USING MULTIPLE SCANNING TECHNOLOGIES FOR THE 3D ACQUISITION OF TORCELLO'S BASILICA

M. Balzani[1], M. Callieri[4], G. Caputo[2], P. Cignoni[4], M. Dellepiane[4], C. Montani[4], P. Pingi[4], F. Ponchio[4], R. Scopigno[4], A. Tomasi[3], F. Uccelli[1]

[1] DIAPReM (Development of Integrated Automatic Procedures for Restoration of Monuments), Univ. of Ferrara, Architecture Dept., Italy
[2] Diocesi Patriarcato di Venezia, Ufficio Beni Culturali, Venice, Italy
[3] Dipartimento di Ingegneria dell'Informazione, Univ. of Pisa, Italy
[4] Istituto di Scienza e Tecnologie dell'Informazione (ISTI), C.N.R., Pisa, Italy

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ABSTRACT:
The paper presents the results of a 3D scanning campaign which sampled both the exterior facades of an ancient Basilica in Torcello (Venice, Italy) and some key elements of its interior. The targets of our scanning project were selected to be representative of different subjects, requiring different digital sampling technologies. We have used a range of scanning devices: a triangulation scanner for medium scale artifacts, a phase-modulation time-of-flight device for larger surfaces (mosaics), and a standard time-of-flight system for the overall architecture. All the data gathered have been integrated and fused in a multiresolution model which can be visualized in real time at full accuracy with an innovative visualization system.

I. INTRODUCTION

We present the results of a recent project, aimed at the acquisition of a digital 3D model of an important romanic complex: the Basilica of Santa Maria Assunta in Torcello (see Figure 1).

Torcello is a village on a small island of the same name in the lagoon of Venice. In the 7th century the people escaping from villages in the mainland due to the barbarian attacks moved to Torcello. Torcello reached its maximum expansion in the 10th century and it was a diocesan centre from 638 to 1689. The Basilica of Santa Maria Assunta (the Virgin Mary received into Heaven) was founded in the 639 by Isaccio, the exarch from Ravenna, and it is considerated the oldest document of the Venetian history. The church was renewed in the 864 and in the 1008 it was enlarged and enriched by the bishop of Torcello"Orso Orseolo".

The pavement, made of polychrome inlays, the wonderful mosaic decorations that cover the walls, and the paintings of the Venetian - Byzantine school ("History of the Christ Apotheosis" and the "Last Judgement" of the XII - XIII century) underline the solemnity of the place and the huge importance that the place represented in the past.

The basilica has long been threatened by rising damp and subsidence problems. Many restoration activities took place between 1975 and 1995 but the problems of the Basilica are not completely solved.

In the framework of the Parnaso *Ecumene* project (an Italian national project aimed at developing tools for the knowledge and promotion of the historical, artistic and archival heritage of the Catholic Church in Italy) the Cathedral of Torcello has been chosen as a representative case study for the documentation, analysis and promotion of an important work of art by means of state-of-the-art 3D scanning systems and visualization tools.

The Basilica presents elements of historical and artistic importance characterized by a wide multiplicity in terms of type and size: from the the architectural structure of the Basilica, to the the mosaics, the marble floors, till to the smallest artefacts. Main goal of this paper is to present the integrated approach we followed for documenting and improving the knowledge of this important and complex work of art. The approach provides the synergic use of multiple 3D scanning technologies in order to let the user appreciate the different aspects of the Cathedral in the same integrated framework.

The elements we are interested are:

- *Overall architecture of the building*. Torcello is a large romanic church, and thus 3D scanning can be performed with *time-of-flight (TOF)* scanning technology.
- *Mosaics*. One of the peculiar aspects of this basilica are the huge mosaics on the internal walls of the apse and of the main facade. The interest of the curators is twofold: they are looking to instruments able to sample the complete mosaic (at a scale sufficient to have numeric info on the potential deformations of the wall) and to produce smaller sampling of selected regions (obtained at a much higher sampling rate). We have thus used two different solutions: an accurate scanning system which allows to sample a large region from a distance (Leica LR200), and a laser-triangulation system which supports the scanning of smaller regions with higher sampling density (KonicaMinolta Vi910).
- *Works of art*. The basilica holds a number of important works of art; some of them have been selected and a digitization with an accurate laser scanning system (*triangulation-based*) has been planned.

All scanned data have been processed with the CNR-ISTI scanning tools, described in Section III. We describe in the following sections IV, V and VI the technical specifications

Fig. 1. The Basilica of Santa Maria Assunta in Torcello (Venice, Italy).

of the three different scanning campaigns and the preliminary results. Finally, Section VIII describes the technology adopted for the interactive visualization of the sampled data.

