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Accurate Documentation in Cultural Heritage by merging TLS and high resolution photogrammetric data

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ABSTRACT

Several recording techniques are used together in Cultural Heritage Documentation projects. The main purpose of the documentation and conservation works is usually to generate geometric and photorealistic 3D models for both accurate reconstruction and visualization purposes. The recording approach discussed in this paper is based on the combination of photogrammetric dense matching and Terrestrial Laser Scanning (TLS) techniques. Both techniques have pros and cons, and criteria as geometry, texture, accuracy, resolution, recording and processing time are often compared.

TLS techniques (time of flight or phase shift systems) are often used for the recording of large and complex objects or sites. Point cloud generation from images by dense stereo or multi-image matching can be used as an alternative or a complementary method to TLS. Compared to TLS, the photogrammetric solution is a low cost one as the acquisition system is limited to a digital camera and a few accessories only. Indeed, the stereo matching process offers a cheap, flexible and accurate solution to get 3D point clouds and textured models. The calibration of the camera allows the processing of distortion free images, accurate orientation of the images, and matching at the subpixel level. The main advantage of this photogrammetric methodology is to get at the same time a point cloud (the resolution depends on the size of the pixel on the object), and therefore an accurate meshed object with its texture. After the matching and processing steps, we can use the resulting data in much the same way as a TLS point cloud, but with really better raster information for textures. The paper will address the automation of recording and processing steps, the assessment of the results, and the deliverables (e.g. PDF-3D files). Visualization aspects of the final 3D models are presented. Two case studies with merged photogrammetric and TLS data are finally presented:

- The Gallo-roman Theatre of Mandeure (France);
- The Medieval Fortress of Châtel-sur-Moselle (France), where a network of underground galleries and vaults has been recorded.

Keywords: Accurate, Documentation, Architecture, Archaeology, Terrestrial Photogrammetry, Matching, Terrestrial Laser Scanning, Close Range

1. INTRODUCTION

Several techniques are available for cultural heritage documentation. Accurate documentation is closely relied to the *advances of technology (imaging sensors, high speed scanning, automation in recording and processing data) for the purposes of conservation works, management, appraisal, assessment of the structural condition, archiving, publication and research* (Patias *et al.*, 2008). Currently, the two most appropriate techniques are photogrammetry and laser scanning, delivering high resolution images and dense point clouds. Both solutions are discussed in this paper. In section 2, a short survey of experiences in documentation for cultural heritage is given, with references to recording approaches before all based on the combination of photogrammetric dense matching and Terrestrial Laser Scanning (TLS). Section 3 is a summary of methodological steps for both methods. Results from two examples are then discussed in section 4 and 5, the first one is about the recording of a Roman Theatre, and the second one a medieval fortress where underground

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tunnels and rooms have been digitized. Finally, we draw the conclusion on accurate documentation by merging high resolution photogrammetry and TLS from these two experiences.

2. TECHNOLOGY AND DOCUMENTATION IN CULTURAL HERITAGE

Many actors are working in the field of heritage documentation. They all agree that *recording, documentation, and information management are among all the central activities of the decision-making process for heritage conservation management and a fully integrated part of research, investigation and treatment* (Letellier *et al.*, 2007). The choice of the appropriate methods depends on the background and level of training or education in surveying of these actors. Sometimes very simple recording methods are adequate but more and more, any 3D- (documentation, reconstructions, representations, surface models, photorealistic models, textured models, point clouds, etc.) are expected from the recording. *The improvement of all methods for the surveying of cultural monuments and sites, especially by synergy effects gained by the combination of methods under special consideration of photogrammetry with all its aspects, is an important contribution to recording and perceptual monitoring of cultural heritage, to preservation and restoration of any valuable architectural or other cultural monument, object or site, as a support to architectural, archaeological and other art-historical research* (<http://cipa.icomos.org>). A documentation project will be successful if data providers and users as architects, archaeologists can meet and work together with surveyors and other experts from the recording and modeling fields. That's why CIPA's main objective is to provide an international forum and focal point for efforts in the improvement of all methods for cultural heritage documentation.

The integration of several technologies in heritage sites is discussed every time a new technology appears. The choice of the most effective technique is not always obvious (El-Hakim *et al.*, 2004; Kadobayashi *et al.*, 2004; Grussenmeyer *et al.*, 2008; Remondino *et al.*, 2010).). There is no single method that is applicable to recording heritage. The experience gained in modeling heritage and sites will help in the integration of several technologies.

For a long time, laser scanning was the main solution to produce dense 3D point-cloud data allowing high resolution geometric models, while photogrammetry was more suited to produce high resolution 3D textured models representing just the main structure (Guarniera *et al.*, 2006). Today, both photogrammetry and laser scanning can produce dense and accurate point clouds. Barazzetti *et al.* (2010) and Ducke *et al.* (2011) published recently papers about methodologies based on multi-image matching techniques from computer vision or photogrammetry in order to produce dense and accurate point clouds from series of overlapping images. Multiview 3D reconstruction solutions with detection of automated image correspondences using area and feature based matching algorithms are key solutions for the future of documentation. Both academic and commercial solutions are available today for this purpose. In Hullo *et al.* (2009), we present such a project based on dense stereo matching approaches for the documentation of a site in a desert where only digital cameras could be used.

Laser scanning systems can produce data that can vary in terms of point density, field of view, amount of noise, incident angle and distribution method (Rönholm *et al.*, 2007) with a high level of automation. After a decade of continuous development, TLS systems have reached an interesting level of productivity allowing fast and accurate surveys (Grussenmeyer *et al.*, 2010; Lerma *et al.*, 2010). But the data processing procedures are complex due to the edge detection, filtering, and other registrations which require dedicated software packages, high performance computers and storage capacity. Data from projects based on TLS recordings are often used only to visualize the colored 3D point cloud and navigate through (mainly for large sites), without any time consuming accurate modeling or reverse engineering process.

