

3D MODELING OF A ROMANESQUE CHURCH IN TUSCANY: ARCHAEOLOGICAL AIMS AND GEOMATICS TECHNIQUES

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ABSTRACT:

In this paper we report on our latest research work in capturing 3D geometrical information of heritage monuments. The work is illustrated through a case study from Tuscany, a small but spectacular Romanesque church close to the castle of San Giovanni d'Asso (Siena, Italy). Using terrestrial laser scanning (TLS) and image-based techniques we were able to create a complete 3D model of the interior and exterior of the church. The images were acquired with consumer-grade digital cameras (6 and 8 mega pixels) along with a small radio-controlled helicopter to capture details of the roof and the apse which was not visible from ground level. Decorations and small details were modeled in high-resolution with an automated image matching algorithm while the simpler geometries of the exterior were reconstructed through a semi-automated approach. TLS was employed for the interior of the church, which consists of a main floor above a very small crypt, the recording of which was complicated by a plethora of columns and arches. The 3D survey, representation and reconstruction of San Pietro in Villore should become a case study of scientific research addressed to test a simulation based open-space where it is possible in every moment to measure and compare historical evidence, stratigraphical relationship and other datasets but also where it is possible to improve and upgrade the record in the future on the basis of new field work or post-processing.

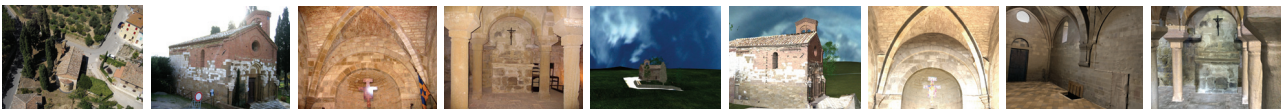


Figure 1: Photos and renderings of San Pietro in Villore church, Siena (Italy).

1. INTRODUCTION: THE ARCHAEOLOGICAL PERSPECTIVE

Since many years, the laboratory of Landscape Archaeology and Remote Sensing focused its attention on underground archaeology developing mainly integrated archaeological prospection tools and strategies. Nowadays our maps are more and more plenty of features previously invisible through field-walking survey and other research methods. While gaps were onwards disappearing we realized that the cultural context we are working on hides a new challenge just under our eyes. Historical buildings, monuments and all the other typology of surface features were documented, analyzed and communicated using standard processes developed, in the best case, between Seventies and Eighties.

The hypotheses that underpin the project is to use new technologies to survey historical buildings, or generally speaking complex "objects", to build 3D models and to develop 3D information systems aimed to improve our analysis capabilities and therefore understanding historical transformation of buildings and their landscape relationship.

The case study we present in this occasion is related to the church of San Pietro in Villore (Figure 1) mentioned in documents for the first time in 1278 and located in the landscape we are studying since the last fifteen years. Today the church is one of the most important Romanesque buildings in the Siena countryside for its rich range of structural and decorative features. The original roof,

now only extant in the presbyterial area, is supported by blind arches set against the walls, as well as the large self-supporting cross-arch, and it is characterized by the presence of diagonal arches with large quadrilateral sections. Under the floor of the church there is a crypt, a feature that is relatively uncommon in the Romanesque churches of the Siena landscape. The crypt is divided into three naves by seven columns. This is a peculiarity not very common in the Romanesque churches of Siena countryside. Although this is a relatively small building we feel that it represents an excellent case study for showing why archaeologists should make use of 3D modelling. On that issue we should recognize that the returns in recent decades of archaeological research from the use of 3D digital documentation and representation, in terms of scientific investigation, are relatively disappointing, bearing in mind the possibilities offered nowadays by newly developed software and hardware.

One major limitation of 3D archaeological site reconstruction is the fact that archaeologists try to rebuild contexts almost always at the end of the research process: ... now that everything has been analyzed and we might propose a "reconstruction"... This is a typical attitude that leaves to archaeological reconstruction mainly an aesthetics role definitively not involved in the research process (Forte, 2007). It is our contention that 3D recording and modelling should constitute a bridge between 'data, knowledge and communication' (Campana et al. 2008). However, this paper should be considered as a report of a work in project describing

the only the starting point of our research focused on survey and data processing to get the 3D model.

