

Virtualizing Ancient Rome: 3D acquisition and modeling of a large plaster-of-Paris model of imperial Rome

Gabriele Guidi^{1*}, Bernard Frischer², Monica De Simone², Andrea Cioci³, Alessandro Spinetti³, Luca Carosso³, Laura Loredana Micoli¹, Michele Russo¹, Tommaso Grasso⁴

¹Reverse Modeling and Virtual Prototyping labs, Dept. INDACO Politecnico di Milano, Italy

²Institute for Advanced Technology in the Humanities (IATH) – University of Virginia, USA

³Lab. Technology for Cultural Heritage, Dept. DET, University of Florence, Italy

⁴System Measurements Services (SMS) – Sutri (VT), Italy

ABSTRACT

Computer modeling through digital range images has been used for many applications, including 3D modeling of objects belonging to our cultural heritage. The scales involved range from small objects (e.g. pottery), to middle-sized works of art (statues, architectural decorations), up to very large structures (architectural and archaeological monuments). For any of these applications, suitable sensors and methodologies have been explored by different authors. The object to be modeled within this project is the “Plastico di Roma antica,” a large plaster-of-Paris model of imperial Rome (16x17 meters) created in the last century. Its overall size therefore demands an acquisition approach typical of large structures, but it also is characterized extremely tiny details typical of small objects (houses are a few centimeters high; their doors, windows, etc. are smaller than 1 centimeter). This paper gives an account of the procedures followed for solving this “contradiction” and describes how a huge 3D model was acquired and generated by using a special metrology Laser Radar. The procedures for reorienting in a single reference system the huge point clouds obtained after each acquisition phase, thanks to the measurement of fixed redundant references, are described. The data set was split in smaller sub-areas 2 x 2 meters each for purposes of mesh editing. This subdivision was necessary owing to the huge number of points in each individual scan (50-60 millions). The final merge of the edited parts made it possible to create a single mesh. All these processes were made with software specifically designed for this project since no commercial package could be found that was suitable for managing such a large number of points. Preliminary models are presented. Finally, the significance of the project is discussed in terms of the overall project known as “Rome Reborn,” of which the present acquisition is an important component.

Keywords: Laser Radar, digitalization of physical models, 3D laser scan, Range map alignment, Meshing, Accuracy, Precision, Virtual Archaeology, Rome Reborn

1. INTRODUCTION

The project discussed in this paper forms an important part of the Rome Reborn Project, an international effort to create a real-time digital model of ancient Rome. The spatial limits of the Rome Reborn model will be the area enclosed by the late-antique Aurelian Wall; its temporal limits will be the Iron Age (10th century B.C.), when the city began to be settled, and the Gothic Wars (6th century A.D.), when the city suffered severe physical damage and significant depopulation. For a variety of practical reasons, work on the model commenced in 1997 with modeling of the late-antique phase (ca. 400 A.D.), which represents the climax of the development of the ancient city in terms of its urban fabric and population. The approach to modeling has been to work out from the city center in the Roman Forum, a multi-purpose space dedicated to political, economic, religious, and entertainment activities.

This phase of the city’s urban history is well documented and studied. There is even a highly-regarded plaster-of-Paris model - the so-called “Plastico di Roma antica,” housed in the Museum of Roman Civilization (Rome/EUR) - that, with the permission of the Museum (which was graciously given), could be used as the basis for the new digital model. The

* g.guidi@ieee.org; phone +39 02-2399 7183; fax +39 02-2399 7809

model, created at a scale of 1:250, represents a three-decade collaboration of model-makers and topographers in Rome. It was completed in the 1970s and has not been changed since.

For the Rome Reborn Project the advantages of using the *Plastico* are that it could: (1) provide an almost instant computer model of the project's first, late-antique phase; (2) repurpose the *Plastico* and keep it constantly updated and therefore useful to students and scholars in the twenty-first century; and (3) offer a total urban context for the new digital models of individual sites and monuments created by the Rome Reborn Project. These new "born-digital" models - such as the Roman Forum, Colosseum, Circus Maximus, and other key public buildings and monuments - were worth creating despite the availability of the digital *Plastico* because they could be made at a scale of 1:1, could be textured photorealistically, could reflect discoveries made since the 1970s, and could (when archaeological data sufficed) include the interior spaces as well as the exteriors. As a physical model created at a small scale and intended to be viewed from a high balcony, these were features that the *Plastico di Roma antica* could not offer and, indeed, did not need to offer. The present project thus entailed creating a hybrid model of late-antique Rome that would be based on the digitized *Plastico* and the new "born-digital" models of specific sites and monuments in the historic city center.

The purpose of this paper is to describe the procedures for acquiring and generating a huge 3D model that presents several difficulties.

In general three-dimensional acquisition techniques are somewhat focused on a particular range of volumes. Most 3D scanners based on the triangulation principle are suitable for small objects and may generally work at distances ranging from one-half meter to few meters. Their measurement accuracy over the whole range image stays below one-tenth of one millimeter, and the uncertainty lies between 50 and 200 microns. On the other hand, laser scanners based on Time of Flight (TOF), used for architectural elements and large structures (bridges, dams, etc.), allow much larger distances to be covered (up to few kilometers). Although accuracy remains high, the major drawback to TOF scanners is the loss of precision since the measurement uncertainty goes down to several millimeters. This absolute value is not a problem for measurements involving large structures because the relative precision remains high, but if the structure is large and if small features must be captured, this kind of system is not usable.

The "*Plastico di Roma antica*" lies unfortunately in the latter category, being a wide object (16 x 17.4 meters) with houses and temples only a few centimeters tall. Therefore in this case, the use of conventional techniques was not feasible. The solution was found in a system created for advanced metrology applications. At first glance, the approach taken resembles TOF laser scanning, but its main improvement is in the procedure employed for detecting the laser time-of-flight. Instead of conventional pulsed techniques, the method used for the *Plastico* uses a principle well known in CW radars, based on transmission and reception of a coherent frequency modulated wave. For this reason the system is indicated as Laser Radar (LR). The actual 3D sensor (LR200) used in this project is manufactured by Leica Geosystems AG, Switzerland in cooperation with Metric Vision Inc., VA, U.S.A. The use of such an advanced laser processing method, together with the capability of precisely re-focusing the laser beam in order to minimize its spot size, allows resolutions to be reached below 1 mm. Uncertainties of the same order can be obtained as those offered by triangulation 3D scanners (from 0.1 to 0.3 mm, depending on distance), with the possibility of covering distances up to 24 meters. In order to minimize the acquisition time, a specific piece of software was designed for managing the instrument at low level. It is capable of focusing the laser at the beginning of each scan-line and maintains a constant surface-to-laser distance during the acquisition.

