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A MULTI-RESOLUTION METHODOLOGY FOR ARCHEOLOGICAL SURVEY: THE POMPEII FORUM

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ABSTRACT:
The article reports about a multi-resolution approach developed for the 3D modeling of the entire Roman Forum in Pompei, Italy. The archaeological area, approximately 150 x 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 potentialities of the actual 3D modeling techniques. Data's resolution spans from few decimeters down to few millimeters. The employed surveying methodologies have pros and cons which will be addressed and discussed. The preliminary results of the integration of the different 3D data in seamlessly textured 3D model, will be presented.

1. INTRODUCTION

The generation of reality-based 3D models of objects and sites is generally 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 (Blais, 2004) 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 used everywhere or at every time and affected by surface properties, active sensors have reached a maturity since some years and the range-based modeling pipeline (Bernardini and Rushmeier, 2002) is nowadays quite straightforward although problems generally arise in case of huge data sets.

On the other hand, image-based methods (Remondino and El-Hakim, 2006) 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. 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 (Guidi et al., 2003; Stumpfel et al., 2003; El-Hakim et al., 2004; Guarnieri et al., 2006). Motivated by the increasing requests and needs of digital documentation of archaeological sites at different scales and resolutions, 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 x 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 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. Indeed the integration of different methodologies is prompted by the increasing requirement for fast and cheap but precise and detailed digital documentation of archaeological sites.

2. THE POMPEII FORUM

2.1 Brief historical background

The Pompeii Forum was the main square of the ancient city. It was the centre of the political, commercial and religious life. Located in the middle of the so-called "Altstadt", the oldest part of the city placed in the South-Western quadrant of the plan (von Gerkan 1940; Eschebach 1970), it is also the key for the interpretation of the town-planning evolution from the VII century B.C. to the final destruction of Pompeii, due to the eruption of Vesuvius in 79 A.D. The interpretation of the various building phases and the examination of the complex

