3D SURVEY TECHNOLOGIES FOR RECONSTRUCTION, ANALYSIS AND DIAGNOSIS IN THE CONSERVATION PROCESS OF CULTURAL HERITAGE

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ABSTRACT:

The recent survey technologies, play a leading role in the process of knowledge of the cultural heritage.
In fact they are finalized to the acquisition of geometric data necessary to describe usefully geometric features and peculiarities of historical monuments necessary for their conservation and safeguard.
Besides digitalisation of the acquired data, allows the same data availability by different typologies of users in order to spread and share knowledge for cultural heritage valorisation.
Quick stereo-photogrammetric systems and laser scanner technology have advantages but also limits referring to the elaboration, management and possibilities of use.
The recent development of digital stereo-photogrammetric systems allows the definition of 3d visualization and navigation environments within which the data referring to geometric consistency is combined, without loss of rigour, with other qualitative, morphological and colour information specific to the photographic document.
The laser scanner technology likewise permits a detailed three-dimensional description of the artefacts geometry, without subjective interpretation from the operators. Therefore laser scanner opens up extremely interesting horizons to possible geometry analyses or to evaluations of monuments state of conservation and static conditions.
The necessity to compare these different survey technologies becomes fundamental to verify the accuracy of acquired numeric data, to evaluate their possible integration and to define different protocols of use in relation to the artefacts morphological-architectural characteristics and to the survey finalities.
The critical aspects of the described topic will be proposed through the analysis of a specific study case: the documentation of the roman triumphal arch of Augustus in Aosta.

1. INTRODUCTION

Geometric survey represents the first step in the process of analysis and diagnosis of architectural monument state of conservation and it allows to define a geometric basis to which relate every other further information, deriving from diversified disciplinary field, so that to achieve an historical-architectural *integrated knowledge* of the monument.
Therefore geometric survey can be considered a fundamental stage for every programmed activity of cultural heritage safeguard and damage prevention.
In this frame, the use of modern survey technologies, like stereoscopic photogrammetric systems and 3D laser scanner technology, allows to obtain an objective, discrete and rigorous representation of the artefact, in order to determine a global documentation (Guarnieri et al., 2004), especially important in the case of archaeological monuments that have complex geometry or irregular shape (Salonia et al., 2006).
The present article describes and compares the two different above-mentioned survey technologies (quick stereoscopic photogrammetric systems and 3D laser scanner technology), used for the 3D geometric documentation of the roman triumphal arch of Augustus in the city of Aosta, within a joint research project carried out by CNR Institute for Technology Applied to Cultural Heritage (CNR-ITABC) and the Superintendence for Cultural and Environmental Heritage of the Valle d'Aosta.
The Valle d'Aosta Autonomous Region (RAVA) determined to direct one's intervention policy, for cultural heritage conservation, towards *preventive programmed maintenance*, based on the constant monitoring of risk situations and the management of systematic conservation interventions. To this purpose the Superintendence needed a precise scientific geometric documentation necessary to help the process of decay condition and possible static damages diagnosis, and to precisely refer to the monument geometry all the data acquired during the monitoring activities and the analyses relevant to materials alteration and decay.
The necessity of this scientifically reliable documentation, sufficiently detailed from the point of view of geometry and colour information, has led to choose a multimodal approach for the survey activities, based on the experimentation and the integration of the two different survey technologies, so as to guarantee the 3D monument representation, both raster and vectorial, with the best optimization of acquisition and processing time. Therefore this research project furnished an important occasion to analyze differences, advantages and limits of these 3D survey technologies.

1.1 Study case description

The imposing roman triumphal arch of Augustus, build in the 25 a.C., is one of the most important architectural testimony of the Augustan period in Valle d’Aosta.
The monument is situated in the east edge of Aosta city and is aligned with the axis between the antique roman bridge, situated nearby the *Buthier* course, and the *Porta Praetoria,* the east access of the walled town.
The arch of Augustus was build as a tribute to the emperor Augustus and also to honour and celebrate the military victory of the roman troop, on whose guide was the second lieutenant of Augustus, Aulo Terenzio Varrone, over the

Salassi tribe that occupied the Valle D'Aosta since the II century a.C (Corni, 1989).
The honorary arch, with only one fornix, is totally 17.5 metres high and 11.5 metres height, till the circular vault.
The arch, build with pudding-ashlars, is a mixture of Doric and Corinthian order.