II. Previous Work

Many previous works concern the use of 3D technology either to reconstruct digital 3D models of Cultural Heritage masterpieces or to present those models through digital media. An exhaustive description of those works goes well beyond the brief overview that we can draw in this section. We prefer to cite here only some seminal papers on the technologies proposed for 3D scanning and interactive visualization.

Automatic 3D reconstruction technologies have evolved significantly in the last few years. An overview of 3D scanning systems is presented in [CS00]. Unfortunately, most 3D scanning systems do not produce a final, complete 3D model but a large collection of raw data (*range maps*) which have to be post-processed. The post-processing pipeline is presented in the excellent overview paper by Bernardini and Rushmeier [BR02]. Many significant projects concerning 3D scanning and Cultural Heritage have been presented in the last few years [LPC+00], [BRM+02], [FGM+02], [PGV+01], [STH+03], [BBC+04], [BCF+04].

The high resolution meshes produced with 3D scanning are in general very hard to render with interactive frame rates, due to their excessive complexity. This originated an intense research on: simplification and multiresolution management of huge surface meshes [GH97], [Hop99], [CMRS03]; and interactive visualization, where both mesh-based [CGG+04] and point-based solutions [RL00], [BWK02] have been investigated.

III. CNR-ISTI Scanning Tools

Scanning any 3D object requires the acquisition of many shots of the artefact taken from different viewpoints, to gather geometry information on all of its shape. Therefore, to perform a complete acquisition usually we have to sample many *range maps*; the number of range maps requested depends on the surface extent of the object and on its shape complexity. This set of range maps has to be processed to convert it into a single, complete, non-redundant and optimal 3D representation. The processing phases (usually supported by standard scanning software tools) are:

- range maps *alignment*, since by definition range map geometry is relative to the current sensor location and has to be transformed into a common coordinate space where all the range maps lie well aligned; after alignment, the sections of the range maps which correspond to the same surface zone will be geometrically overlapping;
- range maps *merge* (or fusion), to build a single, non redundant mesh out of the many, partially overlapping range maps;
- mesh *editing*, to improve (if possible) the quality of the reconstructed mesh;
- mesh *simplification*, to accurately reduce the huge complexity of the model obtained, producing different high quality Level Of Details (LOD) or multiresolution representations;
- *color mapping*, to produce textured meshes which couple the geometry of the object with its appearance representation.

A suite of scanning tools (*MeshAlign*, *MeshMerge*, *MeshSimplify* [CCG+03]) which support all the post-processing phases described above has been designed and implemented by CNR-ISTI. The second generation of the tools has been produced in the framework of the projects MIUR Parnaso *"Ecumene"* and EU IST *"ViHAP3D"* (2002-2005).

MeshAlign allows the registration of multiple range maps; it adopts a classical approach based first on a *pairwise local* and then a *global* alignment [Pul99]. This canonical approach has been implemented with a number of innovations to reduce the user contribution, to improve efficiency and easy of use, and finally to support the management of a large number of range maps (we processed range dataset containing up to six hundreds range maps).

The alignment task is the most time-consuming phase of the entire 3D scanning pipeline, due to the substantial user contribution required by current systems. The initial placement is heavily user-assisted in most of the commercial and academic systems (and it requires the interactive selection and manipulation of the range maps). Moreover, this kernel action has to be repeated for all the possible overlapping range map pairs. This pairwise process can be considered as a graph problem: given the nodes (i.e. the range maps), we have to select a subset of arcs such that every node is linked to some others if they have to be aligned together. If the set of range maps is composed by hundreds of elements (the scanning of a 2 meters tall statue generally requires from 200 up to 500 range maps, depending on the shape complexity of the statue), then the user has a very complex task to perform: for each range map (a) find which are the partially-overlapping ones, (b) given this set of overlapping range maps, determine which one to consider in pair-wise alignment (either all of them or a subset), and (c) process all those pair-wise initial alignments. The goals in the design of *MeshAlign* were:

- to support the management of really large set of range maps (from 100 up to 1000); this can be obtained by both providing a hierarchical organization of the data (range maps divided into groups) and by using multiresolution representation of the data to make rendering and processing more efficient;
- since the standard approach (user-assisted selection and initialization of all the overlapping pairs and the creation of the correspondent alignment arc) becomes impractical on large set of range maps, an automatic setup of most of the required alignment arcs was planned;
- finally, provide visual/numerical presentation of the intermediate status of the alignment process and of the accuracy reached.