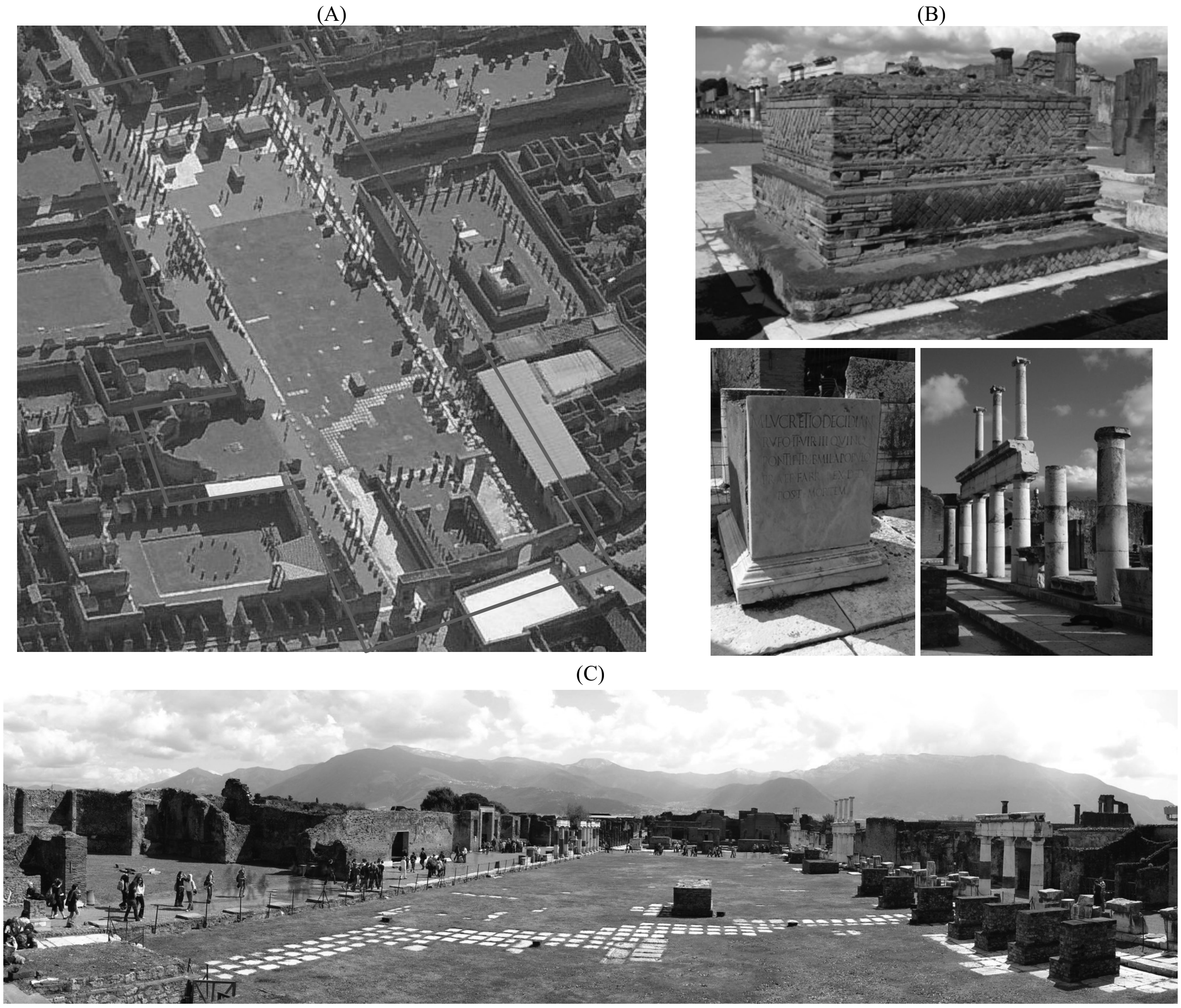


Figure 1: The forum of Pompeii: an oblique aerial view with highlighted the working area (A), some of the finds spread all over the archaeological area (B) and a panoramic view of the Forum, approximately 150 m long and 80 m wide (C).

relationships amongst the walls of the monuments that nowadays are visible in the Forum, are therefore important topics of the archaeological investigation on the urban history of Pompeii.

In its first configuration during the Samnitic period, the Forum had a trapezoidal shape and was oriented following the axis North-West/South-East. This orientation was maintained at least until the second half of the II century B.C., when the Forum was transformed in a rectangular square with a North/South axis, including the Capitolium (Temple of Zeus) in the shorter side, pointing at Mount Vesuvius. The Archaic Forum contained the main square that was paved with pressed volcanic ashes, the Temple of Apollo and some commercial buildings (tabernae) found under the East Porticus. During the late Samnitic period (II century B.C.), the Forum changed completely appearance: the square was paved, the Temple of Apollo was restored and the Macellum was built. Other important buildings were built up during the second half of the century: the Basilica, the Temple of Zeus 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 "Popidian Ensamble" (Dobbins and Ball, 2005). During the Early Imperial Age, in the Roman period, the Forum changed again its aspect and the square was paved with travertine stone, also used for rebuilding the Porch. New monuments were built along the East side of the Forum that was completely transformed with a new complex of buildings dedicated to the Imperial cult: 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. This chronology needs to be further refined on the basis of further archaeological data. Many researches are currently investigating the history of Pompeii Forum and, through this, the evolution of the entire city. The continuously evolving sensor technologies and data capture methodologies, the new techniques for data acquisition and rendering and the multi-resolution 3D representation can contribute with an important support to the refinement of information and to the growth of the archaeological research.

2.2 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, consist 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 also aimed at defining 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.

2.3 Related works

The UNESCO site of Pompeii has been widely surveyed and modeled in the last years. Reality-based reconstructions were already mentioned in the literature on single rooms, houses or monuments (Bitelli et al., 2001; Balzani et al., 2004a; Hori et al., 2007; Iorio et al., 2007). The largest survey was conducted by Balzani et al. (2004b) 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 architecture and decoration 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 (Dobbins, Ball, 2005).

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 (Weichardt, C., 1898) and have been further developed in recent years with Augmented and Virtual Reality technologies using handmade CAD models (Forte et al., 2001; Papagiannakis et al., 2005) or semi-automatically with procedural models (Mueller et al., 2006).