Figure 1. The roman triumphal arch of Augustus in Aosta

In fact the four half columns that adorn the facades and the three half columns on the sides have Corinthian capitals and support a Doric trabeation formed by metopes and triglyfs.
The attic (penthouse) was replaced in 1716 with a slate four pitches roof as a protection from the seepage of water, that, in 1912, was later renewed during consolidation activities.
In 1449 the fourteen century wooden Crucified, named *Saint Voult,* was located under the vault of the arch as a votive offer in order to avoid in that period the frequently inundations of the torrent *Buthier*, whose tumultuous water covered most of the ancient roman traces of Aosta city.

2. METHODOLOGY AND TECHNIQUES USED

The recent technologies used for the survey of the arch of Augustus in Aosta is a quick non-conventional stereo-photogrammetric system and the 3D laser scanner technology. Both technologies have been supported by the same topographical acquisition in order to verify the reliability and the precision of the results obtained, but also to insert the monument in his environmental landscape.

2.1 Quick stereoscopic photogrammetric system

Concerning the stereophotogrammetric survey, the adopted system is *CyclopII* produced by *Menci Software.*
It consists on a digital calibrated photographic camera applied to a sleigh bound that flows on a rectilinear special steel guide mounted on an aluminium bar which is positioned on a common topographical tripod (Menci, 2000).
For the realization of the stereoscopic pair it is fundamental to determine the optimal distance from the object and between the two shots, depending on the characteristics of the study case, on the precision and the detail to obtain and on the objective of the camera used.
Considering the use of a single photocamera, the system has many advantages, as cheapness, accuracy (a single calibration), constructive homogeneity (same response to colour and same defectology in general).

Moreover, the system does not require topographical support in order to obtain single stereoscopic models; the topographic acquisition is nevertheless necessary for linking different stereoscopic models and in order to georeference the final stereoscopic strips.

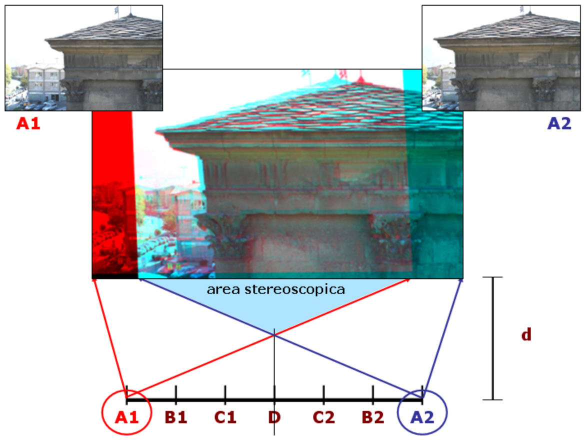

Figure 2. Scheme of the acquisition with the stereophotogrammetric system *Cyclop II* produced by *Menci Software*

2.2 Laser scanner technology

Concerning the 3D laser scanner survey, a Leica HDS2500 laser scanner (former Cyrax 2500) has been used. It is a *time of flight* laser scanner, able to scan objects up to 100 metres with a single point accuracy of 6 millimetres. The acquisition distance can be changed from 1.5 to 100 metres, but the maximum recommended range is 50 metres (Johansson, 2002).
A laptop computer, in which is installed a Cyclone software of Cyrax Technologies, connected to the system, controls the scanner functionality.
Cyclone software allows the acquisition, the registration and the alignment of single points clouds, captured from the different scanner position, and necessary for the complete coverage of the different faces of the monument.
A punctual three-dimensional survey, allowed to take the x-y-z spatial coordinates of numerous points of the monument surfaces, whose reciprocal distance can be chosen in relation to the needed survey precision and detail representation.