MeshMerge [CCG+03], the volumetric reconstruction tool, is based on a variant of the volumetric approach [CL96]. *MeshMerge* can manage large range map set (many million sample points) on low-cost PC platforms with a very good efficiency. Data fusion is performed by the weighted integration of the range maps, and small holes (region not sampled by the scanner) can be optionally filled. Since the adoption of a volumetric approach requires a very large memory footprint on big dataset, *MeshMerge* provides a *split-reconstruction* feature: to process huge dataset it works on sub-sections of the data (out-of-core), loading each time only the range maps involved in the generation of that single section of the voxel set. The various parts of the final model are joined after the split-reconstruction process with a small time overhead; the boundary of the sub-blocks are guaranteed to be identical so the joining of resulting sub-meshes is trivial.

The reconstructed models (when produced using a voxel size equal or smaller than the inter-sampling distance used in scanning) are usually huge in size (i.e. many millions faces). Most applications require significant complexity reduction in order to manage these models interactively. Two problems arise when we try to simplify such models: we need a solution working on external memory to cope with these big models; simplification has to be accurate if we want to obtain high-quality multiresolution models and accurate visualization [CGG+04].

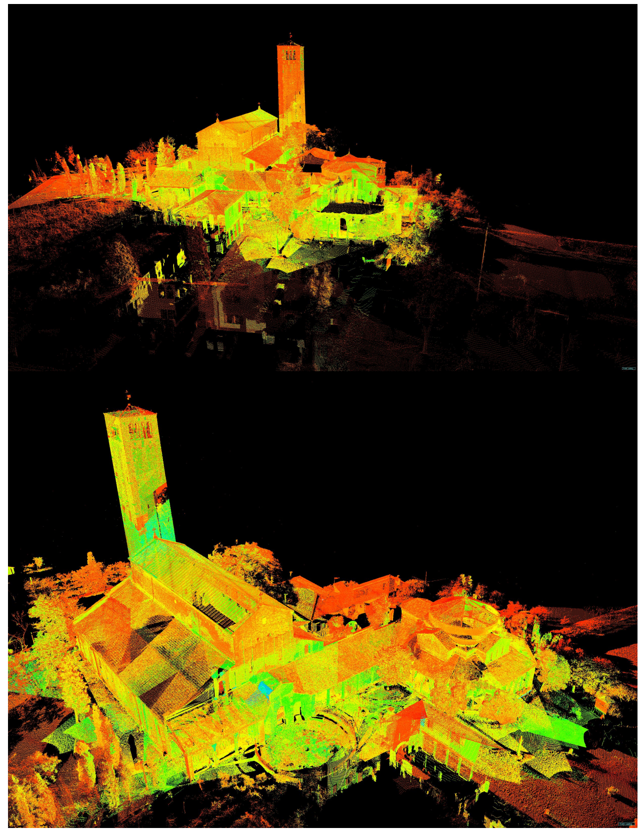

Fig. 2. The digital model of the Basilica rendered point-wise; all the sampled points are rendered here, using the Cyclone system (the image is in color).

The *MeshSimplify* tool [CMRS03] has no limits in terms of maximal size of the triangle mesh in input, sice it adopts an external-memory approach; at the same time, it ensures high-quality results, since it is based on edge collapse and takes into account both geometry accuracy and shape curvature [GH97], [Hop99].

Finally, the *Weaver* tool [CCS02] supports the reconstruction of textured meshes from a sampling of the object appearance. We usually perform the acquisition of the *apparent color* (reflected, illumination-dependent) using digital photo cameras, which is the easier and more practical approach since acquisitions in lab conditions (e.g. controlled lighting) are often impossible in the CH field. To map color data on the 3D model *Weaver* computes first the inverse projection and intrinsic parameters for each photo (from the image to the 3D mesh). Then, it computes an optimal coverage of the 3D mesh with sections of the original images, packs all the used portions in a new texture map and stores UV parametrization in the triangle mesh. Finally, it reduces color (hue/intensity) disparity on boundaries between overlapping photo parcels.

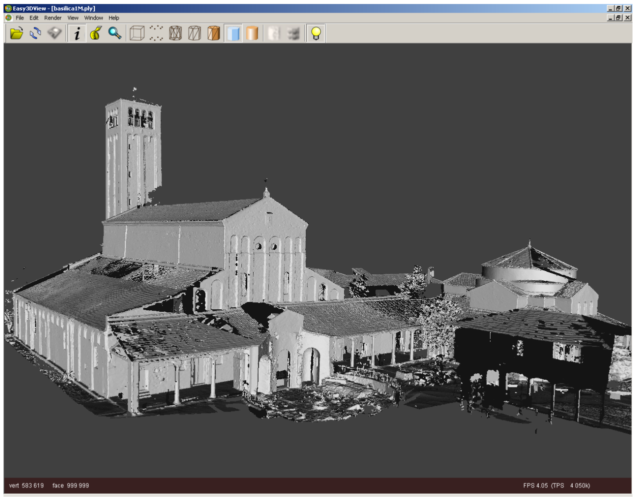

Fig. 3. The digital model of the Basilica rendered after a triangulated surface has been reconstructed from the point-set.