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 between accuracy of geometrical and iconographic representation, acquisition and processing time and size of the integrated model, in order to give to the Superintendence of Pompeii an instrument for controlling the complex conservation of the site and to 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 (figure 2) 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 (Hall, 1990), but with the end of that decade NRC Canada developed a Data Collection and Registration (DCR) system for integrating a 3D sensor with a set of 2D sensors for registration and texture mapping (El Hakim et al., 1998). Guidi et al. (2002) generated high resolution 3D models of roman mosaic fragments with a pattern projection range camera, oriented them with photogrammetry and integrated these data with TOF laser scanner. In order to give guidelines for the proper application of integrated survey technologies Böehler and Marbs (2004) made an exhaustive comparison between active and passive technologies both in the architectural and archaeological field.
Gruen et al. (2006) 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. Bonora et al. (2006) fused multi-resolution range data to model the Rucellai chapel in Florence. El-Hakim et al. (2008) integrated drawings, images, range data and GPS measures for the detailed modeling of castles and their surrounding landscapes.

4. 3D MODELING OF THE FORUM

As demonstrated in the aforementioned literature, the main purpose for adopting an integrated methodology is 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 we employed (Table 1):

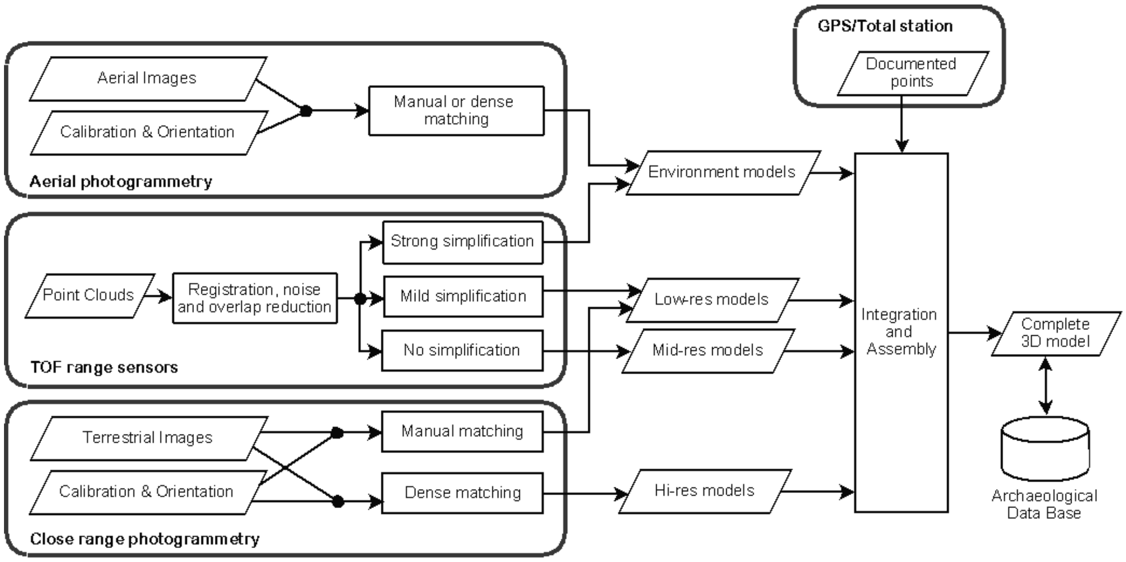


Figure 2: Integration of multi-resolution data for 3D modeling the Pompeii Forum

	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.

1. classical aerial images acquired for a typical mapping project;
2. oblique aerial views for texturing purposes;
3. range-data acquired from the ground with a ToF sensor;
4. terrestrial images to fill gaps, document small finds in higher resolution by means of dense image matching and 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 the texture. The use of oblique images (coming from Pictometry technology) was dictated by the fact that the available vertical 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 DSM generation, the ETH multi-photo matcher SAT-PP was employed (Zhang, 2005; Remondino et al., 2008). The matcher derived a dense point cloud of ca 18 millions points (the area is approximately 1 x 0.8 km).

The range data (ca 1.2 billions points) were processed inside Cyclone and Polyworks. 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 DTM, while 64 million points were needed for 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).

The terrestrial images (ca 3200) were employed to model all the mural structures, the 377 finds and to derive detailed geometric models of some ornaments by means of dense image matching. 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 was used (Zhang, 2005; Remondino et al., 2008).

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, thickened with a dedicated topographic campaign, was used.