3. THE SURVEY ACTIVITIES

The survey activities, necessary for the complete three-dimensional documentation of the roman triumphal arch, provided different specific operating phases for both the described technologies, photogrammetry and laser scanner.
These phases can be mainly subdivided in data acquisition and data processing and are deeply described in the following paragraphs.
They have both presented a great number of operative difficulties: first the acquisition phase, because of the monument position in an urbanized landscape that led many interferences to the survey activities; second the processing phase, because of the artefact morphological configuration that made really complex a truthful and detailed geometric reconstruction, in particular of the decorative elements without a definite geometry and regular edges, even more compromised by the biological and chemical-physical decay.

3.1. Data acquisition

After the execution of detailed preliminary inspections, data acquisition has been planned in such a way as to perform at the same time the stereoscopic coverage and the laser scanner acquisition of the monument, making use of an unique common topographic framing.
The stero-photogrammetric survey has involved a working group composed of three operators: two architects for acquiring the photographic documentation and for taking notes of all the data necessary to perform the next processing phase; a qualified technician for developing support activities and for operating the temporary elevator used during the photogrammetric data acquisition. The use of the elevator was indeed important because of the monument height, in order to realize a stereo-photogrammetric coverage of the artefact with a catch axis perfectly orthogonal to the external façades; besides this possibility of working at different altitude reduced work interferences due to the urban monument position.
High-resolution digital images have been captured by the use of *Cyclope II* stereo-photogrammetric system, fitted with a calibrated Nikon D-100 digital camera (CCD sensor of 6.1 mega pixel, 24mm lens used).
The complete stereo-photogrammetric coverage of each front has been performed, proceeding with the acquisition of several horizontally and vertically overlapping models with at least a stereo-pairs side overlap of 30%*.
Every main front was surveyed with a total number of about 12 models, changing four different photographic station and adopting, for each of them, four different elevator vertical position. On the contrary every minor front required a lower number of models, about 8 models, with the use of only two different photographic station and four different elevator vertical position. Finally, for the survey of the internal triumphal arch surfaces, a great number of models were realized, about 24 models, in order to provide also the complete vault documentation; to this end some shots for the vault stereoscopic coverage have to be realized with a catch axis inclined towards the top, paying attention to adopt a rotation angle, respect to the vertical, of not more than 15°, in order minimize photographic deformations.
In the aggregate 64 stereo-models have been captured in four working days (corresponding to 32 working hours).
The distance of the shooting stations from the object ranged between 7 and 8 metres according to the geometry of the monument and the photogram scale ratio needed.
As regards laser scanner acquisition, the monument position in the centre of a big square, frequently characterized by traffic congestion, necessarily required to perform part of the survey activities during the night hours, so that every external interferences could be easily avoided.
Therefore, in order to reduce the time necessary for the equipment moving, the work group was composed by two operators even if usually only one operator is able to use the instrumentation and to perform laser scanner acquisition by himself. The operative activities are indeed minimized: the expert user has to simply direct the scanner towards the scene, to define the area of the scene that he wants to scan and the resolution for scanning on the laptop computer, connected to the system, and to start the acquisition.
In this case, according to the survey precision and the representation detail needed, point clouds have been acquired with a spatial resolution of 1 cm; however some detailed scans of significant architectural or decorative elements, as for example the Corinthian capitals, were realized, adopting a point to point spacing of 6 mm.

Figure 3. Part of the laser scanner acquisition performed during the night

For the whole laser scanner survey of the monument 19 scans have been performed in two working days (corresponding to 16 working hours): 12 global scans, acquired from a distance to the object variable between 20 and 25 metres; 7 particular scans, acquired from a distance of about 8 metres, in order to complete the hidden surfaces acquisition of the triumphal arch footing that, from a distance to the object of about 20-25 metres, have been occluded by the slight slope of the ground.
Both the stero-photogrammetric and the laser scanner surveys have been supported by topographic survey**.
The acquisition of the space coordinates of significant support points, performed through the use of a total laser station, was indeed necessary to carry out all the next processing phases: either to link different stereoscopic models together, or to align and globally register single points clouds or, finally, to produce orthorectified images for the geometric models texture. To this end particular attention was devoted in the choice of the topographic points, so that they would be suited both to photogrammetry and laser scanner restitution, in order to improve the accuracy of the results integration and to achieve a better overlap between geometric and photographic documentation.
The stero-photogrammetric survey made the support point topographic acquisition particularly onerous, in term of working times and thus of cost, since for each pair of photograms a minimum of three known coordinate points, shared with the preceding stereo-model, must be surveyed in order to perform the next restitution (a total number of 180 topographic support point were acquired). Only a few of these topographic support point have been also used for the generation of the final laser scanner based 3D model.
In order to avoid any possible interference with the surfaces geometry acquisition, significant natural architectural points were chosen as support points, instead of using traditional topographic targets; detailed scan of these points were carried out during laser scanner acquisition, so as to make easier and more precise their identification in the final points clouds.
Contextually to this support points topographic acquisition also the monument planimetric survey has been performed. A system of local polygonals, linked to the main datum points of the topographic network of the city, has been created