Another difficulty was data processing. Two separate sessions were planned: the first massive scan for covering most of the surface was performed from three acquisition points forming an equilateral triangle. The second campaign occurred twenty days later after the study of a "pre-model" generated after the first session. The huge point clouds obtained after each phase were reoriented into a single reference system thanks to the measurement of fixed redundant references, and each was divided into smaller sub-areas, 2 x 2 m each. This subdivision was necessary owing to the huge number of points in each individual scan (50-60 million). All these processes were made with software specifically designed for this project since no commercial package suitable for managing such a large number of points could be found.

2. HARDWARE EQUIPMENT

Working with 3D scanning in a museum is often more complicated than doing the same task in a laboratory: for example, it is likely that no value samples can be moved without risk to a significant example of the world's Cultural Heritage. Additional constraints complicate what in normal conditions could have been done much more easily. Acquiring of the plaster-of-Paris model of ancient Rome was already a job complicated enough, but the addition of further constraints made it almost impossible. For example, the administration of the museum understandably prohibited placement of any measurement machine directly over the "*Plastico*" in order to eliminate the possibility that the

machine, or one of its parts or accessories, might accidentally fall onto the monument and damage it. The initial idea of using a common laser blade scanning device mounted on a rail for covering the whole surface in parts was therefore not applicable, and the sensor was chosen in order to satisfy this primary requirement. The solution was found in a very high-quality (and high-cost) Laser Radar. It is capable of giving the same performance as a relatively low-cost and short-range laser blade triangulation scanner. But the Laser Radar utilized gives reliable results up to 24 meters from the measured surface. Since the only drawback of this extremely powerful system is its slow speed, a simpler triangulation-based laser sensor was also used for capturing the areas close to the border of the “Plastico.”

2.1 Laser Radar

The most commonly used systems for creating a digitized 3D image of an object within a limited range (about one meter) are based on optical triangulation. A laser forms a light stripe scanning the object by means of a rotating mirror or a cylindrical lens, and a CCD camera collects the image of the illuminated area. The range information is retrieved on the basis of the system geometry. An alternative triangulation technique is based on the projection of patterns of structured light, i.e. a light pattern coded as spots or stripes. Both techniques generate a cloud of points that, after suitable processing, allows the creation of a three-dimensional model of the object. The systems based on optical triangulation are the most accurate, allowing measurement uncertainty lower than one tenth of a millimeter. As uncertainty depends directly on the square of the distance between the camera and the object, a high precision is achieved by appropriately limiting this distance and thus the illuminated area. The acquisition of relatively large objects, such as a statue of human size, requires therefore a large number of partial views, or “range maps,” taken all around the object. These are then integrated in order to represent the whole surface.

3D triangulation-based techniques have been directed toward digital modeling of relatively small objects. The acquisition of works of architectural (e.g. a cathedral, a tower, a palace, etc.) is practically impossible using high resolution triangulation-based scanners, because of the great dimensions involved and of the distance of the scanner to object. Architectural monuments are usually acquired by laser scanners based on Time of Flight (TOF) measurement of light pulses, since they operate from distances from ten meters to thousands of meters, and they can acquire millions of points in a relatively short time. Both features of TOF measurement make it practical to digitize large surfaces. Laser radars work by pulsing a high power laser source and gating a counter that measures the transit time to and from the target. Although this is a simple concept, its demands on support electronics are severe, since light covers about 30 cm every nanosecond. Measurement of a few meters with a sub-millimeter resolution would require temporal resolution in the detection and processing of the backscattered signal better than 0.1 picoseconds. Commercial TOF systems have been available since the early 1990s and offer range measuring uncertainty from 0.5 cm to 2.0 cm. Scanning of the laser impinging over the inspected surface is basically implemented by a precise angular positioning device moved by a step-motor. By measuring the TOF needed by a laser pulse for going from the range camera to the surface and back again to the instrument, an evaluation of the camera-to-surface distance is performed. These data, together with the angles determining the laser orientation, permit evaluation of the three spatial coordinates of any scanned point. In order for TOF laser scanners to scan the whole surface of the structure to be digitized, a number of acquisitions taken from different points of view are needed, and their alignments require sophisticated processing techniques.

The new 3D sensor used in this paper for Cultural Heritage modeling makes it possible to overcome all the above-mentioned limitations. It is a laser radar referred to as model LR200, which is manufactured by Metric Vision Inc., VA, U.S.A. and is distributed by Leica Geosystems AG, Switzerland.

The equipment is a TOF range camera, operating on a principle completely different from pulse propagation. Originally developed for microwave radars, the principle is known as *Coherent Frequency Modulated Continuous-wave Radar* (FM CW). The heart of the laser radar is a broadband frequency modulated infrared laser (100GHz modulation), which provides a robust and eye-safe signal. The upsweep and down-sweep comparison provide simultaneous range and velocity data for measurements. The single wide-aperture optical path maximizes signal strength and stability. Extensive signal processing extracts interference frequencies which are directly proportional to distance.

A critical point is the focusing volume depth which in any triangulation-based system ranges from 10-20 cm for fringe projection systems based on white incoherent light and to about one meter for laser blade systems. In general TOF based system do not take into account the laser spot size variations at distances very different from the focusing range because for uses on buildings and large structures it is supposed that ultra-high resolutions are unnecessary. Therefore in a standard TOF system the correlation between two adjacent measurements tend to increase when the related laser spots are partially superimposed, reducing the maximum resolution attainable from the system (generally larger than 10 mm). In contrast, the Leica Laser Radar is built for applications such as industrial metrology where the possible resolution can

be much higher (e.g., far below 1mm), so that the laser spot size is taken under control through a dynamic focusing optical system. The drawback of this sophisticated focusing is represented by the time needed for getting each measured point. In the most precise modality, indicated as “advanced metrology”, only 2 points per second are measured. A peculiar aspect of this laser scanner is the method it uses for re-orienting the data into the same reference system during the acquisition stage, thus eliminating the need of range map alignment, which is typically required in any modeling project. A redundant set of references, represented by steel spherical targets, actually implemented with low cost “tooling balls,” are placed on the scene and fixed in place with a custom metallic ring that holds the ball in a specific position. The ring can be glued to some convenient spots of the scene without touching any delicate or old part of the work of art to be digitized. At the first camera location the position of each tooling ball is determined by measuring the direction of maximum laser reflectivity on the ball. Adding the distance information and the “a priori” knowledge of the ball diameter, a very accurate estimate of the 3D coordinates of each reference target is obtained. For the following camera locations the same targets are measured again to determine the roto-translation transformation with respect to the first one. Once the new camera location is set up, each point is measured and automatically reoriented in the main reference system through a procedure developed for previous projects^{1,2}, implementing the “Unit Quaternions” method³. This eliminated the need of a time-consuming iterative reorientation and of the related data redundancy (30-40% of range maps superposition would be usually needed). This feature significantly speeded up the 3D model generation.