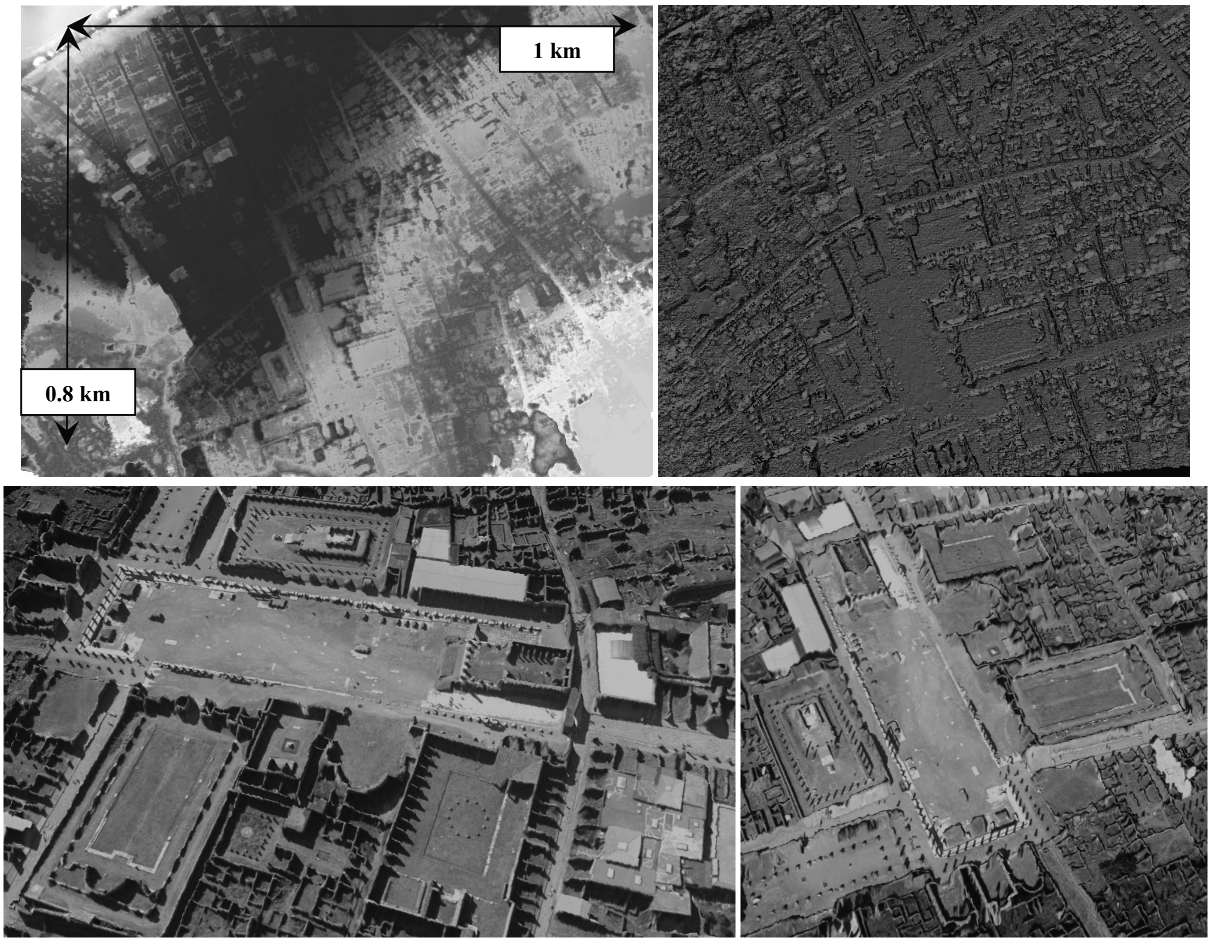


Figure 3: The DSM (18 Mil points) of the archaeological area generated from three aerial images with a multi-photo image matching method, shown in colour-code and shaded mode (above). Two views of the surface model, interpolated at 25 cm and textured with the generated orthophoto (below).

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 scans 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 residual error given at the end of the processing was around 50 cm. The resulting cloud of points (figure 4) was afterwards employed to align each single photogrammetric model and, thanks to redundancy, for checking possible dimensional errors.

For some archeologically interesting large structures, the range data were used also for generating high resolution mesh models such as the ones shown in figure 5 and 6.

5. RESULTS

The aerial images provided a dense DSM 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 (figure 3). This constitutes the first low-resolution level of detail of the entire 3D model of the Forum. Despite the fact that the 25 cm DSM smoothed slightly out the small features of the forum (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 mesh modeled starting from the laser scanner cloud of points, and textured with the acquired digital images. Some preliminary results are reported in figure 5.