* The quick stereo-photogrammetric system used allows to reduce the overlapping value between individual stereo-pairs, typical for conventional stereophotogrammetry, consisting of 55 - 65% overlap.

** All the necessary topographic survey activities were realized by Mario Mascellani of ITABC - CNR.

during the topographic survey, such as to acquire coordinates of some ground control points too, necessary for having the possibility of geo-referencing the final 3D model.
The triumphal arch of Augustus 3D geometric survey, carried out by the combination of photogrammetry and laser scanner technologies, has led to make a few useful remarks about differences, limits and opportunities offered by these two measurement techniques.
As regards the operative phase of data acquisition the application of laser scanner technology allows to obtain some advantages in term of working times and costs since it requires less human and instrumentals resources than photogrammetry. A single operator can acquire millions of points x-y-z spatial coordinates in a very short time. Moreover the topographic survey operations are minimized: only few known coordinate points are necessary for geo-referencing the global points cloud since the registration of the single scans can be performed through the use of special Leica targets that can be automatically recognized by the instrument during the point clouds acquisition[*].
Nevertheless if detailed materials colour information are necessary, for example in order to texture the final 3D architectural model, the laser scanner acquisition has to be anyhow supported by a photographic survey[**]; on the contrary photogrammetric acquisition allows to achieve, at the same time, a complete geometric and colorimetric documentation of the monument.

3.2. Data processing and treatment

The photogrammetry elaboration phase consisted in loading the single digital images acquired, into an ad hoc software, *Cyclop II* of Menci Software, which allows to create immediately the single stereoscopic couples in order to obtain three-dimensional management (control, measurement, etc.).
The use of topographic control points in a dedicated software, *Stereo View* of Menci Software, allows to link together the stereoscopic couples in order to explore the single faces of the monument without interruption: using a specific module of the same software (*SV Plotter*) it is indeed possible to navigate the metric raster stereoscopic strips, in a stereoscopic environment, so as to perform three-dimensional measures and conservation status analyses (Menci et al., 1999).
The raster strips own such a notable quantity and variety of information deriving from the geometrically controlled stereoscopic pairs, that the vectorial phase, which often represents a subjective abstraction from the truth, can be superfluous.
The creation of all stereoscopic couples of the triumphal arch, globally 64 models, has been performed in a very short time considering the rapidity and use facility of the adopted software.
Moreover the linkage of the single models employed more time, totally fourteen days, because of the necessity to recognize the acquired topographic and natural points on the images of the single stereoscopic couples.
The topographical points were also adopted to produce monoscopic orthorectified images required by the Superintendence as a basis for the decay mapping but also for geometric model texture.

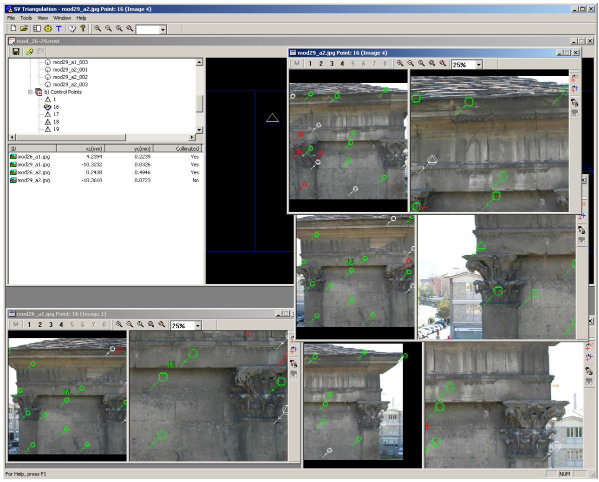

Figure 4. Union of different stereoscopic models through the collimation of topographic control points

As regards laser scanner elaboration phase the different types of point clouds processing (decimation, meshing process, 3D modelling, etc.) were critically chosen according to the kind of analyses carried out and to the final pursued aim.
The result of the laser scanner acquisition was a global points cloud of about 30 millions of points.