It is clear that no single technique is capable of giving satisfactory results in all measuring conditions (Voltolini *et al.*, 2007). More there is no single method that is applicable to recording every subject of cultural heritage and hence there is a strong demand for a hybrid method that exploits several technologies (Kadobayashi *et al.*, 2004). Therefore, it is interesting to consider different levels of integrated laser scanning and photogrammetric data (Rönholm *et al.*, 2007): object-level integration, photogrammetry aided by laser scanning, laser scanning aided by photogrammetry and tightly integrated laser scanning and photogrammetric data.

In Al-Kheder *et al.* (2009), the authors use both photogrammetry and laser scanning to record desert palaces in Jordan, but only the geometric accuracy and visual quality of the collected textured 3D models are thus optimized, showing finally a low level of integration between both technologies. As far as that goes, Yastikli (2007) presents successively

products available from photogrammetry, followed by a description of TLS technology and finally the possibility to generate the 3D model and digital ortho-image using generated 3D point cloud and recorded digital images. A more integrated study of merging digital photogrammetry and laser scanning to produce a unique detailed 3D model of a complex historical building is proposed by Guarniera *et al.* (2006). The basic shapes (e.g. walls and other main structures) were determined by image-based methods using a digital camera while fine details or more complex shapes were surveyed with a TLS. An experimental 3D measurement of Byzantine ruins on Gemiler Island (Turkey) has been proposed by (Kadobayashi *et al.*, 2004) to compare and evaluate laser scanning and photogrammetry and their combined use to digitally record cultural heritage objects from the point of view of producing accurate and expressive models and efficient data processing. Medieval castles are often used as test bench for modeling issues related to the automation of photogrammetric methods and to the fusion of 3D models acquired with different techniques, at different point densities and measurement accuracies (Voltolini *et al.*, 2007; Grussenmeyer *et al.*, 2008). Finally, in a recent paper of Remondino *et al.* (2010), some important documentation requirements and specifications, the actual 3D surveying and modeling techniques and methodologies with their limitations and potentialities as well as some visualization issues involved in the heritage field have been reported and discussed.

From this short review, we can conclude that considering the different levels of integration between laser scanning and photogrammetric as proposed by Rönholm *et al.* (2007) is an interesting topic to investigate. In the next section, we propose to summarize the main methodology steps of both TLS and photogrammetry approaches developed in our projects.

3. TLS AND PHOTOGRAMMETRY

3.1 TLS

For the practice of terrestrial laser scanning, the reader can refer to the guidelines given in (Lerma *et al.*, 2008) and (English Heritage, 2007). The scanning process follows a pipeline where all the steps are by no means automated (only the scanner can be considered as robotic application controlled by the scanner software):

- Survey planning
- Field operation
- Data preparation
- Data registration
- Data processing
- Quality control and delivery

With the objective of merging with data from photogrammetry (as dense point clouds), the data registration and geo-referencing steps are very important. Each scanner position and orientation must be defined according to a local or global site coordinate system. An accurate geo-referencing is the root of an accurate project.

Direct Geo-Referencing (figure 1, left) of point clouds is possible with scanners like Trimble GX or Leica Scan Station C10. Indirect Geo-Referencing (figure 1, right) is applied when the leveling, centering and orienting options are not available in the scanner. For the post-processing of dense point clouds from photogrammetry, the indirect Geo-Referencing (figure 1, right) is also applied.

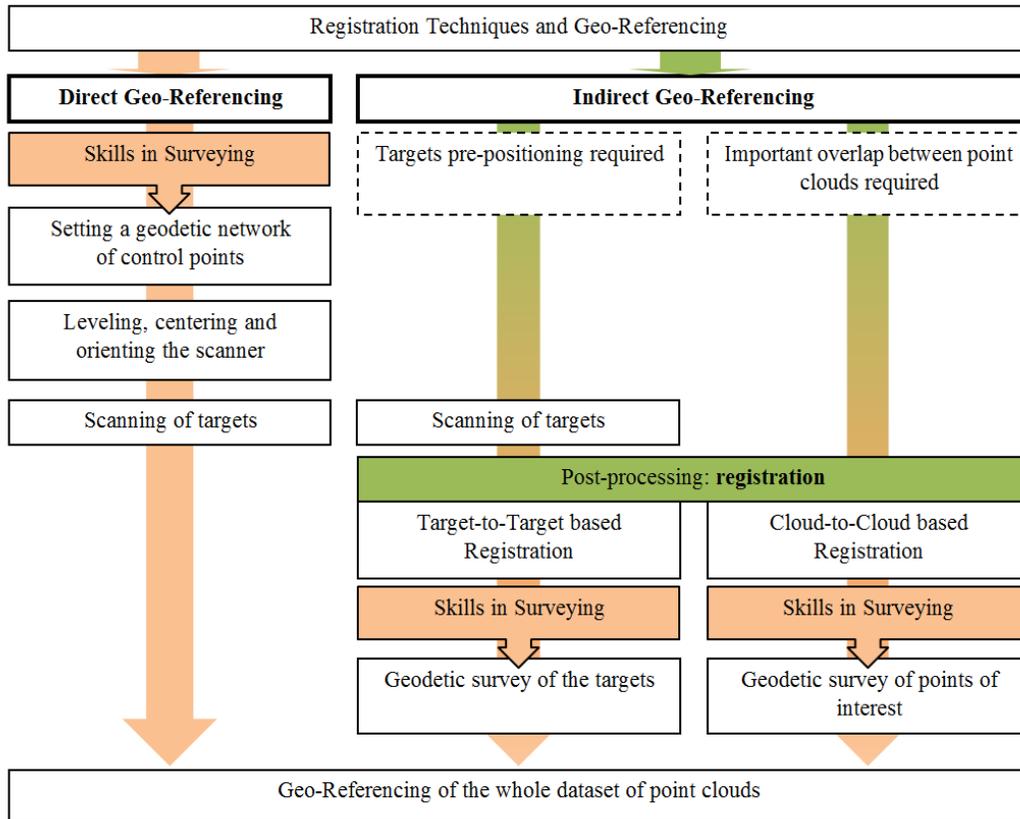


Figure 1. Solutions for the Geo-Referencing of dense point clouds. Figure modified from Lerma *et al.*(2008).