2.2 Laser blade triangulation scanner

A VIVID 910 (produced by Konica Minolta, Japan), mounted on a tripod as shown in figure 1b, was the portable laser system used for integrating part of the 3D acquisition of the model of ancient Rome. It has three interchangeable lenses with different focal lengths (tele, middle, wide). The maximum measuring distance is about 2 m with the middle lens. An approximate resolution of 0.5 mm was obtained at that distance. The corresponding measurement uncertainty, evaluated by acquiring a planar reference, was estimated on the order of 0.3 mm. This setting permitted the acquisition of range maps characterized by a suitable resolution and uncertainty with respect to the other data acquired with the laser radar. The two sets of data could be therefore conveniently merged.



Figure 1: Equipment employed for the model of ancient Rome (“Plastico di Roma antica”): a) Laser Radar LR2000 by Leica MetricVision for long range; b) Vivid 910 by Konica-Minolta, a triangulation-based laser scanner, for close-ups

2.3 Software packages

The Laser Radar LR200 gives a simple unstructured cloud of points in the form of an ASCII file containing a long list of triplets, representing the (x,y,z) coordinates of each measured point. In order to triangulate them the software package RapidForm was used (INUS Technology Inc., Korea). It has an effective tool for creating a mesh from an unstructured cloud of points generated with a spherical symmetry, such as those produced by the LR200 scanner.

For the other steps involving mesh editing, both the module IMEdit of the Polyworks modeler (Innovmetric, Quebec, Canada) and the editing module of the RapidForm package were used, depending on the kind of mesh correction to be applied.

All the additional software was written at the Technology for Cultural Heritage Lab (University of Florence), utilizing two platforms: Matlab (The MathWorks, Inc., USA) and Visual C++ (Microsoft Corp. USA).

3. PLANNING

3.1 Preliminary study

The “Plastico” has an irregular shape and is installed in a special area, 16 x 17.4 meters, surmounted by a balcony, the floor of which is elevated about 2.7 meters respect to the level of the city model. The internal perimeter of the balcony is covered by a balustrade 1.2 m high.

In order to respect the limitations imposed by the museum, the equipment had to be raised higher than the balustrade by mounting the scanning equipment over a stand 1 meter high. The set-up is illustrated in figure 2.

Since the laser beam turns out to be very inclined with respect to the main plane of the “Plastico”, the sensor-to-surface distance covered a wide range, going from 7 to 24 meters.

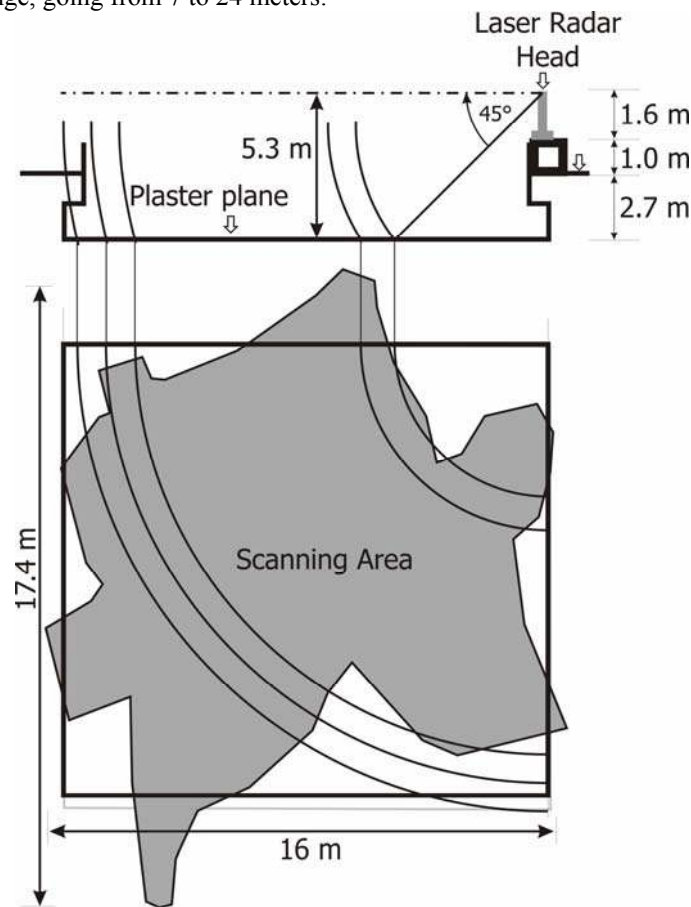


Figure 2: Schematic diagram of the scanning area in vertical (top) and horizontal (bottom) section. The laser radar was set up for covering circular paths in order to limit the need for re-focusing when the scan-line was changed. The thick square represents the balcony from which the museum visitors can view the plaster-of-Paris model of ancient Rome

The critical point of measurements having large depth variations is the Depth of Field (DOF) of the measurement device. DOF is influenced by the laser beam divergence that makes the spot size too large out of the focal zone, making

a suitable resolution impossible to obtain. The LR200 solves this problem by dynamically re-focusing the laser beam in order to minimize the spot size over the measured surface.

This re-focusing is implemented in the measurement modalities called “Metrology” and “Advanced Metrology”. With these approaches the operator simply has to define a perimeter over the surface to be acquired. The perimeter can include points at ranges very different each other thanks to the re-focusing of the laser beam for each new position. The acquisition may therefore progress without any human control, even if it lasts for a long time (e.g., overnight). The “price” for such a flexibility is a slow acquisition process, capable of giving, at best, only 10 points/second. With this digitizing speed, the time needed for a single scan of the “Plastico” area would be on the order of several months (nights included). This was obviously not acceptable because of the costs involved and since it would have entailed reducing the access of museum visitors to the monument.

In contrast, with an alternative measurement approach, known as “Pseudo Vision”, the LR200 is capable of acquiring hundreds of points per second. Even if not so fast, this operating mode could be fast enough to complete the job in a reasonable time and was therefore explored as a good candidate for measuring the model of Ancient Rome. In this work modality, each measurement can be additionally averaged over several repeated measurements to lower the electronic noise responsible for generating measurement uncertainty. The number of measurement to be averaged is indicated by the instrument as “stacking level”. By increasing the number of averaged points the time needed obviously increases. Preliminarily to the proper set-up definition the “speed vs. stacking level” relationship was experimentally evaluated by measuring the certified planar surface of a metrology test object (Johnson block).