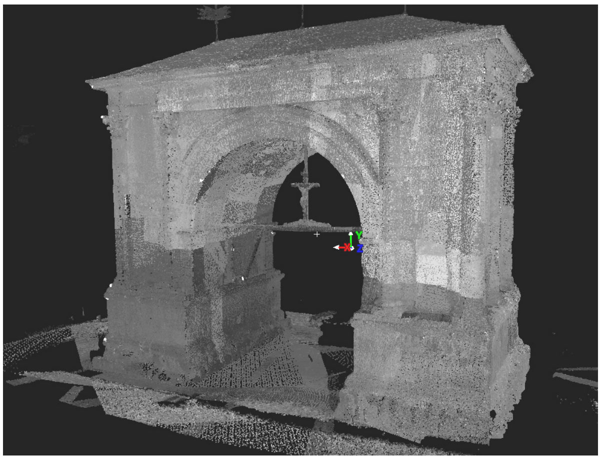

Figure 5. The final points cloud before the meshing of the arch

Post processing data has been carried out with the standard software for 3D scanners Rapidform XoV^{Tm} of INUS technology, Inc.
The dataset obtained in a non selective way, in which irrelevant information is mixed with proper one, has been managed in a several station procedure so to adjust data clouds and control errors propagation mainly in the orientation phase.
Depuration of the point cloud has been the first step of data processing. Spatial filters has been applied to eliminate overlapped areas and to erase noisy information. Manual segmentations were also applied to eliminate those features not eliminated automatically by the software so to obtain the reduction of the point cloud of about 2.000.000 of points.

[*] During the triumphal arch laser scanner survey no special Leica targets were used; then, for each pair of scans, three common known coordinate points were acquired. The total topographic support points number needed is anyhow lower than that one needed for photogrammetry, since the number of laser scanner scans is lower than the number of stereoscopic models required for the complete coverage of the monument.
[**] This problem can nowadays easily overcome by the use of a new type of laser scanner that are provided with an high-resolution calibrated digital camera so as to simultaneously acquire x-y-z spatial coordinates and RGB value of every single points.

The semiautomatic registration of the multiple clouds based on the closest point ICP algorithm, since the Superintendence for Cultural and Environmental Heritage prohibited the use of retro reflective targets as tie point for the cloud merging, provided a residual error of 3.2 mm, obtained as RMS of the standard deviations of the image pair alignments.
To improve laser scanner point cloud registration digital images have been used to extract information on edges and linear surface features.
Once obtained the global georeferenced cloud dataset we proceeded trough out the reconstruction of the polygonal 3D digital model to provide a basis for generating drawn Cad elevations, section and plans of the arch.

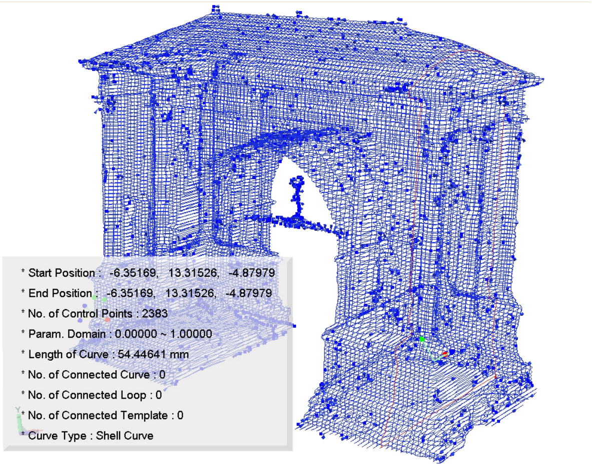

Figure 6. Automatic generation of horizontal and vertical sections from the 3D model