3.2 Photogrammetry

We focus here only on methods of generation of dense 3D point clouds and detailed surface models of physical objects from calibrated cameras, sometimes called photo-based scanning. An example of detailed workflow summarizing all the steps from automated image orientation to surface measurement, mesh generation and texture mapping is given in (Barazzetti *et al.*, 2010).

The reader can also refer to a practical example of documentation of a cultural heritage site by Dense Stereo Matching (DStM) in (Hullo *et al.*, 2009). The overall steps (workflow is in figure 2) for DStM carried out by means of Photomodeler Scanner can be summarized as follows:

- Distortion free images are processed after calibration
- Automated image orientation (with or without coded targets) at a sub-pixel resolution is applied
- The project is scaled either by defining a given distances between points or by importing control points
- After selection of "best" stereo-pairs and accurate definition of the area(s) of interest in order to minimize the computation time and to avoid generate points in non interesting areas, the point clouds are created by cross-correlation
- Automatic detection of homologous points is made according to a defined sampling rate by the correlation algorithm.

Data acquisition	<ol style="list-style-type: none"> 1. Calibration 2. Targets on the object * 3. Stereo pair acquisition 4. Distortion free images
Orientation of the images	<ol style="list-style-type: none"> 1. Homologous points determination (automatic; manual) 2. Orientation Process 3. Scale 4. Epipolar geometry determination
Dense Stereo Matching	<ol style="list-style-type: none"> 1. Epipolar rectification * 2. 3D to 1D search interval 3. Epipolar homologous points 4. Meshing
Post processing	<ol style="list-style-type: none"> 1. Segmentation of the cloud (denoise, fusion...) 2. Mesh processing 3. Cleaning of the mesh (smoothing, filling holes in meshes, unify normals...)

* : Optional, but useful

Figure 2. Detailed Dense Stereo Matching framework (Hullo *et al.*, 2009)

3.3 Merging TLS and Photogrammetry

Both TLS and Photogrammetry deliver dense point clouds. Compared to TLS, the photogrammetric solution is a low cost one as the acquisition system is limited to a digital camera and a few accessories only. Indeed, the stereo matching process offers a cheap, flexible and accurate solution to get 3D point clouds and textured models. The main advantage of this photogrammetric methodology is to get at the same time a point cloud (the resolution depends on the size of the pixel on the object), and therefore an accurate meshed object with its texture. After the matching and processing steps, we can use the resulting data in much the same way as a TLS point cloud, but with really better raster information for textures. Solutions for the Indirect Geo-Referencing of dense points clouds (figure 1) can be applied for both TLS and photogrammetric data.

In section 4 and 5, two examples showing different levels of integrated photogrammetry and TLS data will be discussed.

4. THE GALLO-ROMAN THEATRE OF MANDEURE (FRANCE)

4.1 Scope of the documentation

The populating of the site of the modern city of Mandeuere begins on the Gallic period at the third century B.C. At the roman era, the city used to be known as Epomanduodurum. Its overall area is estimated to 2 km². Epomanduodurum used to be an important city, the second of the Sequane people, the capital city of Sequany being Vesontio (Besançon). The development of the city actually starts at the beginning of the 1st century A.D. with the buildings of the big therms and later of the theatre. The latter, leaning on a hill of the river Doubs, has a diameter of 142 meters and its capacity is

estimated between 15000 and 18000 seats. These characteristics make of this theater the second biggest in Gaule behind the one of Autun. Excavations have been carried out for about ten years. Figure 3 shows an aerial image of the site.

The main objective of the recording project consists of the realization of a digital terrain model and built elements of the theater in its current state. Because of the size of the site and the resources available we opted for a combination of photogrammetric methods and TLS. The hybrid model is thus obtained from the fusion of different data:

- Terrestrial Laser Scanner (Trimble GX)
- Aerial LiDAR (from Aerodata International Survey)
- Dense Stereo Matching Photogrammetry (PhotoModeler Scanner)

In this example, we put the focus on the processing of the data originating from TLS and DStM Photogrammetry.



Figure 3. Overall view of the Gallo-roman Theatre of Mandeuire (France)

4.2 Instrumentation - Procedures

Because of the size of the site, a long-range TLS is needed. On the other hand, the remains of the building would have required a very large number of stations. Since, the GX TLS has a quite narrow field of view and a low scanning speed, it became obvious that this technique is not well suited for some parts of the site (the remains of the buildings and the excavations). We chose then to complete the TLS point cloud by data obtained by DStM Photogrammetry (figure 4).

A global geo-referenced point cloud has first been obtained by Terrestrial Laser Scanning which consists of 8 Million points obtained from 14 different stations. The spatial resolution is comprised between 1 cm and 5 cm and the accuracy is estimated to 1 cm. Then, another 16 million points cloud has been obtained by DStM which has involved the following equipment:

- Canon EOS-5D (sensor size 24 mm x 36 mm)
- Objectives : focal lengths of 20mm and 28mm
- Tripod

To take the pictures, the autofocus function has been deactivated, the focus manually set on infinite, aperture and exposure time set as a function of the ambient light and distance to the object. As a typical case, the aperture was oftentimes set to 11 and the exposure time to 1/100 s.