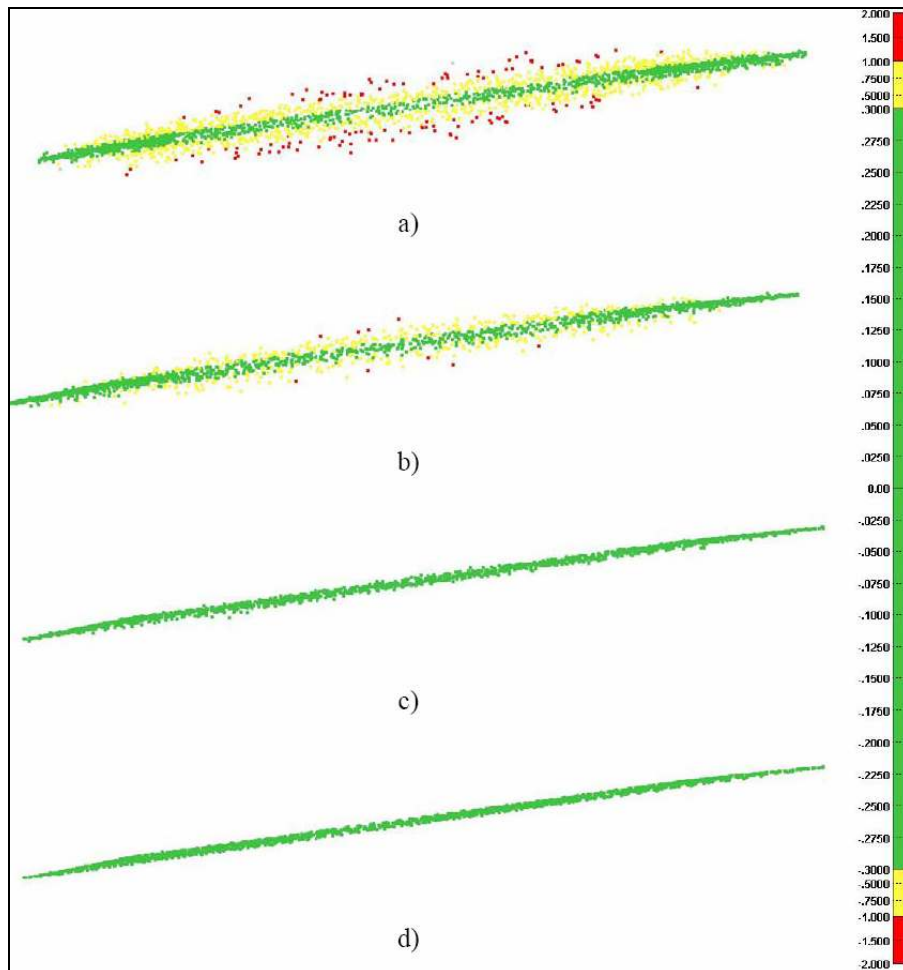


Figure 3: Effects of averaging on laser radar measurements performed in “Pseudo-Vision” mode, over the planar surface of a Johnson block: a) stacking=1 (no averaging); b) stacking=2; c) stacking=5; stacking=10. The scale on the right is graduated in millimetres

The point clouds measured on such an area are reported in figure 3 in vertical section, in order to make clear the level of randomization associated with each measured point. The measurement uncertainty, calculated on the data set as the root mean squared distance from the plane best fitting the noisy 3D points, gave the following results:

| Stacking | σ (μm) | Speed (pt/s) |
|----------|----------------------------|--------------|
| 1 | 315 | 231 |
| 2 | 218 | 129 |
| 5 | 49 | 52 |
| 10 | 19 | 37 |

A last parameter must also be considered: the “decimation factor.” It takes into account the fact that the measurement process is longer for far points than for close ones. The measurements reported above were acquired with the slower set-up (measurements at long range).

The superior performance with respect to the “metrology” modes is obtained basically by inhibiting the real-time laser refocusing so that the process works well only on surfaces where variations in range are limited. Unfortunately this condition does not hold for the Ancient Rome model, hence a certain degree of customization of the equipment was needed.

3.2 Equipment customization

The main idea for enhancing system performance was to permit laser refocusing only at the beginning of each scan-line, maintaining the sensor-to-surface constant for the following scan. This approach was calculated to give a scanning performance comparable to that of the “metrology” mode, allowing in the mean time overnight measurement to be performed, indispensable to completing a full scan of the monument in a reasonable period of time. In such conditions the predicted scan time was 3-4 days for each point of view, and this was considered acceptable by the museum.

Unfortunately the system did not have (at least in the system release 3.21, used for this project), the functionality for performing spherical scanning, hence a special piece of software, capable of driving the beam along circular trajectories, was specifically developed. It relies on a software library used by the system manufacturers for developing their measurement software, and Metric Vision kindly provided the library so that we could solve our measurement problem. The software we developed was designed as a stand-alone program, capable of moving the beam along circular trajectories computed in advance, and of appending the coordinates associated with each scan line to an ASCII file. Such incremental saving of data was introduced in order to minimize any possible data loss in case of blackouts during the long scanning sessions. In this way, a data acquisition speed of 170 points/second was obtained, using “Pseudo-Vision” mode with stacking=2, and refocusing at the beginning of each scan-line.

3.3 Acquisition project

The scanner position was chosen on the basis of some geometrical considerations. Let r be the distance between the scanning head and the measured point over the plaster surface. The focused area is a spherical shell including the two spheres with radius $r-dr/2$ and $r+dr/2$, with dr on the order of 20 cm for the closer ranges, which represent the “thickness” of the shell. By positioning the instrument at a corner of the city model, as shown in the lower part of figure 2, the intersection between any spherical shell and the model’s main plane is a ring section covering a quarter of a circle, the size of which gets smaller as the scanner frames areas farther away (see, again, fig. 2).

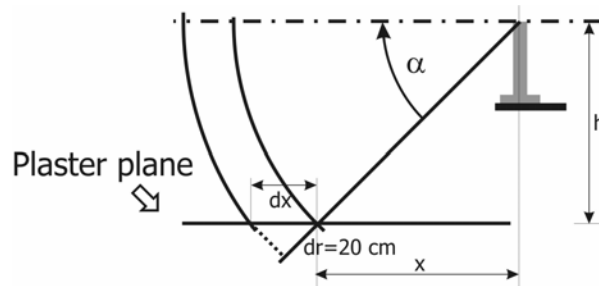


Figure 4: Detail of the focused area

With reference to figure 4, it is possible to see that the angle α , between the laser direction and the horizontal plane, is given by:

$$\alpha = \arctan\left(\frac{h}{x}\right)$$

Since the maximum horizontal angle allowed by the Laser Radar is $\alpha=45^\circ$, the “blind” area from each station will be a circular sector whose radius is equal to the height h . Therefore, depending on the shooting height, the “blind” area will vary consequently. With height equal to 5.3 m, the “blind” area with the instrument located in a corner is a quarter of a circle:

$$\text{BlindArea}(\text{mm}^2) = \frac{\pi \cdot 5300^2}{4} = 22\,000\,000$$

One must take into account the fact that the irregular shape of the city model, as shown in figure 2, covers only a fraction of the whole rectangular surface, corresponding approximately to 86%. The $16 \times 17.4 \text{ m}^2$ area will therefore not have to be entirely scanned.