A multiple resolution TIN, from a 1.000.000 up to a total of 20.340.000 polygons, was obtained through the meshing automatic process of the INUS software.
In order to generate a complete model of the arch some editing of the TIN was required, as detecting and fixing topological or geometrical defects and unnecessary data. The scan workbench of the software provided indispensable functions for processing raw scanned data and building up the whole polygonal model.
A high number of triangles is preserved even in presence of flat areas so to be able to highlight differences between different material, identify different phases of repair or use the resulting TIN in several types of analysis as detection and monitoring of cracks or documentation of tool marks on specific areas of the arch itself.
Trough the analysis of the morphology of the model it is possible to quantify weathering process and determine the different weathering rates of each part of the arch.
A high quality TIN despite difficulties in handling the large volumes of three-dimensional dataset permits to measure fractures orientation, physical weathering such as microcracking and disintegration of exposed irregular and rough surfaces of ashlars or even chemical ones such as dissolution of component mineral grains. The loss in volume can be assessed quantitatively by the measurement of the single ashlar volume loss in the model (Accardo et al. 1997).
Using digital surface high detailed model of the arch has the advantage to be able to measure the deformed shape by comparing with digital surface model generated at later time.
Laser scanning has been very useful for direct scanning of the irregular and rough surface of ashlar of the basement which has been well reconstructed.

Figure 7. 3D model of the basement of the Augustus arch

Some problems seems to be due to reflection on specific surfaces located on the columns capitals. There could in fact be potential problems in data acquisition in laser scanning surfaces of certain minerals such as of granite, marble or limestone.
A low resolution TIN has been also build so to have the base for a textured model.

Figure 8. Comparison between the original and the compressed version of the 3D model

Normal mapping was used to re-detail simplified meshes.
Normal mapping adds details to shading without using more polygons and one of the most interesting use of this technique is to greatly enhance the appearance of the low poly model exploiting a normal map coming from the high resolution one.
An algorithm for the automatic generation of this map is coupled with the vertex removal mesh compression method. It requires that, during the geometric compression, the algorithm keep track of where each removed vertex projects on the compressed version of the model. When the desired level of compression is reached, the original vertices are transposed into the associated triangle in a tessellated map.
The high resolution model with his more than 20 millions of shape information in a 2 Gb file represents the archival quality model used for research application and to prepare lower resolution models suitable for interactive web display. When the texture maps are applied to the compressed models, it generates a 3D appearance that approximates the one of the full resolution model. Thus a close approximation to the fidelity of the high resolution model is retained in the 3D model used for museum visualization as well as web application.

4. CONCLUSIONS

Both the two survey technologies described offer several advantages but also disadvantages, and only their combination can allow to efficiently achieve an historical-architectural building 3D documentation, detailed either from a geometric and from a colour information point of view.

On the one hand the stereo-photogrammetric survey allowed to produce, in a relatively short time, 3D raster models, metrically correct, in which morphological details, architectural materials and colorimetric definitions are easily singled out, so as to help chemical and technician experts in the description of the different monument phenomenology of materials alteration and decay. The stereoscopic survey can be indeed considered, without any vectorial restitution, as a representation of the artefact state of conservation in a specific time, on which the expert user can perform analysis, reports of the decay pathologies, hypothesis in order to program restoration interventions (Salonia et al., 2005).

On the other hand the use of laser scanner technology allowed to efficiently provide the Superintendence for Cultural and Environmental Heritage of the Valle d'Aosta with a complete 3D model of the arch from which it was possible to quickly and automatically extrapolate geometric elaborations of the monument (as for example horizontal and vertical sections), necessary for searching into the presence of monument static damages.

On the same 3D model it was possible to report the exact position of the several sensor that were arranged on the monument in order to estimate the variation of climatic conditions around artefact surfaces.

Referring to the same geometry all the other data relevant to the monument state of conservation, the analysis of the complex relationship between materials and different alteration phenomenology would be facilitated, as well as the analysis of decay pathologies variability in relation to their manifestation in the artefact or to the influence of the environmental context.

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