With the 20mm focal length, respectively 28mm, and for a five meters distance to the object, one obtains an object-pixel size of 2.1mm, respectively 1.5mm. We have used standard Photomodeler coded targets to ease the orientation step and the scale setting step. Both objectives have been calibrated first.

We have chosen to cut the whole site in zones themselves cut into little zones forming a Photomodeler project. Each project contains from 2 to 6 pictures and results after processing in a local point cloud which has been obtained independently.

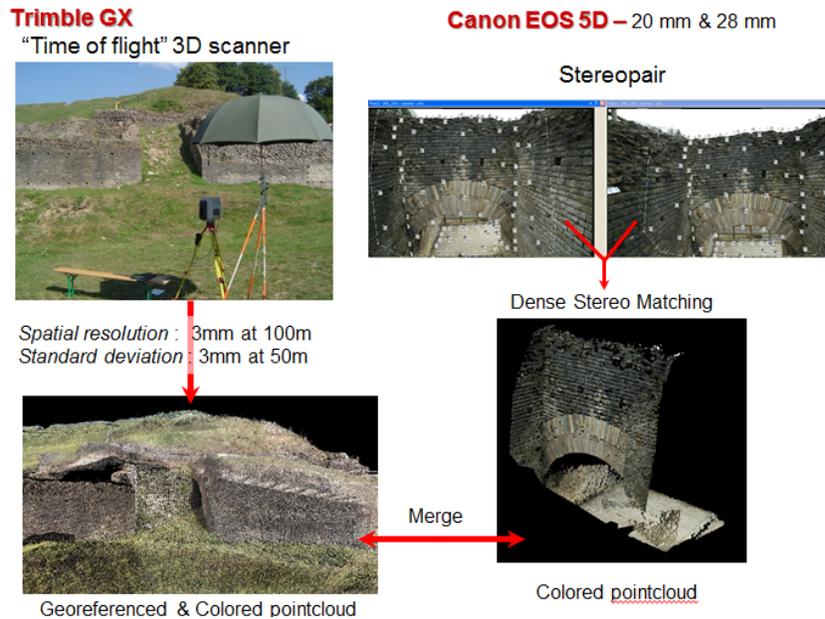


Figure 4. Overall view of the acquisitions by TLS and photogrammetry and the resulting point clouds (Mandeure, France)

Altogether, 500 images have been used for the DStM part in 125 sub-projects. The total acquisition time was about 20 hours. The local spatial resolution was about 5 to 10 mm. Then, thanks to overlapping areas, we have merged the different projects in order to obtain « blocks » (figure 5). At last, after registration of the “blocks” together with the TLS point cloud, they are getting geo-referenced as described hereafter. This has been achieved through the 3DReshaper © software by means of two steps. A first coarse registration is made by selecting manually corresponding points in the two different clouds. As a second step, an automatic fine registration is being processed by means of a 7 parameters transformation (ICP algorithm) with the geo-referenced TLS cloud as the reference (figure 6). One can notice that the scale factor in this transformation has proved to be very close to unity because the clouds originating from photogrammetry had already been scaled.

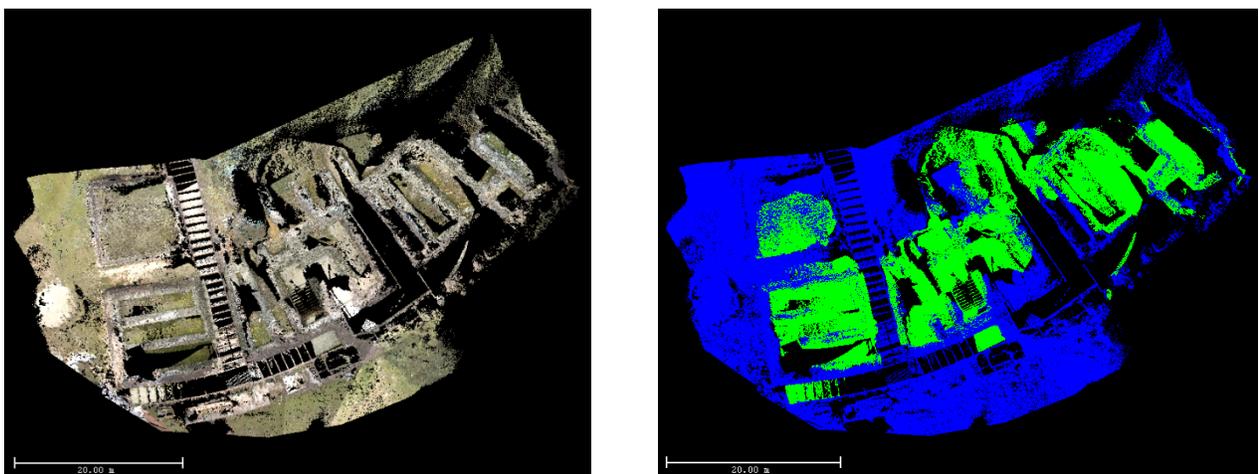


Figure 5. Southern part of the theatre
Left: True colors Right (color by cloud): green for the DStM cloud and blue for the TLS cloud

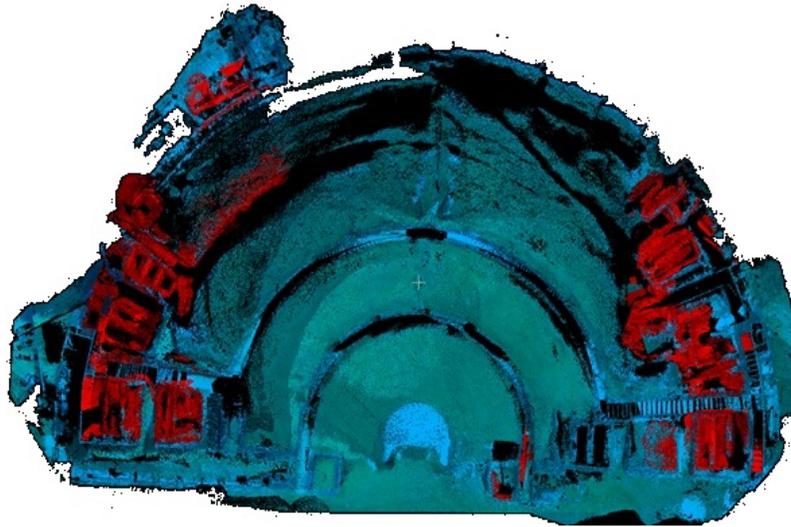


Figure 6. Complete 3D point cloud of the theater of Mandeure (France). Point clouds (in red) based on DStM are combined with TLS data (green-blue).