Assuming the acquisition of one point each 2 mm, the total number of points to be acquired will be given by:

$$N_{\text{points}} = [\text{TotalArea}(\text{mm}^2) - \text{BlindArea}(\text{mm}^2)] * \text{PointsPerMillimeter}^2(\text{mm}^{-2}) * \text{coverage}(\%)$$

Given an area 270 m^2 wide, this gives approximately:

$$N_{\text{points}} = (270\,000\,000 \text{ mm}^2 - 22\,000\,000 \text{ mm}^2) * \left(\frac{1 \text{ point}}{2 \text{ mm}}\right)^2 * 0.87 = 54\,000\,000$$

The acquisition time predicted for each point of view is therefore:

$$t(\text{s}) = \frac{N_{\text{points}}}{170 \text{ pts/s}} + N_{\text{scan-line}} * t_{\text{initialization}}$$

where the focusing time term is added to the scanning time.

The number of scan-lines needed to cover the whole plaster area is given by:

$$N_{\text{scan-line}} = [\text{FarDistance}(\text{mm}) - \text{NearDistance}(\text{mm})] * \text{PointsPerMillimeter}(\text{mm}^{-1})$$

With the data of the problem, the maximum distance ranges from 20 to 24 meters. Using a value of 21.3m to simplify the numbers, we obtain

$$N_{\text{scan-line}} = [21300 - 5300] * 0.5 = 8000$$

Therefore, considering that each scan-line initialization requires about 3 seconds, a suitable prediction for the scanning time needed for a single view is:

$$t(\text{h}) = \frac{t(\text{s})}{3600} = \frac{\left[\frac{54 \cdot 10^6 \text{ points}}{170 \text{ pts/s}} + 8000 \cdot 3 \right]}{3600} = 95 \text{ hours}$$

Two additional hours were calculated for moving the Laser Radar from one position to a new one, giving a global time of 97 hours per scan (4 days).

4 PRIMARY DATA ACQUISITION

4.1 Point clouds pre-processing

Three scans were arranged for the first massive acquisition. They were taken from three points of view located approximately at the vertices of an equilateral triangle. In figure 5 the station positions and the related blind areas are shown.

According to the planning already described, the operations made for each new position were:

- measurement of a few fixed reference points from the new position, made for properly reorienting all the data sets into a single coordinate system;
- measurement of the border of the city model from the new position, in the local instrument coordinate system;
- evaluation of intersections between the border of the model and circular trajectories (scan-lines at fixed focusing) spaced 2 mm apart;
- loading of intersections in the custom scanning software, interpreted as beginning and ending trajectory points;
- scanning start.

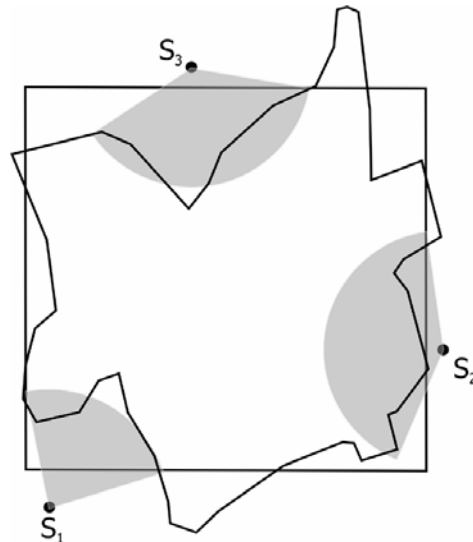


Figure 5: Positions of the first three scans. The blind areas are highlighted in gray

In the event, the time predicted agreed closely with the actual measurements, totalling, with small fluctuations, around four full days. To give an idea of the number of details to be captured a picture of the city model taken approximately from the S_2 position is shown in figure 6.

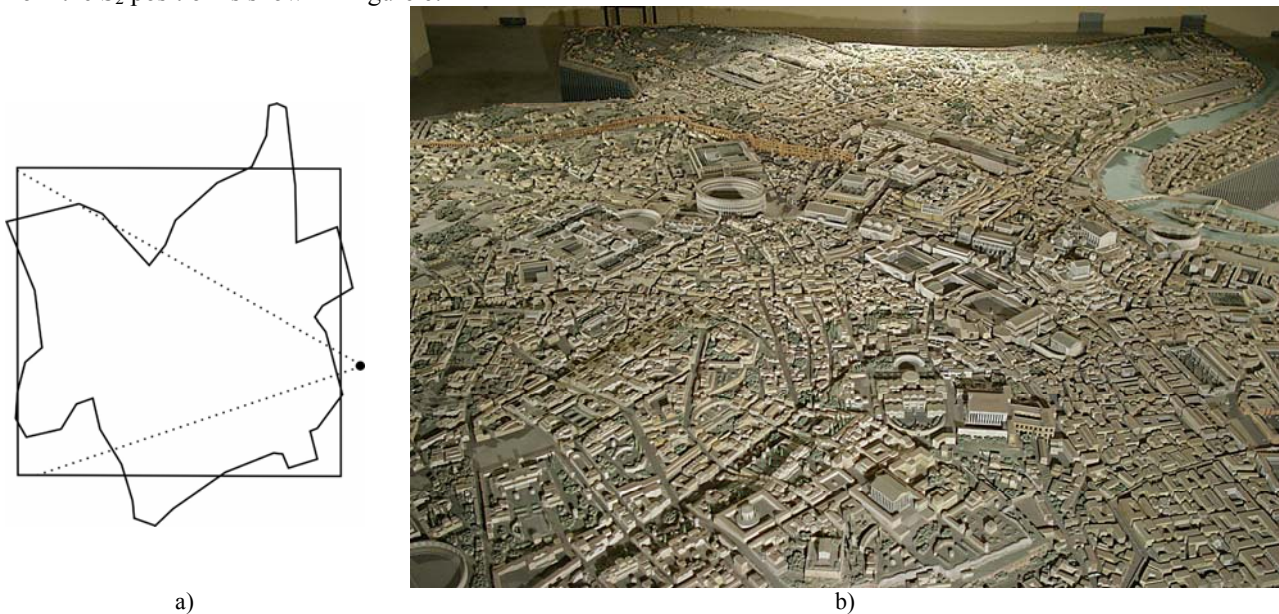


Figure 6: Portion of the city model seen by the laser radar from position S_2 : a) schematic orientation of the photo camera; b) picture taken from S_2

4.2 Point clouds subdivision

The amount of data originating from the first 3D scanning campaign was so heavy as to be not manageable with current 3D software. Therefore the entire city model was subdivided into several sub-areas, dimensionally compliant with the post processing packages used for the project.

An approximate estimate of the number of points, calculated in section 3.3, is that there were approximately 50 million points (MPts) per point of view. Considering that the object had been framed by three different points of views, a rough estimate of 150 MPts had to be treated at the end of the primary data acquisition.