IV. Scanning the Basilica's architecture

The basilica has been scanned by the DIAPREM staff using *time-of-flight* technology. More specifically, a Leica Geosystems HDS 2500 system was adopted.

The 3D scanning activity has been coupled with a topographic survey in order to define, by means of targets acquisition, a plano-altimetric reading to be used for the registration of the information acquired and for the correct location and orientation of the 3D model in the framework of a national reference coordinate system. This aspect is particularly important in the scanning of buildings and/or sites.

The scanning activity consisted in 205 range maps (40 placements of the scanners, 190 different targets) because of the complexity of the building but also because of dense vegetation and narrow spaces between buildings.

Thanks to the presence of a survey reading, the registration of the range maps has been carried out by DIAPReM by means of the software tool Leica Geosystems Cyclone. The average measurement error is less than 7mm.

The point set resulting from the registration (see Figure 2) has been processed with *MeshMerge*, reconstructing a triangulated surface at resolution (discrete voxel grid extent) of 3 cm. The reconstructed mesh is thus a complex one (around 110 million faces) and has been simplified to different target sizes. As an example, the simplified model shown in Figure 3 is just one million faces.

The resulting mesh has some holes due to unsampled regions of the building. Small holes have been filled by our reconstruction tool (which is based on a discrete distance field approach and implements an hole-filling strategy [DMGL02]). On the other hand, holes characterized by a large extension are due to the specific spatial structure of the architectural complex: the basilica is on the side of a small island and some sections of the building can be sampled only from the sea; the view positions choice was strongly constrained by the water front boundary and the presence of vegetation. We have left these unsampled regions unfilled, due to a specific request of our CH supervisor who asked us to avoid to introduce fake data (i.e. data in some way *guessed* according to an interpolation criterion rather than *sampled* from reality).

Another issue that has to considered in processing TOF data is the noise of the data and the different sampling density in the multiple range maps which sample the same building region. We show in Figure a raw range map (sampling a small basrelief on the external wall of the Basilica), the same data after noise removal with a smoothing filter, and finally the same region of the building after the merge of all the range maps which cover those area. If the sampling resolution varies significantly, we loose some of the detail available in most densely sampled ones. From this example originates the need to be able to classify and weight any sampled data in terms of the sampling resolution. We are planning to modify our merging tools accordingly.

V. Scanning the Mosaic - medium resolution

The complete mosaic of the "Giudizio Universale" has been scanned using a scanning device based on *Frequency Modulated Coherent Laser Radar Technology*, the Leica Geosystems LR200 system. This system is an improved *time-of-flight* solution, where the frequency modulation of the optical signal allows to produce samplings much more accurate than the ones characteristics of other *time-of-flight* solutions. The only disadvantage of this device is the very slow acquisition times: in accurate sampling mode the system acquires only a few samples per second. For this reason, we could not apply a dense sampling in the acquisition of the large mosaic wall. The average inter-sampling distance used is around one centimeter (i.e. the typical one used with *time-of-flight* devices). On the other hand, the sampling accuracy of the Leica LR200 is around one or two orders of magnitude better than the one of standard *time-of-flight* devices.

The acquisition with the Leica LR200 device has been performed with the help of dr. Tommaso Grasso, a consultant who has also rented us the device. The scanning time has been 3 days (including night time). The raw data were processed with *MeshMerge* producing a mesh with 16 million faces (merging has been run with voxel size equal to 0.5 cm). An image of the results obtained is presented in Figure 4.

VI. Scanning the Mosaic - high resolution

A portion of the mosaic (see Figure 6) has also been sampled with the Konica Minolta VI 910. In this case we acquired 70 range maps from a distance of approximately 80 cm. (a scaffolding has been used to get in proximity of the sampled region). Inter-sampling distance has been around 0.5 millimeters. Range maps have been aligned with *MeshAlign* and fused with *MeshMerge* producing a mesh with 30 million faces (merging has been run with voxel size equal to 0.4 mm).