2. SURVEYING AN ANCIENT BUILDING: THE ROMANESQUE CHURCH OF SAN PIETRO IN VILLORE (SI-ITALY)

In archaeological research is essential to apply geomatics techniques to represent correctly all peculiarities of the investigated object. Nowadays we can employ a wide amount of geomatics tools to obtain results usable in different scales of archaeological investigation (Campana et al., 2008). The most common used techniques for 3D documentation, reconstruction and interpretation process are image-based and range based data (Remondino and El Hakim, 2006).

In order to obtain a virtual 3d model of San Pietro in Villore at local scale, useful to be used in intra-site archaeological analysis, we employed a strategy based on integration between multiple techniques: a multi-resolution and multi-sensor approach has been used choosing the most appropriate methods in relationship to research scale. The integration between different data sources was essential to overcome some limits of each method and to have as result the complete geometric information of the heritage.

The first step of reverse engineering process was the survey of the monument. We used a laser scanner for massive data collection of the shape. TLS survey of the Church has been made using the flight time scanner Leica Scanstation I: the scanner has been used at the resolution of 5 millimeters. We acquired both internal and external part of the monument. The acquisition has been influenced by some limits due to occlusion and position of the surfaces. In the external side we were unable to acquire part of the roof and an half of the posterior apse. In the right side we spent time to move the scanner to overcome the trees located at about 1,5, 2 meters from the building side. In the interior we acquired quickly the main floor. The data collection of the crypt, a room with 12 columns and several arches, we needed 13 TLS stations to overcome occlusions and cover all surfaces. Totally we acquired 130 millions of points. The TLS acquisition process is quite fast and simple from technical point of view, it doesn't require particular skill: though the proprietary software the user can easily manage the survey, choosing area of interest to capture and setting the resolution.

To overcome the limits of TLS survey we used images to apply "dirty" photogrammetry method. Images on the ground and from the air have been acquired with consumer digital cameras (6 and 10 mega pixel). A small remote-controlled drone (UAV) has been used to collect the aerial stereo pairs of the roof and of the apse which was not accessible from ground (images acquisition using Microdrones GmbH helicopter has been performed by D.Sarazzi, Zenit s.r.l., www.zenit-sa.com).

At end of the survey process we got the full geometry of all visible features: only some small parts of the left side are not acquired because they were occluded by trees and we can't remove it.

The final step of the survey was the acquisition of HDR textures of all surfaces: in fact in Cultural Heritage it is very important to value the true color of the analyzed object. 3D models generally should represent a virtual copy of an object that means we need either a precise color mapping or an accurate shape reconstruction. The generation of a photo-realistic result essentially requires that there is no difference between a view rendered from the model and a photograph taken from the same viewpoint. Create a photo-

realistic model is the base to make a realist virtual copy but it isn't enough for restoration and preservation purpose. For this reason it's necessary to know the real radiometric value of the photographed material. Generally the images are exposed with the illumination at imaging time but it may need to be replaced by illumination consistent with the rendering point of view and the reflectance properties (BRDF) of the object (Lensch et al., 2003). High dynamic range (HDR) images might also be acquired to recover all scene details (Reinhard et al., 2005) whereas a calibrate pattern give back the radiometric correction.

Images taken at different exposure setting, different angles, or different imaging devices on the same point can present different appearance.

The terms High Dynamic Range (HDR) is used whenever intensity values that span three or more orders of magnitude are acquired, stored or displayed. A High-Dynamic Range image is an image that has a greater dynamic range than can be shown on a standard display device or that can be captured with a standard camera with just a single exposure. A related term Low Dynamic Range refers to digital systems supporting only 8 bits per color channel.

HDR images have many advantages over standard low dynamic range images (Debevec and Malik, 1997), and several applications have been demonstrated where such images are extremely useful (Debevec, 1998; Cohen et al., 2001).

The model was textured using 8.2 Mpixel Canon EOS 20D digital images, acquired with 17 mm objective. The assisted procedure employed 14 for the external side, 22 internal and 46 crypt side digital images and obtained a seamless textured model displayed in Figure 2 and Figure 3.



Figure 2: The internal and external 3D model.