4.3 Results and deliverables

Visual analysis: A first quick control of the data may be done by visualizing appropriate sections as seen on figure 7. It allows to take note instantly that a gross error has been done and then to correct the process. However, in order to certify the quality of the whole process, it remains necessary to achieve quantitative control.

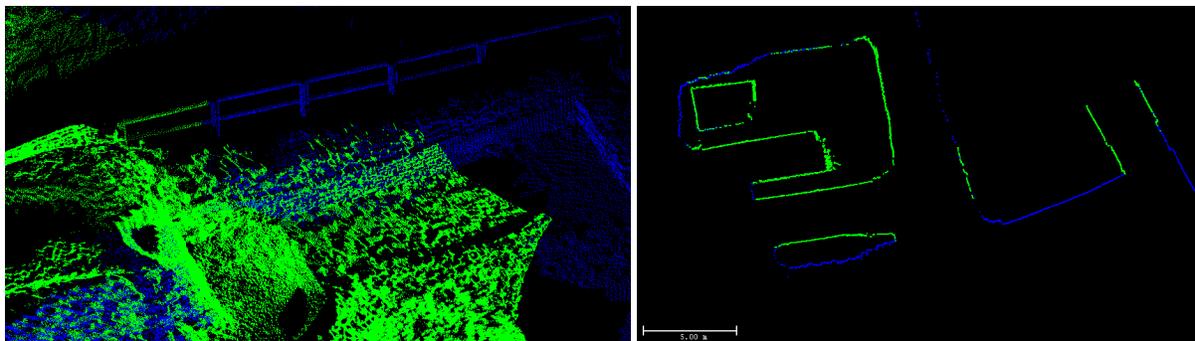


Figure 7. Zoom on a portion of a wall and wooden balustrade (left). Section of the southern part (right) color by cloud: green for the DStM point cloud and blue for the TLS point cloud)

Quantitative analysis: The quantitative control consists in measuring the distance between both clouds and is achieved by means of the CloudCompare software developed by the research department of EDF (France). The Hausdorff distance is computed on overlapping areas of both point clouds and the results are given hereafter.

The standard deviation of the error has been computed to 2.8 cm which has been judged as being satisfying as regard to the global size of the archaeological site. One can notice on the histogram of the error that 57 % of the points have an error inferior to 2 cm, 66 % inferior to 3 cm and 87 % inferior to 4 cm. Some quite important errors are reported on current excavations as seen on figure 8. It is most likely that these errors originate from the fact that elements (blocks) may be displaced slightly during the excavation period, both clouds having not been acquired simultaneously.

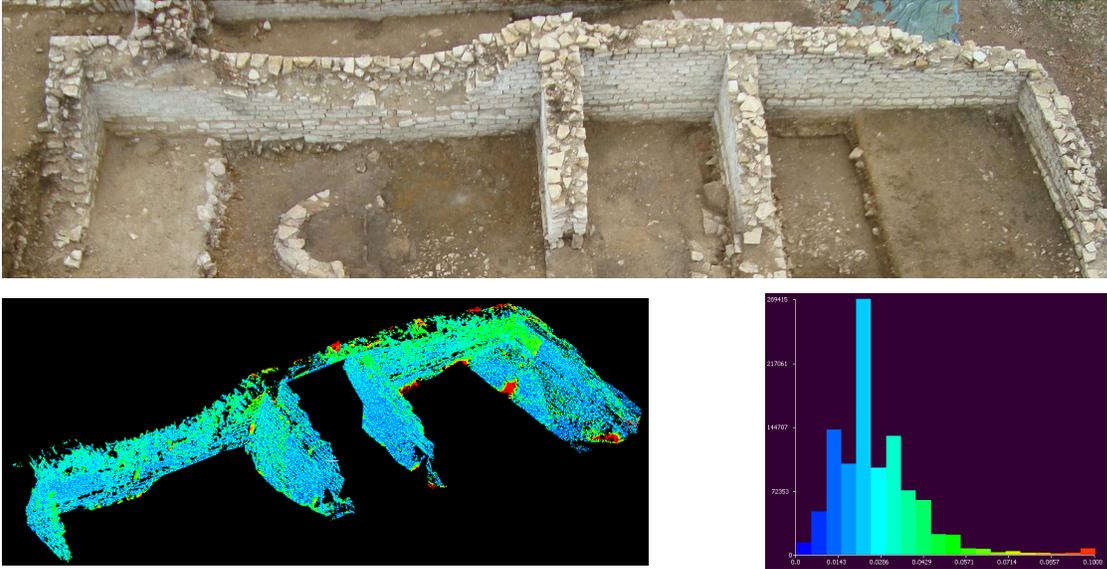


Figure 8. Photography of the area used for quantitative control (above), error map (bottom left) and error distribution (bottom right)

Deliverables: The 3DReshaper® software already used for cloud registration is also used for the modeling and texturing of the global point cloud. At last, pdf3D are produced for easy communication. Since this paper deals with the merging of two types of acquisition, we do not describe the modeling and texturing process and simply illustrate here some results including the final one on figures 9 and 10.