The acquisition with the Konica Minolta system produced results of quality lower than required/expected, due to the specific material of the mosaic: most of the "tessere" are in glass; moreover, most of them are gilded and therefore highly specular. The result of laser scanning on such a critical surface is a noisy sampling. Even if we used a sufficiently dense sampling (with the goal of reading the "tessere" borders in

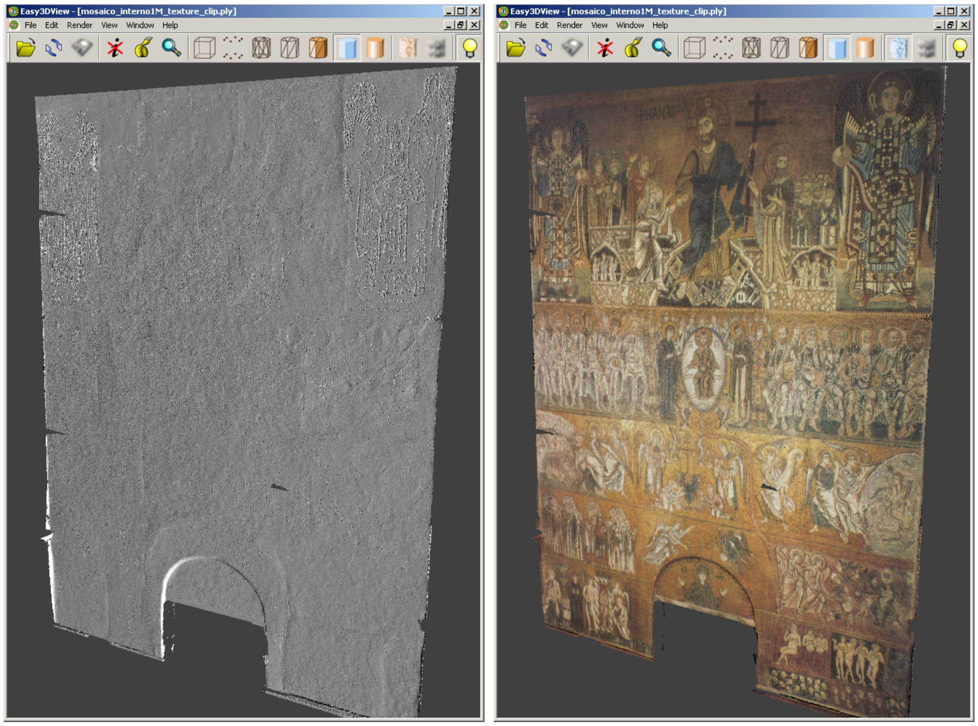

Fig. 4. The digital model of the “Giudizio Universale” mosaic, rendered without and with the corresponding texture map.

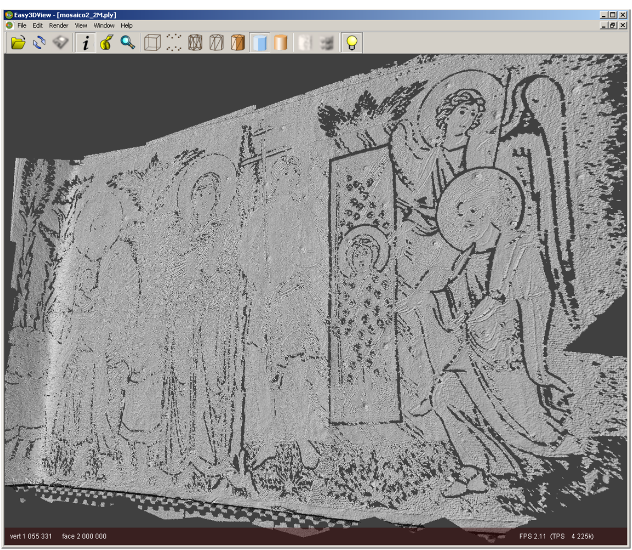

Fig. 6. A portion of the “Giudizio Universale”mosaic, scanned at high resolution with a Konica Minolta VI910.

the 3D model), the high degree of noise makes the 3D model highly random when we zoom at the single tessera scale. Much better results could be produced if the mosaic surface is sprayed with a matte, grey dust before scanning; this is a procedure that we adopt usually on shiny materials, but in the case of the mosaic scanning we were not able to apply it because we were not able to obtain the required authorization by the curators in time. In any case, the results are of sufficient quality (see Figure 6), especially when we are not requested to zoom to the level of the single mosaic tile.

VII. Scanning a funerary stele

A funerary stone (probably the bishop Orso Orseolo’s stele) laying on the pavement of the basilica, has also been scanned. The material was in this case highly cooperative: a light-brown stone, mostly reflective in a diffuse manner.