Figure 3: The crypt 3D model shown respectively in textured, shaded and wireframe mode.

Many difficulties in this way can be found during the image acquisition, due to occlusions or narrow areas. Figure 4 reports the example of the crypt. The narrow distance limited the location of the image acquisition. Moreover, the vegetation, Figure 5, could not be removed without creating an occlusion.

Different methods were published to overcome this problem (Boehm, 2004; Ortin and Remondino, 2005). These methods are based on statistical image analysis techniques and therefore require a large numbers of views to remove the unwanted occlusions, redundancy which is not always assured in this kind of modelling project.

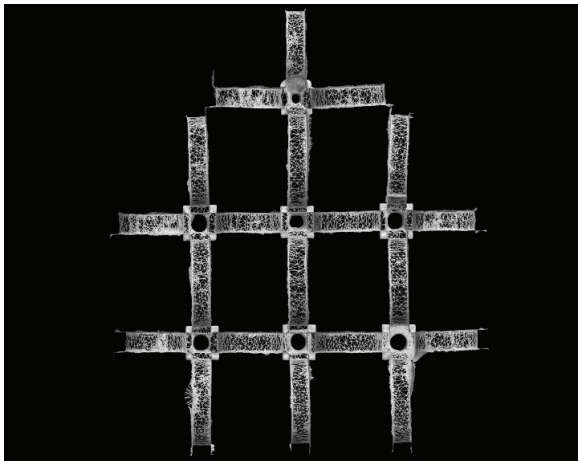


Figure 4: Range data of the crypt.

Figure 5: Examples of occlusion on the external wall.

The acquisition of high dynamic range images is an easy task and should become even simpler in the future. There are two principal methods for making HDR images: physically-based rendering and multiple exposure image capture. One approach to this problem is to take multiple photographs at different exposures (Figure 6) and merge together to create a single high-dynamic range image (Debevec and Malik, 1997). Some commercial applications already use this technique. The weakness of multi-exposure technique lies in the requirement for the camera to be mounted on a tripod. Alternative method of collecting HDR images use cameras that allows storage of a broader dynamic range. HDR capturing devices are very expensive and taking a series of multi-exposure pictures is tricky, because in the real world, scenes are dynamic, Canon's RAW format comes in handy. Canon RAW does not store the full spectrum of brightness but it broadens the dynamic range significantly because its sensors capture unprocessed data. We took at least three RAW images for every view with the camera on a tripod. In some shots a color pattern has been put in the sight.



Figure 6: Multiple photographs at different exposures.

3. DATA PROCESSING

On the contrary of data collection stage, data processing step is quite hard in term of skills: each kind of datasets have to be processed with specific software to extract a clear dataset ready to be integrated with all the others.

Firstly, TLS data has been cleaned from noise and edited to remove unwanted features (Figure 7). TLS point clouds in fact needs a manually removal of noisy measurements, generally concentrated on the borders of some edges, but we also needed to remove some unwanted elements, as electric cables and furniture. On the other hand the image data have been processed with the typical photogrammetric pipeline consisting of calibration and orientation, 3D surface measurement (i.e. image matching) and texture mapping. The surface measurement had been performed using a multi-image approach, developed at ETH Zurich and able to simultaneously match multiple images avoiding occlusions and achieving a higher reliability of results (Remondino et al., 2008).

After image processing and data cleaning, both TLS and Image based datasets have been merged using the software Innometric Polyworks: the alignment has been performed aligning all point clouds in one reference point cloud. The aligning method works choosing at least 3 approximate homolog points between the reference cloud and another one, and after that, running an iterative alignment algorithm to maximize the accuracy.

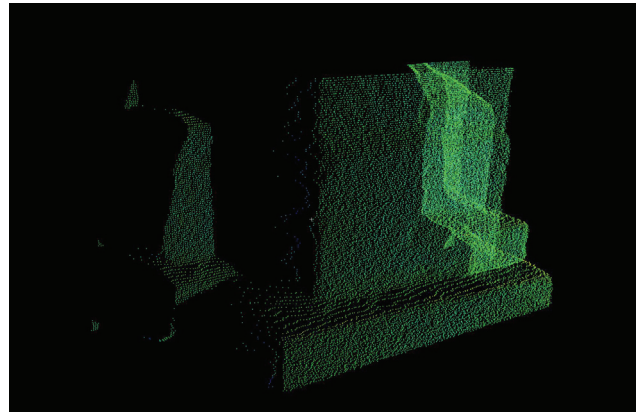


Fig. 7: Raw TLS point cloud: noisy points in blue.