Figure 9. 3D Model of the site after merging of both TLS and photogrammetric data, without (left) and with textures (right)

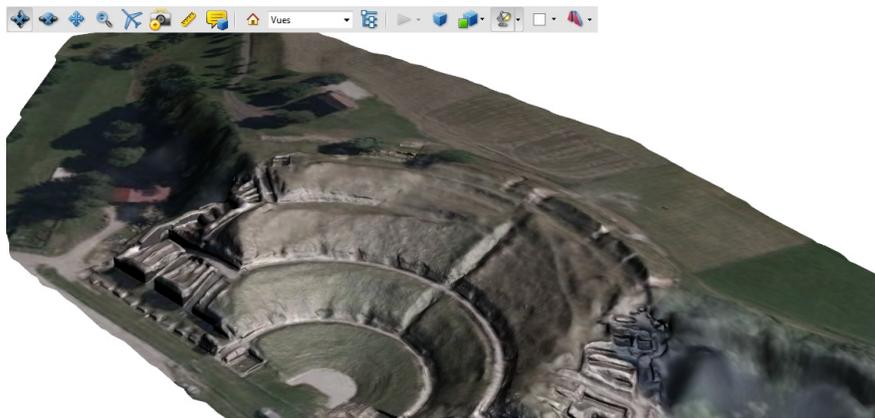


Figure 10. A screen capture of the produced PDF 3D.

5. THE MEDIEVAL FORTRESS OF CHÂTEL-SUR-MOSELLE (FRANCE)

5.1 Scope of the documentation

The medieval fortress of Châtel-sur-Moselle (Vosges, France) is a French heritage site. This heritage is one of the largest castle in Europe with 22 towers and three floors of galleries and underground chambers. This building has experienced architectural developments mainly in terms of fortification, from the eleventh to the sixteenth century, always ahead of the defense strategies of other military fortresses in Europe. A huge work of excavation and research has been carried out by the Association of « Vieux Châtel » for the past 40 years. Today with the help of local, regional and national funds, a project of digital documentation fortress has begun. This project consists, on one hand of scanning and modeling of exteriors and interiors of the castle, on the other hand in the development of a Web Information System, and lastly in the virtual reconstruction of the fortress. In terms of production, four parts are distinguished. The GeoPhenix Company is in charge of the LiDAR and 3D modeling of the exterior of the castle. Our research group at INSA Strasbourg is responsible for digitizing and modeling the interior spaces of the fortress, and the Web Information System. Architects from the CRAI-ENSA Nancy laboratory will reconstruct the model of the original fortress based on the current situation and archaeological hypotheses. The project is supervised by Mr. René Elter, archaeologist and project manager.

5.2 Instrumentation - Procedures

The equipment used in this project is the same as for the theatre of Mandeuve (Section 4). As the Trimble GX TLS has a field of view limited to 60° and a minimum distance of acquisition (2m) it makes it inadequate for special situations. Whenever the objects are long, narrow, with low ceilings, or in the case of dead-end clearances, overlapping of the stations are difficult. Some places have dimensions such that the field of view causes gaps (e.g. rooms with high ceilings). Photogrammetry, whose acquisition procedure allows multi-view projects, makes possible the documentation of such complex places without any limit as regard to the angles and distances and therefore is a complementary technique of TLS.

A geodetic network has been set prior to the recording so that each interior space can benefit from control points in one unique coordinate system. The Trimble GX scanner enables direct acquisition of geo-referenced data provided that three known points are within the range of the scanner for each station. If the geo-referencing has been carried out accurately, the registration step is thus not necessary, which significantly reduces the post-processing. The resulting point cloud is then directly usable for modeling purposes. But the configuration of a few areas makes this direct geo-referencing impossible. In such cases, the point cloud resulting from such a station will be registered in post processing either by integration of control points or by ICP (Iterative Closest Point) with overlapping areas of previously geo-referenced point clouds.

The point clouds obtained by photogrammetry are generated by DStM as explained in section 4. One or more stereo pairs are necessary to generate a dense point cloud. They are scheduled according to the gaps observed in the TLS point clouds. The recording by photogrammetry comes hence as a second stage after TLS acquisition. One has to define precisely the area covered by the stereo pairs depending on the gaps in the laser point cloud and one has to make sure that there will be overlapping areas with the already geo-referenced data to achieve the registration of the upcoming cloud. This overlapping may also be used for a quantitative control of the acquisition as previously exposed. In the case of the fortress, the TLS point cloud has a 1cm spatial resolution; the sampling rate for the correlation algorithm in the DStM is set to this same value.

5.3 Results and deliverables

The combination of TLS and photogrammetric data exposed here is performed on the so-called “Hall of sources” whose ceiling vault has not been acquired by TLS because of its large height. Once the TLS and the photogrammetric clouds have been obtained, one has to merge them. Scaling of the whole photogrammetric project is obtained by the measure of 4 points on each wall and the vault (15 points all together) which are recorded by total station. All the photogrammetric point clouds are first registered together by means of a conformal transformation and then, the global resulting photogrammetric cloud is registered with the TLS one.

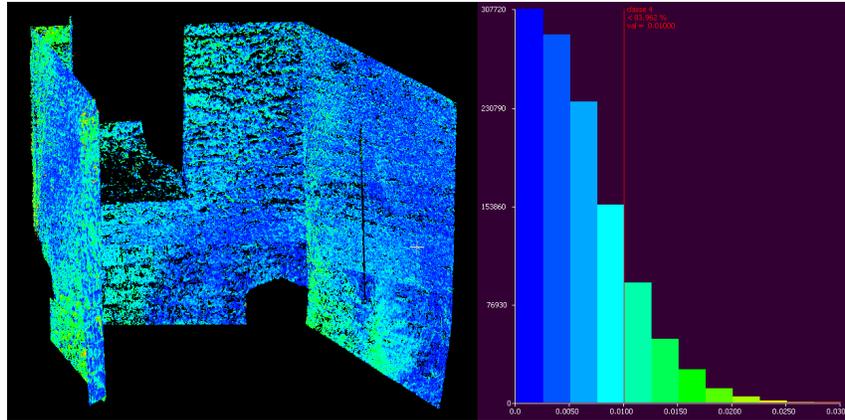


Figure 11. Comparison of TLS and photogrammetric point clouds

In dark blue, the points whose distance between the two clouds is less than 5 mm; In light blue, distances prior to 1 cm

After registration of the DStM point cloud onto the TLS one, we observe that 80 % of the points have a distance shift inferior to the centimeter as shown on figure 11. This error distribution is fully consistent with the accuracy of the TLS.