We scanned it with the Konica Minolta VI910, acquiring around 40 range maps with inter-sampling distance of around 0.5 millimeters. The raw data have been aligned with *MeshAlign* and fused with *MeshMerge* (0.5 mm voxel size); the output mesh is 25 million faces. The simplified mesh shown in Figure 7 is one million faces.

VIII. Showing complex scanned datasets with Virtual Inspector

*V*irtual Inspector is a new visualization system that allows naive users to inspect a large complex 3D model at interactive frame rates on standard PC’s. This system evolved considerably from the preliminary version presented in [BCS01]; we describe here briefly its new features. To support the efficient manipulation of massive models, *V*irtual Inspector adopts now a multiresolution approach where view-dependent variable resolution representations are extracted on the fly using a new and highly efficient approach [CGG$^+$04]. For each frame, the best-fit *variable resolution* LOD is selected according to the current view frustum and the requested visualization accuracy. LOD selection and rendering are very efficient since we adopt a patch-based representation, where a coarse-grain multiresolution hierarchy is visited on the fly and ready-to-render geometry patches are associated to each logical node of the variable LOD produced. 3D data are therefore not reconstructed on the fly, but efficiently fetched from disk on

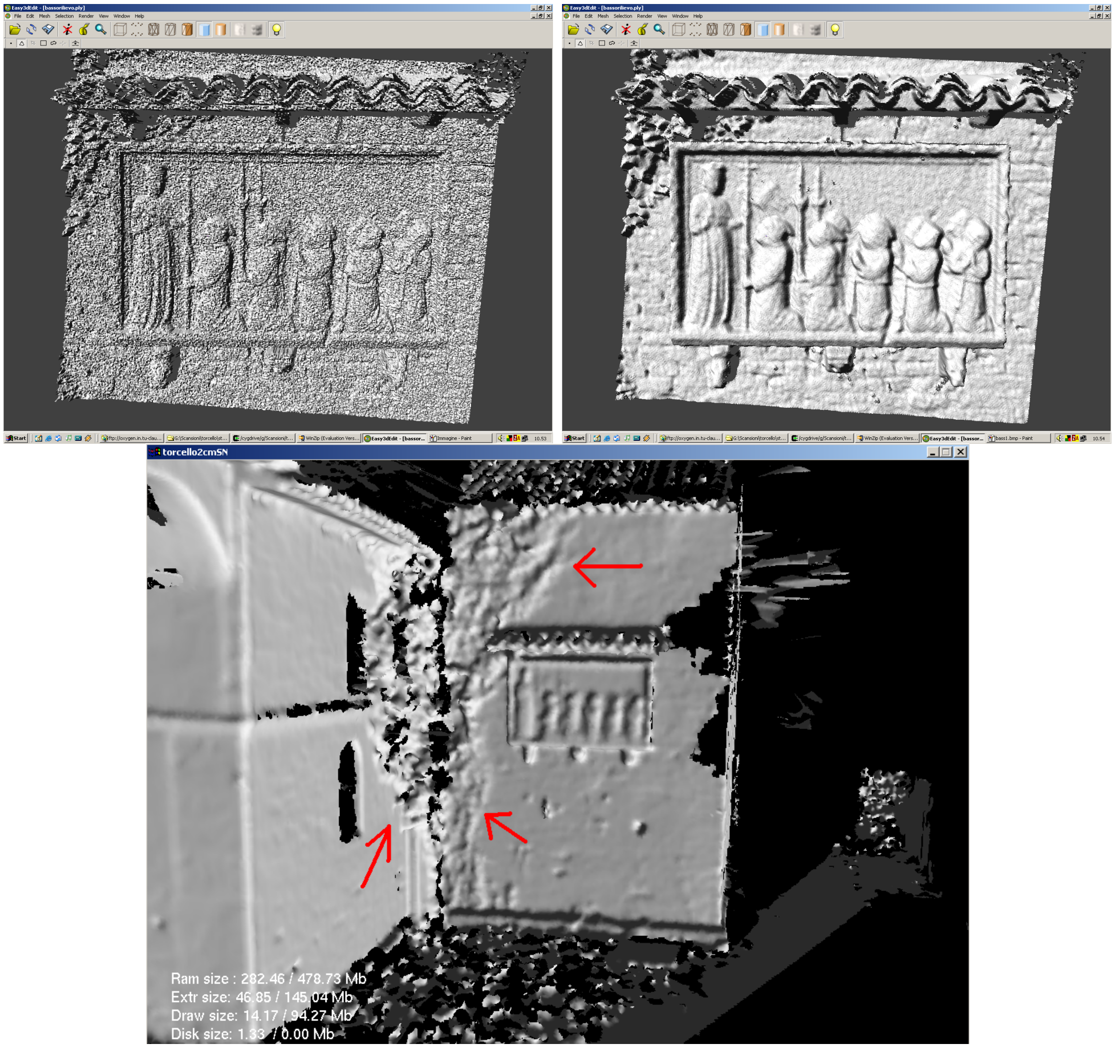

Fig. 5. A range map obtained at high sampling rate (0.5 cm), before and after smoothing; the final model obtained after merging multiple range maps at different sampling rates. The red arrows indicates portion of the wall which were covered by ivy, and thus where the sampled geometry is very low quality.

demand and copied on GPU memory for maximal rendering efficiency.