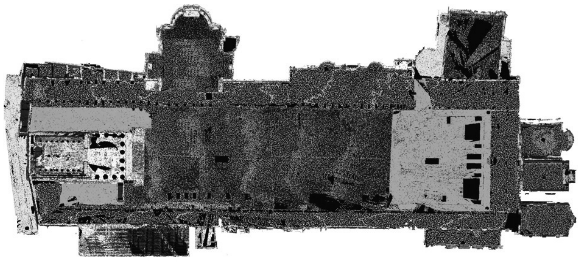
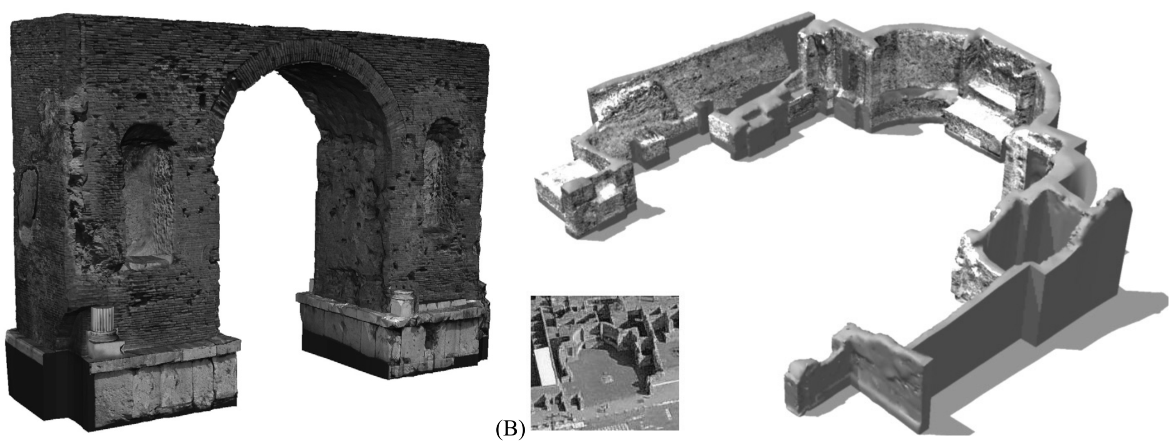


Figure 4: The range data seen from above classified in layers for faster handling and manipulation.

Independently from the possibility of generating different LODs, a special care was given to model optimization. Indeed the models generated from laser scanning were initially extremely detailed due to the high density of geometrical data collected from the scanner, but, in order to optimize the following visualization step, the models were then selectively simplified leaving a high geometrical resolution only on the areas indicated by the archaeological team involved in the project.

The level of texture mapping resolution was also considered independently by the geometric resolution for maximizing the level of information associated with any specific artifact. In this way we obtained low geometric resolution and high texture mapping resolution 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. The photogrammetric processing of all the 3200 terrestrial images produced 3D models of simple structures (arches, walls, columns) or larger complexes (e.g. temples) (figure 6).

Detailed ornaments, modeled in high resolution with image matching (figure 7), were afterwards integrated with the other low resolution data.



(A) (B)

Figure 5: 3D model of the Nero Arch (10m x 2.5 m x 7.5m) produced from the acquired range data and textured with digital images for photo-realistic visualization (A). Photo-realistic range-based 3D model of the Lari's temple (27m x 27m x 6m). In the left-lower corner an image of the temple from an oblique aerial view (B).