In order to separate all the acquired data into sub-areas, a 3D grid was constructed, obtained with a set of planes orthogonal to the main plane of the city model, as shown in horizontal section in figure 6. The approximately square zone containing the city model has been divided into a 9 x 9 grid. Since the area is 16 x 17.4 m², we can consider 81 blocks, 2 m x 2 m each, covering a 18 m x 18 m area, large enough to cover all the irregular extensions of the city model.

| | | | | | | | | |
|----|----|----|----|----|----|----|----|----|
| I0 | I1 | I2 | I3 | I4 | I5 | I6 | I7 | I8 |
| H0 | H1 | H2 | H3 | H4 | H5 | H6 | H7 | H8 |
| G0 | G1 | G2 | G3 | G4 | G5 | G6 | G7 | G8 |
| F0 | F1 | F2 | F3 | F4 | F5 | F6 | F7 | F8 |
| E0 | E1 | E2 | E3 | E4 | E5 | E6 | E7 | E8 |
| D0 | D1 | D2 | D3 | D4 | D5 | D6 | D7 | D8 |
| C0 | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 |
| B0 | B1 | B2 | B3 | B4 | B5 | B6 | B7 | B8 |
| A0 | A1 | A2 | A3 | A4 | A5 | A6 | A7 | A8 |

Figure 7: Subdivision of the area of the city model into sub-areas for reaching a data set size compliant with current 3D software packages

Each block is made by $1000 \times 1000 = 1,000,000$ points per take, or 3 MPts once the acquisition was completed from the three points of view.

Since the city model does not cover the whole fractioned area, some blocks turn out to be empty or partially occupied by 3D data. In order to have the same subdivision for any of the three views, each cloud of points was properly processed. Firstly the cloud was oriented in the global coordinate system, defined as the one associated with the first scan (S_1). This point is necessary in order to define the same blocks for all the data sets. The cloud was then subdivided in blocks according to the subdivision defined by figure 7. At the end of this step the raw data had to be transformed in a piece of mesh, generating a set of triangles by properly connecting points close each other. This specific process, that is

generally performed with the Delaunay algorithm, can be much more efficient if the data set is in the original coordinate system, thanks to its spherical symmetry. For this reason the next step was to reorient each single block into its original coordinate system.

4.3 Point processing and mesh generation

Once the single point cloud associated with a block is extracted from the whole data pile, it is then cleaned in order to reduce the amount of data to the minimum necessary for meshing. Three steps were always performed:

- moderate filtering for noise reduction;
- cloud thinning, for reducing the number of points in the planar zones;
- regularization of the cloud of points for eliminating points closer to each other than 0.5 mm—the distance that typically creates topological anomalies at the meshing stage. These kinds of points were generated by the scanner corresponding to the beginning and end of any scan-line, owing to the fixed signal sampling corresponding to accelerations and decelerations of the deflection mirror.

The following phase was the mesh generation from the pre-processed points, for each of the blocks. This process, may be performed in different ways depending on the acquisition set-up.

In this case a specific module of the software package RapidForm was employed. It is delivered by the producers (INUS Technology Inc., Korea) as a separate dll that performs the 3D point cloud triangulation in spherical coordinates. This procedure is based on the Delaunay triangulation algorithm that typically projects the data set onto a plane for finding the most probable connections between close vertices and re-locates in space the connected vertices at the end creating a triangular mesh^{4,5,6}. Of course the system works well if the data set is 2.5D rather than fully 3D. Thus, properly orienting the projection plane may dramatically change the final results. Some systems leave to the user the responsibility of orienting the plane, while others allow the user to choose the 3D sensor optical axis as the normal to the most convenient projection plane. The spherical triangulation tool of RapidForm permits the automatic definition of the projection center as the center of the coordinate system, and, more importantly, projects the nodes onto a sphere rather than onto a plane. As a result, nice and uniform meshes are obtained from data sets created from sensors with spherical symmetry such as, for example, the LR200. Once the mesh is generated, it has to be relocated into the global coordinate system, using, again, the rototranslation matrix used at the beginning. While the first step makes use of a custom software capable of rotating 50 MPts clouds, in this case the module IMInspector of the Polyworks Modeller package was used, which is capable of performing mesh rototranslations according to a matrix given in homogeneous coordinates (4 x 4). When the three meshes produced by the different points of view are generated and rototranslated into the same coordinate system, these are merged through the editing tool of RapidForm.

5 SUPPLEMENTARY DATA ACQUISITION

5.1 Definition of optimal points of view for data integration

In order to optimize the surface coverage of integrative scans, a Matlab procedure for evaluating a set of candidate 3D sensor positions was developed. It relies on the possibility, offered by the Polyworks-IMInspector module, to move and orient the viewport framing the model, according to a specific rototranslation matrix. This script, developed by Matlab, generated a set of matrices defining possible scanner positions along the extension of the museum balcony, making it possible to view the global mesh as seen from the scanner head. The visual evaluation of the mesh in the different cases permitted calculation of the best positions for closing as many gaps in the mesh as possible. It was evident that for examining the city model on a PC, it would be indispensable to reduce the model through a very strong polygonal simplification, involving the loss of several details, but, on the other hand, making clear what was missing from the mesh of the city model.

5.2 Data acquisition

This stage was intended to actually measure the missing sections according to the positions determined at the previous step. In contrast with the first massive acquisition, this campaign was marked by a large number of small views. As shown in figure 8, ten different acquisition points were used. In the figure, S_1 to S_3 indicate the first massive scans, while S_4 to S_{10} are the seven integrative ones. In position S_4 the scanner was still positioned on the balcony (the black dot on the right side of figure 8a), the following locations were located on the lower floor where the city model is situated (white dots in figure 8a). In this way, all those surfaces could be captured which were in the “blind” zones in the scans from the balcony.