The overall point cloud has been triangulated in order to generate a polygonal mesh of the heritage. We set the parameters of meshing algorithm in order to preserve peculiarities in the geometry of heritage and to obtain at the same time a manageable model in terms of computer performance. The resulting mesh has been manually edited to close holes and to fix defects (Figure 8). Finally, as last stage of the virtualizing process, HDR images have been used to texture the 3D model.

Our approach for radiometric texture corrections has been divided in two steps:

1. first correction with our own in-house software to create a set of images to recover all scene details;
2. final correction based on the method developed by El-Hakim et al. (1998) and improved subsequently.

In some conditions, if we can determine the characteristic function for a given camera in a controlled environment, as a calibration process, then we apply it to the project images.

The digitized brightness value for a pixel is not a measure of scene radiance (radiance is the amount of light energy reflected from a surface in all directions). There is an unknown non-linear mapping between the pixel value and the scene radiance. This non-linearity is largest near the saturated part of the response curve and represents the characteristic function.

The result allows to compute a function that is used to recover the scene radiance, up to a scale (Debevec, 1997). The response function can be applied to any image taken by the imaging system. In the first step we took at least three RAW images with Canon EOS 20D on tripods to acquire a HDR 16 bit tiff image in every viewpoint. The radiometric value image result has been calculated by calibrate color pattern recover in some images. After image calibration in singles viewpoint we adjusted the differences along the border of adjacent HDR images sets that are minimized by commercial software like Photoshop. There are some different approaches to adjust HDR images (Zhang and Zhou, 2004).

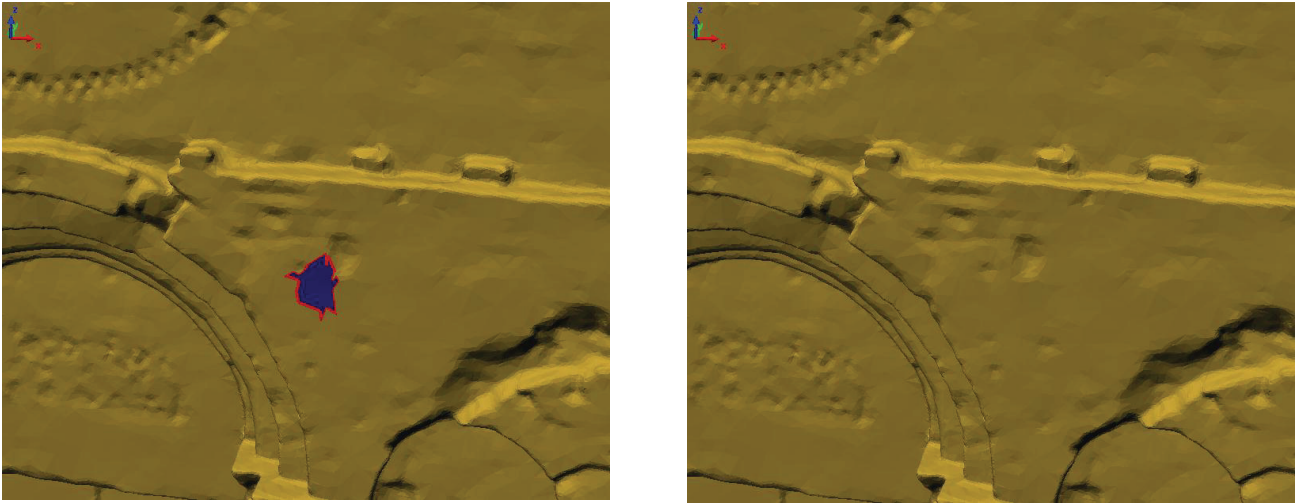


Fig. 8: Hole in the mesh and its correction.

With this process it's possible to adjust variation in lighting, colour and intensity for a pair of HDR images. However, this method can be time consuming, semi-automatic techniques were developed.