*V*irtual Inspector is mainly oriented to the visualization of single works of art (sculptures, pottery, architectures, etc.), and adopts a very intuitive approach to guide the virtual manipulation and inspection of the digital replica, based on a straightforward metaphor: we provide a *dummy* representation of the current inspected model on a side of the screen, which can be rotated on its axe; to select any given view the user has just to point with the mouse the corresponding point on the *dummy* (see Figure 8). *V*irtual Inspector supports interactive modification of the lighting, to simulate in real time the “luce radente” (grazing light) effect that is usually used in real inspection to enhance the visualization of small-scale surface detail.

Other important characteristics of *V*irtual Inspector we want to emphasize here are its flexibility and configurability. All main parameters of the system can be easily specified via XML tags contained in a initialization file, such as: which are the 3D models to be rendered (a single mesh or multiple ones), the system layout characteristics (i.e. how the different models will be presented on the screen), the rendering modes (e.g. standard Phong-shaded per-vertex colors or BRDF rendering) and the interaction mode (e.g. model manipulation via the standard virtual trackball, the dummy-based “point and click” interaction, or both).

Finally, we introduced support for *hot-spots*. Hot spots are a very handy resource to associate multimedia data (e.g. html pages) to any point or region of a 3D model. This allows to design interactive presentations where the 3D model is also a natural visual index to historical/artistic information, presented using standard HTML format and browsers.
The specification of hot spots is extremely easy in *V*irtual Inspector; modifications to the 3D models are not required. We provide a simple 3D browser to the person in charge of the implementation of the multimedia presentation, which allows to query the 3D coordinates of any point on the surface of the artifact (by simply clicking with the mouse on the corresponding point). Then, a new hot spot is specified by introducing a new XML tag in the *V*irtual Inspector