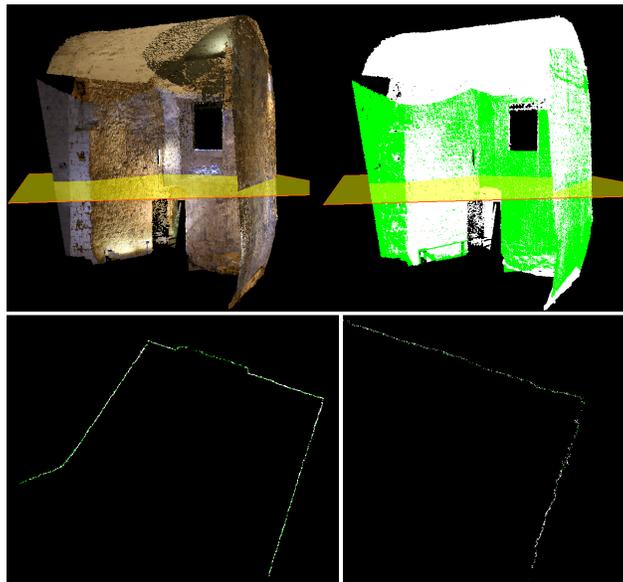


Figure 12. Point clouds of the "Hall of sources" (TLS in white and DStM in green) and horizontal sections showing correct distribution of the corresponding TLS and DStM points.

There is no systematic error in the distribution of the distance shifts observed on the sections of figure 12. This visual control reinforces again the result of the registration step. One may wonder why the TLS cloud has been chosen as the reference for the registration step since at first sight, the DStM cloud be more precise (subcentimetric accuracy down to 3 mm). However, the TLS cloud is spread on the entire archaeological site and the DStM point cloud is supposed to « plug holes » by means of local clouds. Besides the registration of the DStM together propagates errors and reduces the DStM cloud quality. Figure 13 shows the overall view of the point cloud corresponding to a subset of the interior galleries of the fortress.

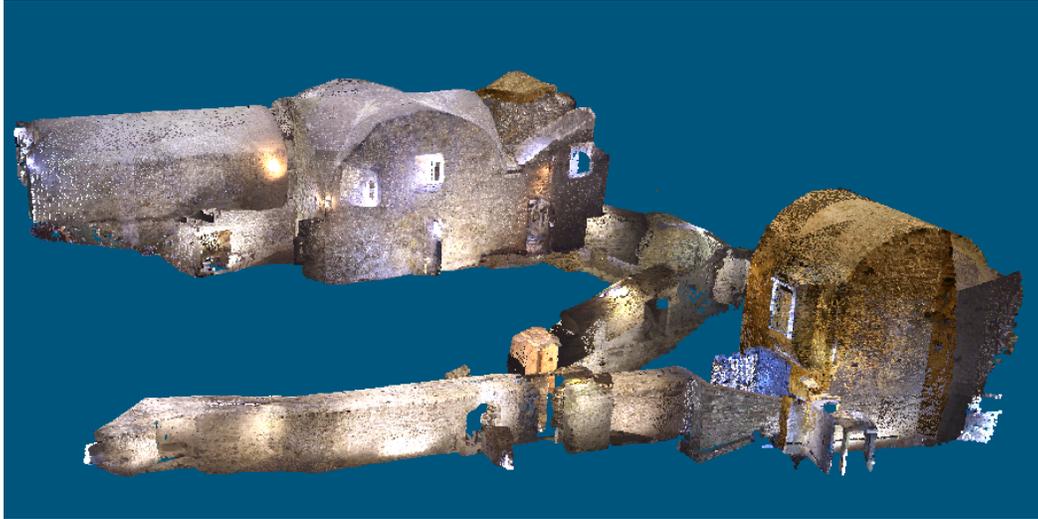


Figure 13. Point cloud resulting from the combination of the two techniques of acquisition
 TLS (light-colored) and DStM cloud (dark-colored)

6. CONCLUSION

The approach proposed in this paper has shown that point clouds from TLS and DStM can be merged for accurate documentation in cultural heritage. Both techniques can deliver dense point clouds, but require accurate registration and direct or indirect geo-referencing. Accurate network of geodetic control points well distributed on the study area is advised to ensure accuracy. Different levels of integrated TLS and photogrammetry data are therefore possible. In the two examples discussed in the paper, the TLS available was not suited for the recording of specific types of objects and areas in the projects. TLS aided by DStM finally show that a high level of integration is possible for tightly laser scanning and photogrammetry data.

