simplifying the mesh off-line at different levels and generating a single multi-resolution file including all the LODs, similarly to what happen in 2D with pyramidal images.

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 Reality Server). These systems are mainly developed for visualizing CAD models represented by a set of mathematical surfaces such as NURBS or B-Splines, tessellated at the visualization stage at optimized level (the lowest possible number of polygons for the best visual effect), and finely enriched in real-time with raytracing features such as mapping of textures, bump, transparencies, reflections, etc., allowing therefore 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 kind of information (text info, images, other 3D models), useful in the some specific applications. The main disadvantage is that their architecture is not oriented to virtually unlimited LODs and the model is often just preloaded into the Computer RAM before navigation.

Therefore, despite the latter kind of systems seems less suitable for mesh models originated by acquired data and textures (reality-based 3D models), respect to regular CAD models with synthetic procedural textures, the realized large 3D model of the Pompeii Forum (ca 600K polygons) was force to fit the requirements of one of these commercial packages (RTT Deltagen), in order to evaluate their performances and to prepare an engineered ready-to-use version for virtual reality, suitable to a museum or a public institution (Figure 7). The model texture was simplified to 1/4 of the original in order to fill-up the on-board memory on the specific PC used (8 GB), including geometry and texture.

► Figure 7. The final 3D model of the entire Forum (150 × 80m) after the integration of all the different sources. The interactive visualization is performed with RTT Deltagen.



Real time rendering visits have been tested with a smooth navigation into the digital version of the Pompeii Forum, with a frame rate between 10 and 15 frames per second, in a virtual theater equipped with active stereoscopy.

7. CONCLUSIONS

In this contribution 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. Indeed the final and complete 3D model should be also 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 allowed to exploit the intrinsic advantages of each technique, 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 helped also in the generation of the level of details of the final 3D model of the large site. Indeed 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 detail of particular archaeological interest.

The entire 3D model, since it is geo-referenced, can be easily linked to existing archaeological databases, using the spatial coordinate as query. The database model relationship is planned to be implemented 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 for helping

a) the complex conservation activity of the Pompeii Superintendence,
b) the general archaeological study of the area and
c) the explanation of the Forum ruins to the common public.

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