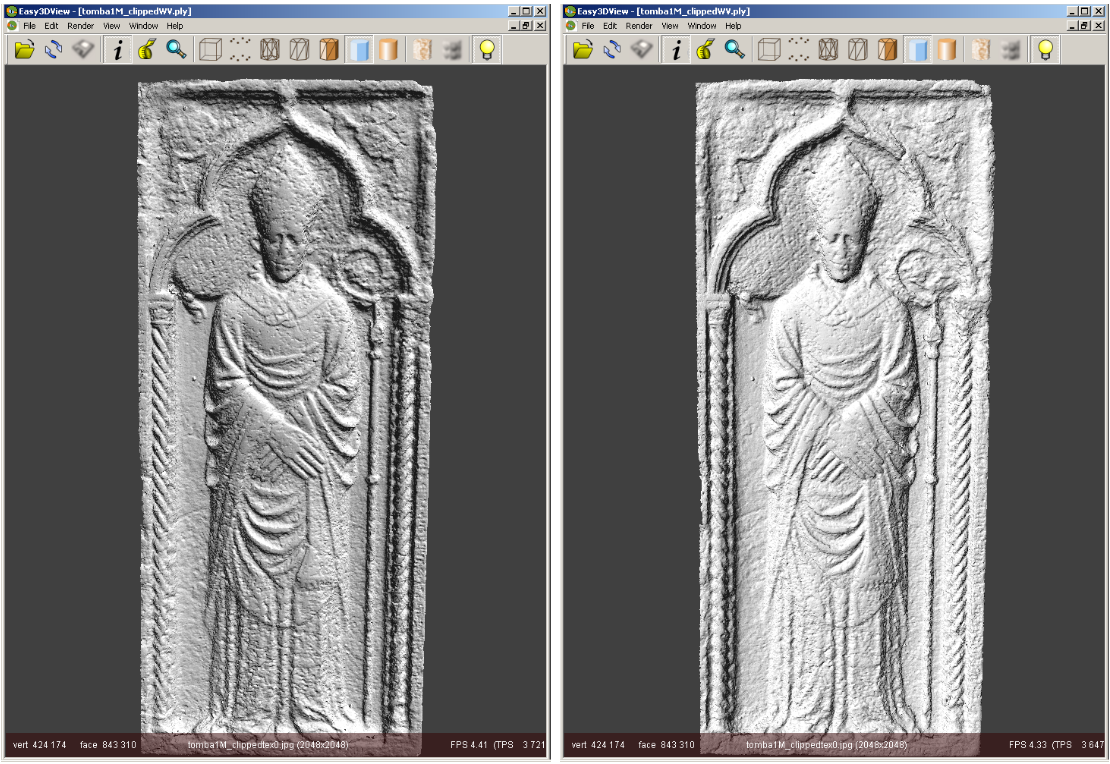

Fig. 7. A funerary stone, scanned at high resolution from the pavement of the basilica using a Konica Minolta VI910; the model is rendered with two different grazing light directions.

specification file. The hot spot XML tag specifies basically the 3D location and the action that has to be triggered when clicking on the hot spot (e.g. the name of the html file, if we want to open a multimedia page). After activation, the control passes to the html browser, while *V*irtual Inspector remains sleeping in the background and regains automatically the control of the interaction whenever the html browser is closed.

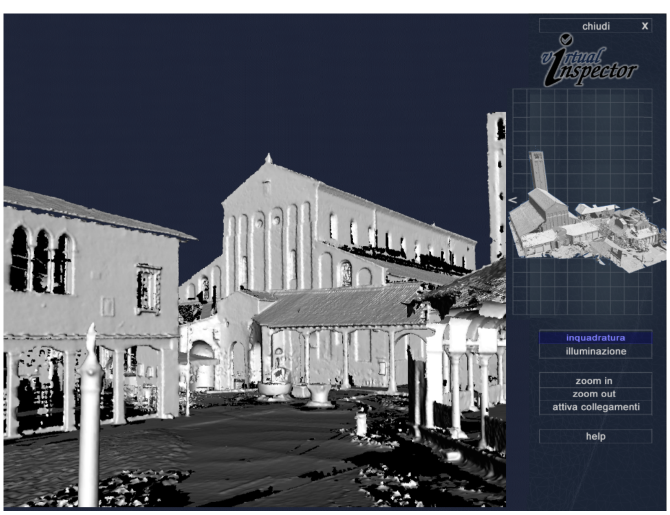

Fig. 8. *V*irtual Inspector showing the 3D model of the Basilica.

IX. Conclusions

3D scanning can be considered as a nearly mature technology. The research performed in the last few years has produced significant results, but some issues still remain open. We have presented some recent results from the 3D scanning acquisition campaign we performed in the Basilica of Torcello (Venice); data gathered have been integrated and can be presented at full resolution using an interactive visualization tool.
The surface data coming from 3D scanning has been presented also in a web-based archival system (developed by other partners in the framework of the Parnaso Ecumene project), using low resolution models and a commercial 3D browser (Cult3D). These 3D models have been integrated by panorama Quick Time VR images documenting visually the exterior and the interior of the basilica. These latter are not described in the paper because they were generated by means of standard technologies. The important aspect to be underlined is that the panorama views offer a global knowledge of the work of art and then the integrated use of multiple 3D scanning technologies allows to modify the *resolution* of the analysis while maintaining an overall control of the whole heritage.

We believe that the digital archival and promotion of important and complex artworks has to be implemented by the joint use of multiple 3D acquisition technologies, each one used in its preferred working domain, and by the integration of all these into a single system for virtual navigation and analysis.

One issue on which we are now focusing is how to manage a high-resolution sampling of color (i.e. hundreds of high-resolution digital images) on a high-resolution 3D model. Especially for the restoration of Cultural Heritage, curators need to manage large set of photos, and how to map on a complex geometry all those pixel data and how to render at interactive rates is still a serious open problem.

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The laser scanning reliefs (stele and mosaic) have been operated by the CNR-ISTI staff (C. Montani, A. Fasano, P. Pingi, M. Callieri), with the cooperation of dott. T. Grasso for the mosaic relief.

The TOF scanning of the Basilica has been conducted by DIAPReM (staff directed by M. Balzani; relief coordinated by M. Incerti; 3D relief by N. Zaltron, S. Settimo; topographic relief by G. Galvani, M. Beltrami, C. Traina; 3D data registration by N. Zaltron, F. Uccelli).

Final data integration and visualization has been operated by CNR-ISTI staff (F. Ponchio, M. Dellepiane, P. Cignoni, R. Scopigno).

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