REFERENCES

- [1] Al-kheder, S., Al-shawabkeh, Y., Haala, N., "Developing a documentation system for desert palaces in Jordan using 3D laser scanning and digital photogrammetry", *Journal of Archaeological Science*, 36 (2), 537-546 (2009), DOI: 10.1016/j.jas.2008.10.009.
- [2] Barazzetti, L., Scaioni, M., Remondino, F., "Orientation and 3D modelling from markerless terrestrial images: combining accuracy with automation," *The Photogrammetric Record*, 25(132), 356-381 (2010), DOI: 10.1111/j.1477-9730.2010.00599.x
- [3] Dücke, B., Score, D., Reeves, J., "Multiview 3D reconstruction of the archaeological site at Weymouth from image series", *Computers & Graphics*, 35(2), 375-382 (2011), DOI: 10.1016/j.cag.2011.01.006.
- [4] El-Hakim, S.F.; Beraldin, J.-A.; Picard, M.; Godin, G., "Detailed 3D reconstruction of large-scale heritage sites with integrated techniques," *Computer Graphics and Applications IEEE*, 24(3), 21-29 (2004), DOI: 10.1109/MCG.2004.1318815
- [5] English Heritage, [3D Laser Scanning for Heritage: advice and guidance to users on laser scanning in archaeology and architecture], Product code 51326 (2007), www.english-heritage.org.uk
- [6] Guarnieria, A., Remondino, F., Vettore, A., "Digital photogrammetry and TLS data fusion applied to Cultural Heritage 3D modeling", *Int. Archives of Photogrammetry Remote Sensing and Spatial Information Sciences*, XXXVI (5), 6 pages (2006), www.isprs.org/proceedings/XXXVI/part5/paper/1216_Dresden06.pdf
- [7] Grussenmeyer, P., Hanke, K., "Cultural Heritage Applications", Chapter in Vosselman & Maas Editors of *Airborne and Terrestrial Laser Scanning*, Whittles Publishing, 271-290 (2010).

- [8] Grussenmeyer, P., Landes, T., Alby, E., Carozza, L., “High Resolution 3D Recording and Modelling of the Bronze Age Cave « Les Fraux » in Périgord (France)”, *Int. Archives of Photogrammetry Remote Sensing and Spatial Information Sciences*, XXXVIII(5), 262-267 (2010), www.isprs.org/proceedings/XXXVIII/part5/papers/221.pdf
- [9] Grussenmeyer, P., Landes, T., Voegtle, T., Ringle, K., “Comparison methods of terrestrial laser scanning, photogrammetry and tacheometry data for recording of cultural heritage buildings”, *Int. Archives of Photogrammetry Remote Sensing and Spatial Information Sciences*, XXXVII (B5), 213-218 (2008).
- [10] Hullo, J.-F., Grussenmeyer, P., Assali, P., Smigiel, E., “Dense point cloud acquisition via stereo matching applied to: the Kilwa archaeological site and the Gallo-Roman theatre of Mandeure,” *The 11th International Symposium on Virtual Reality Archaeology and Cultural Heritage VAST*, 4 pages, (2010), <http://dx.doi.org/10.2312/PE/VAST/VAST10S/067-070>
- [11] Hullo, J.-F., Grussenmeyer, P., Fares, S., “Photogrammetry and Dense Stereo Matching Approach Applied to the Documentation of the Cultural Heritage Site of Kilwa (Saudi Arabia),” *CIPA International Archives for Documentation of Cultural Heritage*, XXII, 6 pages (2009), <http://cipa.icomos.org/KYOTO.html>
- [12] Kadobayashi, R., Kochi N., Otani H., Furukawa R., “Comparison and Evaluation of Laser Scanning and Photogrammetry and their Combined Use for Digital Recording of Cultural Heritage,” *Int. Archives of Photogrammetry and Remote Sensing*, XXXV(B5), 401-407 (2004), <http://www.isprs.org/proceedings/XXXV/congress/comm5/papers/586.pdf>
- [13] Letellier, R., Schmid, W., LeBlanc, F., [Recording, Documentation, and Information Management for the Conservation of Heritage Places], Los Angeles The Getty Conservation Institute (2007), www.getty.edu/conservation/publications/pdf_publications/recordim.html
- [14] Lerma, J. L., Navarro, S., Cabrelles, M., Villaverde, V., “Terrestrial laser scanning and close range photogrammetry for 3D archaeological documentation: the Upper Palaeolithic Cave of Parpallo as a case study”, *Journal of Archaeological Science*, 37(3), 499-507 (2010), DOI: 10.1016/j.jas.2009.10.011
- [15] Lerma, J. L., Van Genechten, B., Heine, E., Quintero, M. S., [3D RiskMapping – Theory and practice on Terrestrial Laser Scanning], Editor Universidad Politecnica De Valencia, 261 pages (2008).
- [16] Patias, P., Grussenmeyer, P., Hanke, K., [Applications in Cultural Heritage Documentation], Chapter in Li Chen and Baltsavias Editors of *Advances in Photogrammetry Remote Sensing and Spatial Information Sciences ISPRS Book Series 7* Taylor & Francis Group, 363-383 (2008).
- [17] Remondino, F., Rizzi, A., “Reality-based 3D documentation of natural and cultural heritage sites: techniques, problems, and examples”, *Applied Geomatics*, 2(3), 85-100 (2010), Doi: 10.1007/s12518-010-0025-x
- [18] Rönnholm, P., Honkavaara, E., Litkey, P., Hyyppä, H. and Hyyppä, J., “Integration of laser scanning and photogrammetry,” *International Archives of Photogrammetry Remote Sensing and Spatial Information Sciences*, 36(3/W52), 355–362 (2007), http://www.isprs.org/proceedings/XXXVI/3-W52/final_papers/Ronnholm_2007_keynote.pdf
- [19] Voltolini, F., El-Hakim, S., Remondino, F., Girardi, S., Rizzi, A., Pontin, M., Gonzo, L., “Digital documentation of complex architectures by integration of multiple techniques: the case study of Valer Castle,” *Proc. SPIE*, Volume 6491, pp. 64910U, DOI: 10.1117/12.702727 (2007).
- [20] Yastikli, N. “Documentation of cultural heritage using digital photogrammetry and laser scanning”, *Journal of Cultural Heritage*, 8(4), 423-427 (2007), Doi: 10.1016/j.culher.2007.06.003.