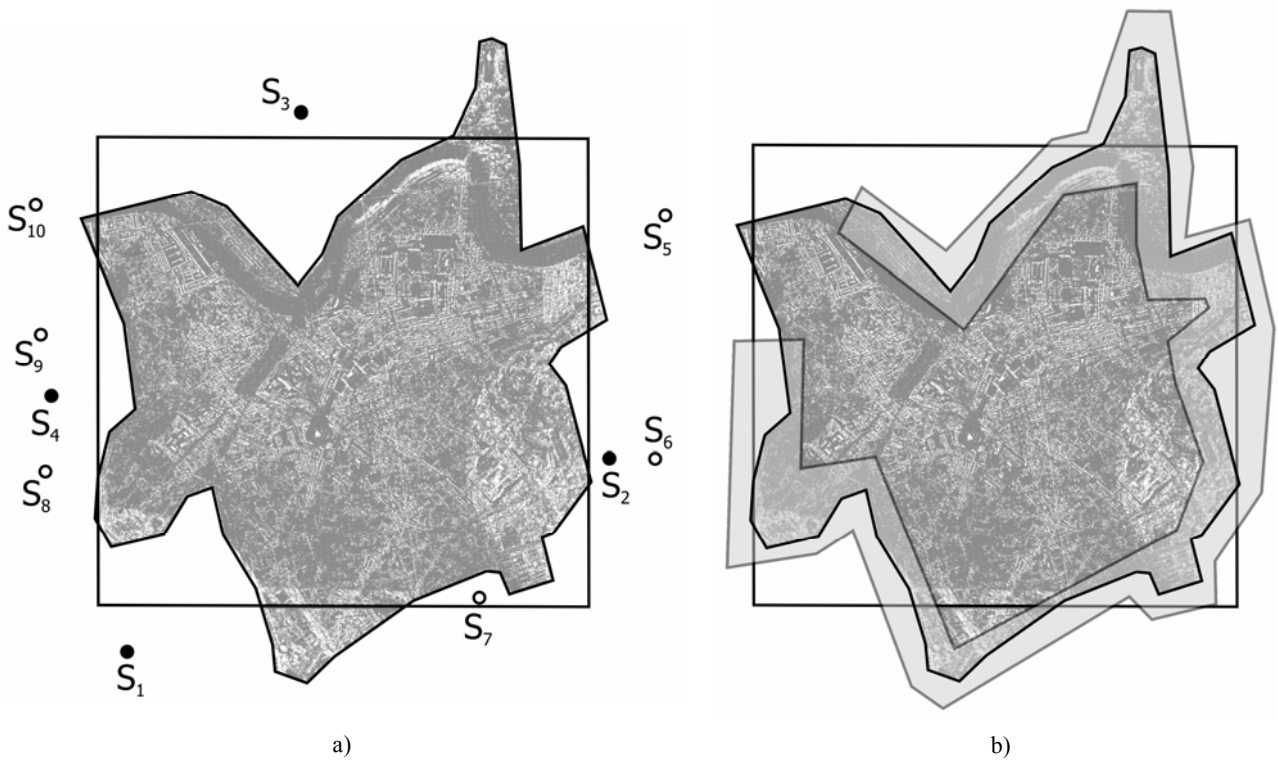


Figure 8: Data integrations generated with the two scanners used in the project: a) LR200 positions. The black dots represent acquisition points on the balcony level; the white dots indicate the digitizing points on the lower level; b) border area and city walls acquired with the Minolta Vivid 910 system.

The main problem for this instrument configuration is the angle between the laser beam and the city model. As a matter of fact, owing to the low height of the laser head, the beam direction is almost tangent to the main plane of the “Plastico.” For example, when the laser impinges on a building’s vertical wall, the points on that surface are in the focused range and are properly acquired. On the other hand, if the new distance is out of the focal zone, the points correspondingly acquired are not to be considered valid (see fig. 9).

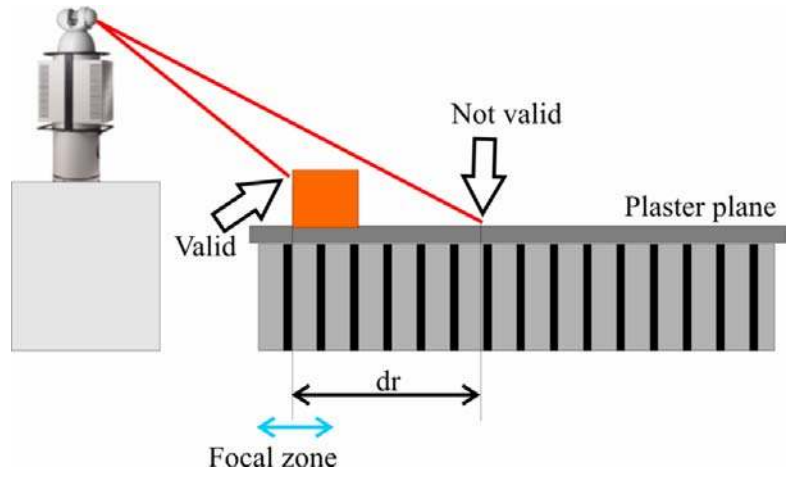


Figure 9: The points acquired when the laser impinges on a building’s vertical wall are properly acquired. If the new distance is out of the focal zone beyond the border of the wall, the points acquired are not to be considered valid and have to be deleted at the post-processing stage

For this reason the point clouds acquired at this step were characterized by a mix of properly measured points, characterized by a low level of noise, with a few extremely noisy measurements, superimposed on the “good” point cloud. A specific software was designed to confront the problem of separating the valid from the invalid clouds (see section 5.3). Since the laser radar has a minimal range of 2 m, the city model areas very close to the border (such as the city walls or the aqueducts) were acquired with two Minolta Vivid 910 scanners, as shown in figure 8b. In this way the integrative acquisition stage, intrinsically very slow because the Laser Radar had to be moved several times, were considerably speeded up by simultaneously working with three laser devices.

5.3 Integrative point clouds processing

At this stage the point clouds coming from the LR200 needed to be purged of the noisy points described above, and the Vivid 910 acquisitions had to be aligned to the main LR200 coordinate system. An interesting feature offered by the LR200 was employed in order to solve the problem of disentangling the noisy measurements from the good ones: the possibility of saving data with a “quality” factor represented by a score associated with each measurement based on the estimated Signal to Noise Ratio (SNR) when receiving the backscattered optical signal. Of course when the equipment works out of focus, the laser beam divergence produces a spreading in the light energy, and the amount of backscattered light falls below the suitable threshold. If the score is low, its value can be used to cut away the (bad) points measured out of the focal zone. But this value may not always be the same, so a tool for dynamically defining which points should be cut from the whole cloud was developed. It is software, written in Visual C++ and based on the OpenGL libraries, that shows the point cloud in 3D and simultaneously makes it possible to cut out points based on the quality factor. The user can therefore decide what is the acceptable noise level looking in real time at the “cleaned” 3D point cloud.

Triangulation and merging of the LR200 points were based on the same procedure described for the first acquisition stage. The range maps captured with the Minolta device were then aligned on the main set of data with the Iterative Closest Point (ICP) algorithm, implemented with the IMInspect module of the Polyworks software package. The data from the Vivid 910 and the LR200 were merged and simplified with RapidForm tools, in a way similar to the process executed at the first acquisition stage.

A mesh subdivision according to the 3D grid initially defined at the first stage was arranged for obtaining a set of about 60 blocks of mesh corresponding to the un-empty areas of figure 7.

6 MODELING

In order to complete model, suitable to be the platform into which could be inserted synthetically generated models such as the Roman Forum, Colosseum or the Circus Maximus, it is necessary to fill up as much as possible the (inevitably) missing areas through careful editing of the mesh. Each block has been processed separately by first purging all topological errors, followed by the smoothing of the building facades in order to lower the measurement noise. The missing areas have been supplemented with semi-automatic procedures implemented by editing tools of RapidForm and Polyworks, based on the analysis of the borders or in the fitting of polynomials surfaces over the mesh below. The editing work is still in progress. A preliminary merge of the data acquired up to now has been generated and simplified in order to create the pictures in figure 10, where synthetically shaded images of the model, taken from the three primary points of view (S_1 , S_2 and S_3), are shown.