The texturing of meshed range data requires the selection of homologues points between the 3D mesh and the 2D image to-be-mapped. For this reason the 3D model has been segmented on the basis of images suitable for a complete texture mapping without occlusions. When these images are stitched together, discontinuity artifacts may still be visible.

We address this problem by a correction method termed "*global color adaptation*" (El-Hakim et al., 1998). The adaptation estimates color offsets between images (Figure 9). The color (red, green, or blue value) differences along the border area of images are minimized by least-squares adjustment. Here the observed height differences are replaced with color differences along region borders. Additional weighted observations ensure non-singularity and prevent the offset from drifting away across larger scenes. The approach has been implemented in software tool that automatically correct adjacent images once the user points to a common region.

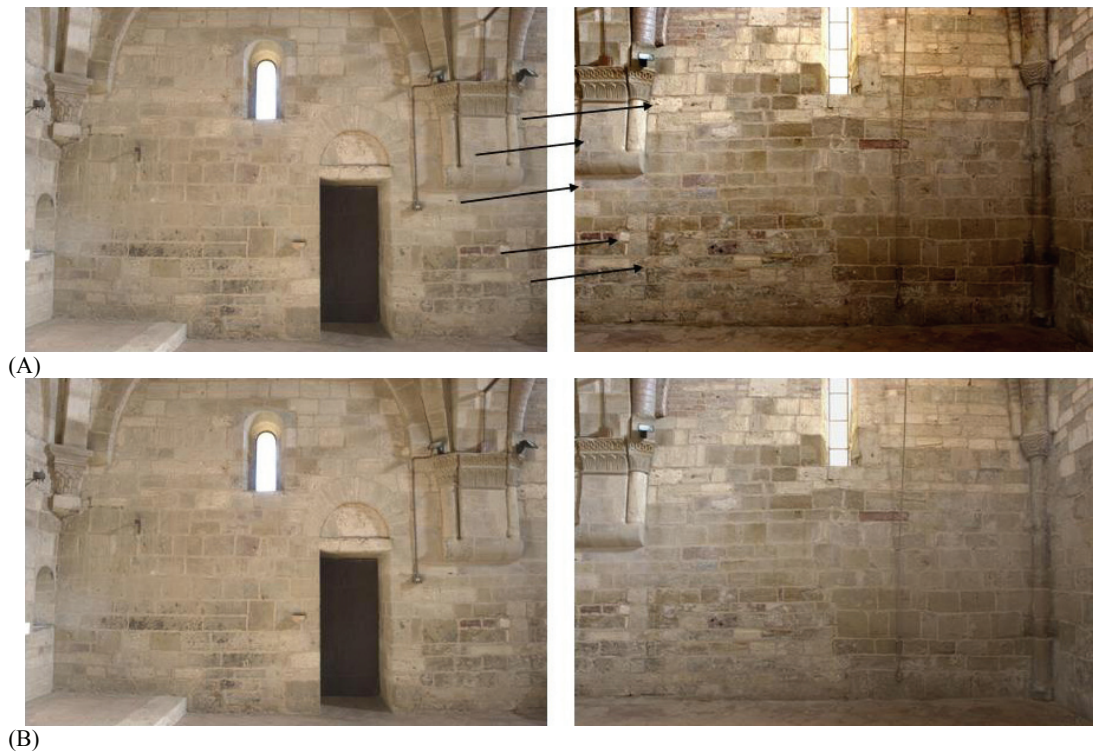


Figure 9: Two adjacent images before (A) and after (B) their radiometric correction.

We finally textured the model using TexCapture. This software can texture a mesh by the selection of homologous points between the 3D model and the 2D image. This is still an interactive procedure as no automated and reliable approaches were proposed yet. Indeed the identification of homologous points between 2D and 3D data is an hard task much more complex than image to image or geometry to geometry registration. Furthermore, the approach used to compute the intrinsic and extrinsic camera parameters so we must use a calibrate camera.

If the image to-be-mapped covers the entire 3D model, the silhouette of the model can be used as matching feature (Lensch et al., 2000; Pulli et al., 1997) proposed to fix the camera onto the active sensor so that the relative position between the two sensors is known.