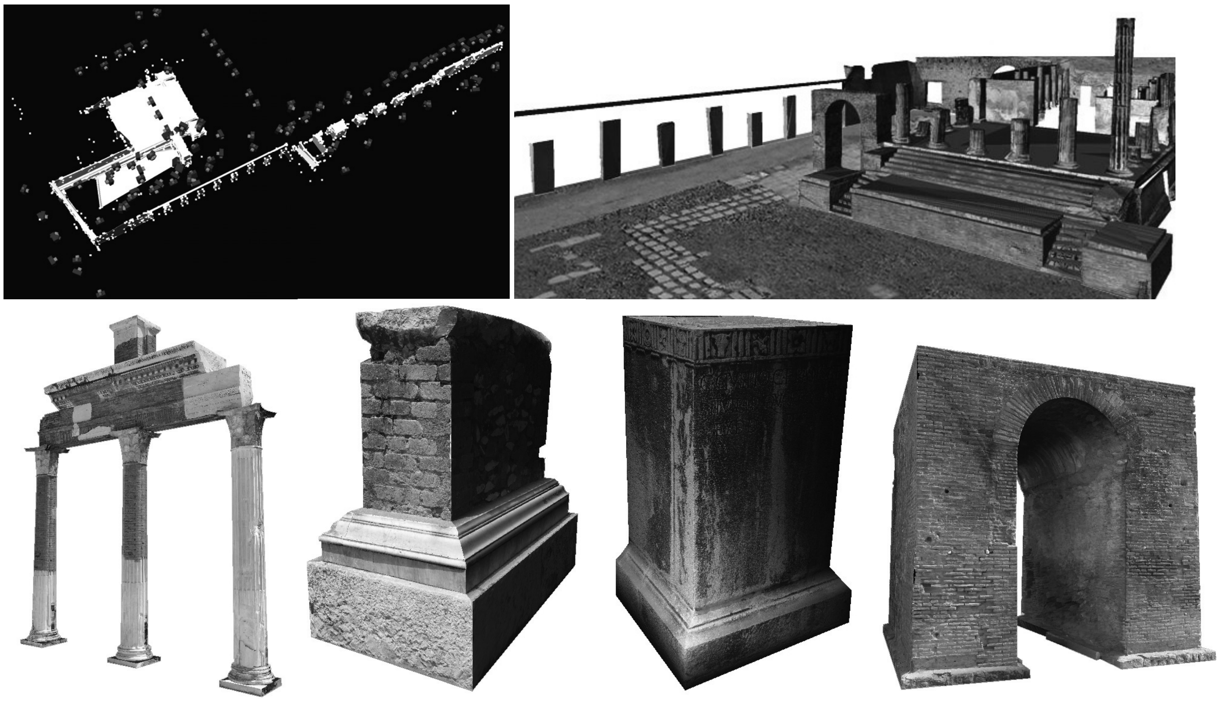


Figure 6: An example of the terrestrial photogrammetric block for the modeling of the mural large structures (Zeus Temple, above). Photogrammetric 3D models of finds, columns and arches.

6. CONSIDERATIONS AND CONCLUSION

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. The integration of multiple modeling methodologies allowed to exploit the intrinsic advantages of each approach 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. Furthermore, in the visualization of the large and complex model, low resolution data in one level are overridden and replaced by higher resolution meshes of the successive levels of resolution.

The entire 3D model, since it is geo-referenced, can be easily linked to existing archaeological databases, using the spatial coordinate as query. The data-base model relationship is planned to be implemented in both ways: from the geometrical model to the connected data, for explaining historical and conservation details of a specific artifact in the forum, and from a specific document or philological detail to the corresponding location in the 3D space. This tool is intended as a instrument for helping: a) the complex conservation activity of the Pompeii Superintendence; b) the general archaeological study of the area; c) the explanation of the forum ruins to the common public.

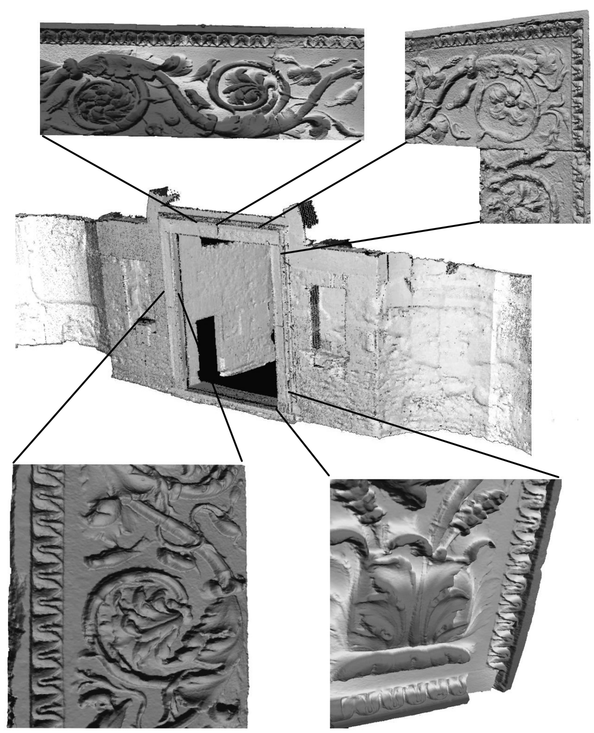


Figure 7: The ornament around the Eumachia door, modeled in high-resolution with a dense image matching and shown in colour-code or shaded mode.

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