7 CONCLUSIONS

As noted in the Introduction, the project discussed in this paper forms an important part of the Rome Reborn Project. The success of the project, in its initial phase, is indeed dependent on digitizing the impressive work of topographical representation and reconstruction accomplished by the twentieth-century archaeologists and physical modelmakers responsible for the “Plastico di Roma antica.”

Digitization of the monument makes it possible to launch the new digital model to be produced in the coming decades by the Rome Reborn project by inheriting the most accurate and detailed physical model developed in the previous century. Digitization of the Plastico gives an instant urban context to the new, “born-digital” models of individual sites and monuments being produced by the Rome Reborn project. Moreover, once the Plastico has been scanned, it can be updated as new discoveries come to light; its errors can be corrected; and, with additional work, it can be improved with

respect to its scale and the photorealism of its surfaces. Meanwhile, a highly accurate digital scan of the Plastico offers essential documentation of a fragile monument that has come to have great historical value in its own right.

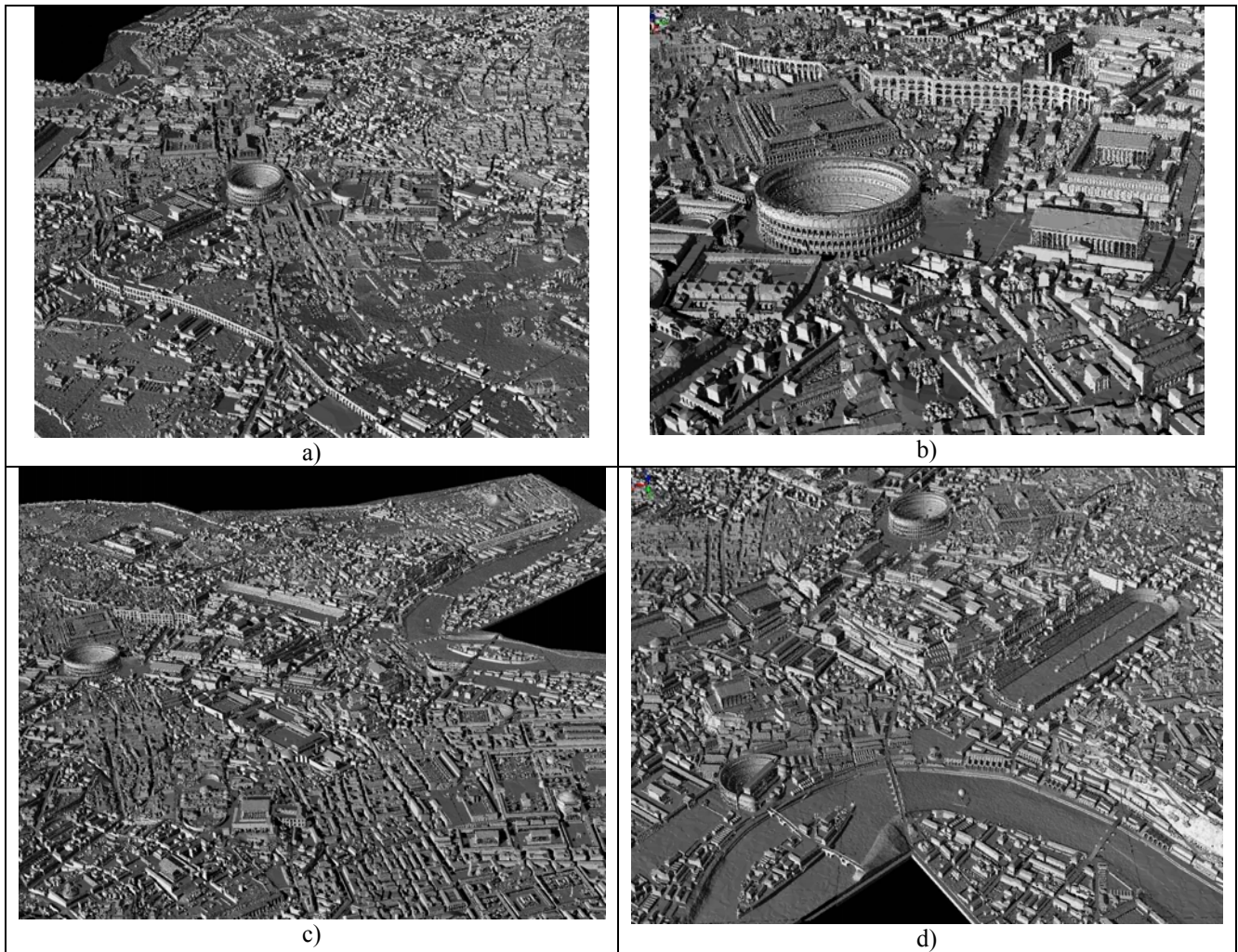


Figure 10: Preliminary models, oriented as seen by: a) position S_1 ; b and c) position S_2 ; d) position S_3 . Some of the most famous Roman monuments, such as the Colosseum (a,b,c, and d) and the Circus Maximus (a, c, and d), are clearly seen.

The challenge of digitizing the Plastico lies in the very excellence of the model, which is large in size but tiny in detail. Digitization projects normally work with objects at one end or the other of the physical scale. This paper has shown the instruments, algorithms, and procedures used to sublimate these contradictory characteristics of the Plastico and to translate them, with minimal loss, into a new digital format. Since the Plastico is but one example of many physical models of cities that have been made since the Renaissance, the methodology developed for digitally capturing the authoritative model of ancient Rome should find useful application elsewhere⁷.

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REFERENCES

1. G. Guidi, J.-A. Beraldin, S. Ciofi, C. Atzeni, "Fusion of range camera and photogrammetry: a systematic procedure for improving 3D models metric accuracy", *IEEE Transactions on Systems Man and Cybernetics Part B-Cybernetics*. Vol. 33-4, 2003, pp. 667- 676.
2. G. Guidi, J.-A. Beraldin, C. Atzeni, "High accuracy 3D modeling of Cultural Heritage: the digitizing of Donatello's Maddalena", *IEEE Transactions on Image Processing*, Vol. 13-3, 2004, pp. 370-380.
3. B.K.P. Horn, "Closed-form solution of absolute orientation using unit quaternions", *J. Opt. Soc. Am. A*, vol. 4, n. 4, 1987, pp. 629-642.
4. R.Sibson, "Locally equiangular triangulations", *The Computer Journal*, Vol.2-3, 1973, pp. 243-245
5. M. H. Ilfick, "Contouring by Use of a Triangular Mesh", *Cartographic Journal*, Vol. 16, 1979, pp. 24-28
6. L. Guibas, J. Stolfi, "Primitives for the Manipulation of General Subdivisions and the Computation of Voronoi Diagrams", *ACM Transactions on Graphics*, Vol.4, No.2, 1985, pp. 74-123.
7. D. Buisseret, ed., *Envisioning the City: Six Studies in Urban Cartography* (Chicago).