4. CONCLUSIONS AND NEXT DEVELOPMENTS

As we argued in the introduction, this paper describes only the first step of our research. Indeed, at this stage, our contribution demonstrates mainly how accurate and detailed 3D results can be relatively readily derived from the integration of the multiple available geomatics tools.

The 3D survey, representation and reconstruction of San Pietro in Villore should become a case study of scientific research addressed to test a simulation based “open-space” where it is possible in every moment to measure and compare historical evidence, stratigraphical relationship and other datasets but also where is possible to improve and upgrade the record in the future on the basis of new field work or post-processing. This approach should, therefore, allow us to achieve:

- better understanding of analytical study of the building - stratigraphy, structural, architectural, stylistic also assisted by automatic extraction of cross-sections, longitudinal sections and prospects;
- the interpretation of archaeological features in deep association with their physical and cultural context exploring relationships across a landscape;
- overcoming space and time sharing complex “objects” with other experts all around the world;
- the demonstration (firstly addressed to archaeologists) that digital reconstruction is a complex exercise and projective interpretation and also is much more than a graphic reconstruction, is a simulation, that allows exploration of three-dimensional model perspectives through endless investigations and non-invasive documentation;
- virtual reconstruction and simulation scenarios address to specialist as to the general public developing new tool to share but also preserve the memory of cultural heritage;
- development of 3D archaeological thinking.

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REFERENCES

- Boehm, J., 2004: Multi-image fusion for occlusion-free façade texturing. *IAPRS*, 35(5), Istanbul, Turkey, pp. 867-872
- Campana, S., Remondino, F., Sordini, M., 2008: Integration of geomatics techniques for the digital documentation of building and archaeological excavations, 1st Workshop Earth Observation: "Advances in Remote Sensing for Archaeology and Cultural Heritage Management", Organised by EARSeL, CNR - National Research Council, 1, Rome
- Cohen, J., Tchou, C., Hawkins, T., And Debevec, P., 2001: Real-time highdynamic range texture mapping. In *Rendering Techniques 2001*, S. J. Gortler and K. Myszkowski, Eds. Springer-Verlag, 313–320
- Debevec, P. E. and Malik, J., 1997: Recovering high dynamic range radiance maps from photographs. In *Proc. ACM SIGGRAPH 97*, T. Whitted, Ed., 369–378
- Debevec, P., 1998: Rendering synthetic objects into real scenes: Bridging traditional and image-based graphics with global illumination and high dynamic range photography. In *Proc. ACM SIGGRAPH '98*
- Forte M. (ed), 2008: La villa di Livia, un percorso di ricerca di archeologia virtuale. L’Erma di Bretschneider. Roma, pp.54-68
- Lensch, h., Heidrich, W., Seidel, H., 2000: Automated texture registration and stitching for real world models. *Proc. 8th Pacific Graphics 2000 Conf. on Computer Graphics and Application*, pp. 317-327
- Lensch, H. P. A., Kautz, J., Goesele, M., Heidrich, W., Seidel, H. 2003: Image-based reconstruction of spatial appearance and geometric detail. *ACM Transaction on Graphics*, 22(2), pp. 234–257
- Ortin, D. and Remondino, F., 2005: Generation of occlusion-free images for texture mapping purposes. *IAPRS*, 36(5/W17), on CD-Rom, Venice, Italy
- Pulli, K., Cohen, M., Duchamp, T., Hoppe, H., Shapiro, L., Stuetzle, W., 1997: View-based rendering: visualizing real objects from scanned range and color data. *Eurographics Rendering Workshop 1997*, pp. 23–34
- Remondino F. and El Hakim S., 2006: Image based 3D modeling: a review, *Photogrammetric record*, Vol. 21(115), pp. 269-291

Remondino, F., El-Hakim, S., Gruen, A., Zhang, L., 2008: Development and performance analysis of image matching for detailed surface reconstruction of heritage objects. *IEEE Signal Processing Magazine*, Vol. 25(4), pp.55-65

Zhang, W and Zhou, B., 2004: An HDR Brightness Correction Algorithm for Panorama Images. *Visualization, Imaging, and Image Processing*, pp.189–198