THREE FOCAL PHOTOGRAMMETRY APPLICATION FOR MULTI-SCALE AND MULTI-LEVEL CULTURAL HERITAGE SURVEY, DOCUMENTATION AND 3D RECONSTRUCTION

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ABSTRACT:

Survey technologies play a leading role in Cultural Heritage knowledge and so far they have been finalized to the acquisition of data for describing geometric features and peculiarities of historical monuments with the purpose of conservation and safeguard. Moreover the demand for 3D models of historical monuments is continuously growing in the field of archaeological and architectural applications. The two main sources that can provide detailed and reliable 3D surface models are Terrestrial Laser Scanner through laser scanning techniques, and photogrammetry through image-based modelling. Among the many works so far presented, the use of laser scanner for Cultural Heritage survey seems to gain a monopoly position in the 3D modelling pipeline. This technology permits a detailed 3D description of the artefacts geometry, without subjective interpretation. Nevertheless, some related geometric issues still remain unsolved and thus a great amount of post processing work is required to obtain final results. Recently, on the other hand, development of digital photogrammetric systems allow to define 3D visualization and navigation environments; data referring to geometric consistency are combined, without loss of rigor, to other qualitative, morphological and colour information. This paper aims to present how wide can be the application range of quick three focal photogrammetric system finalized to the digital scanning of high quality images, within the context of Cultural Heritage artefact surveying at different scales and for different purposes.

1. INTRODUCTION

Cultural Heritage documentation is leading the development and the adoption of tools and methodologies capable of creating interactive 3D representations with far greater informational content, visual richness, scientific reliability, and long-term sustainability (Beraldin et al., 2005).
This paper describes the methodology adopted and the results obtained experimenting a new comparatively low cost technology, entirely based on digital scanning of high quality images through the application of photogrammetric principles.
A presentation of several operative experiences is the occasion for formulating reflections on its multi-scalar nature.
Digital scanning allows to achieve a scientifically reliable documentation, enough detailed as far as geometry and color information are concerned. It permits to obtain RGB point clouds and geometries at different levels of complexity, simply starting from processing a number of images taken with a calibrated digital camera (with a limited set of constraints and using a special acquisition equipment) through an image matching algorithm.
The high quality results achieved in digitization and 3D model reconstruction of both architectural environment and historical artifact, ranging from macro to micro scale, allows to consider this technology as a valid alternative to laser scanner, that is more affected by the scale of the artefact in terms of LOD and requires shifting from the time of flight sensor to the optical one in the context of multi-scale surveys.
The occasion to analyze advantages and limits of this new survey technology was represented by several research projects, aimed to produce a rich 3D documentation regarding important historical artefacts in the Valle d'Aosta region (N-W Italy). Projects were sponsored by the local Public Administration, represented by the Superintendence for Cultural and Environmental Heritage of Valle d'Aosta bureau, which was determined to create a digital archive with a scientific, reliable, and accurate range of measurement for the involved artefacts, not only as a tool for analyzing decay conditions or historical-critical investigations, but also for valorisation and fruition purposes.

2. PRELIMINARY REMARKS

2.1 The study cases

Four study cases are taken into consideration, all in the above mentioned Valle d'Aosta area (city and outskirts): the medieval frescos at Quart Castle, the cloister capitals of St. Orso Church, the ancient Roman bronze belt "Balteus", and the frescoes of St. Maxim Church (near Verrès), all carried out by the Institute for Technologies Applied to Cultural Heritage of the National Research Council and by the Superintendence bureau.

Medieval Quart Castle near Aosta (Figure 1) is formed by a set of buildings arranged within a fortified perimeter, adapting to the natural contour of a difficult rocky slope. Medieval frescoes surveyed decorate the internal walls of the *donjon*, and actually they are being restored with laser based cleaning techniques by Anna Brunetto (Vicenza), under direction of the Superintendence of Valle d'Aosta region.

The medieval cloister of St. Orso (1133) in Aosta (Figure 2), with its 37 outstanding marble engraved capitals, is a unique example of this genre. The capitals complex geometry is characterized by decorative figures in high-relief representing several scenes from the Old Testament or from episodes of the life of St. Orso.

The 2nd century ancient Roman bronze belt "Balteus" (Figure 3) was found in Aosta during 1953 excavations (Carducci - Finocchi, 1953). The belt presents a lower maximum diameter of 43 cm, an higher maximum diameter of 32 cm, a width of 10.8/18 cm, and at last an height of 20.7 cm. Its morphology is very complex, being featured by bronze figures in high relief over a semicircular bronze background belt, with deep shadows (Salonia et al., 2008).

The medieval St. Maxim Church (XII century) near Verrès is a small single nave church with frescos covering the apse and the triumph arch before (Figure 4). The church needs a repair intervention, and a restoration project based on the exact apse structural shape survey, along with a contextual documentation on frescoes detachments.

Figure 1. Detail of Quart castle's fresco

Figure 2. St. Orso medieval cloister

Figure 3. Ancient Roman bronze belt "Balteus"

Figure 4. St. Maxim church: fresco painted apse

2.2 Guidelines

These projects were aimed to achieve a complete documentation of the artefacts, through the reconstruction of detailed 3D digital models that could be interactively explored within suitable environments in order to allow interdisciplinary analysis. Such provided documentation was intended as a research tool for conservators, archaeologists and researchers, with the purpose of increasing historical-artistic knowledge, allowing the assessment of the state of conservation and identifying the necessary restoration interventions. Balteus case study was also a unique occasion to provide a tool for valorisation and fruition of archaeological artefacts.

The survey results had to fulfil some specific qualifications:

- provide detailed metrical and morphological information, with particular reference to construction peculiarities, in order to allow stylistic investigations or physical and analysis of structural pathologies;
- provide qualitative information through the detailed recording of actual colour values, in order to identify alterations due to a number of possible causes (chemical-physical events, human interventions, weather influence, etc);
- assure a reliable geometry documentation with extended levels of precision and accuracy (paramount in study case of St. Orso capitals and Balteus) in order to allow the replacement of original artifacts with solid prototyping copies, in case of damage or conservation necessities;
- share in the experimentation of new documentation methodologies based on digital surveying techniques;
- test the operative limits of these techniques.

All these aspects led to the decision of adopting an unconventional, low cost technology that, even if at an experimental level, would guarantee that the two main aspects of geometry and colour information would be provided by just one single equipment, with the best possible optimization of acquisition and processing time, and without neglecting the precision and quality needed for the survey. An innovative comparatively low cost technology entirely based on digital scanning of multi-view high quality images sequences, through the application of photogrammetric principles, was experimented; it allows image capture and RGB point cloud extraction from image pixels, thanks to a specific algorithm for image processing and feature matching. Compared to other range-based techniques, even more expensive, such as laser scanner based on optical triangulation, this technology makes possible to optimize acquisition time and data consistency, because both geometrical and colour information are captured simultaneously and within millimetric accuracy. Moreover, because geometrical and colour information are consistent, also post processing times are reduced.

Accuracy, consistency, reduced post processing times, and low cost equipment also offer to small Public Administrations or local museums the opportunity of planning documentation, conservation and exploitation activities of their own Cultural Heritage. Activities otherwise not always possible employing more traditional techniques. Quite often, economic inadequacies compel local authorities engaged in preservation of Cultural Heritage to destine the most part of their financial resources to face urgent restoration interventions, thus neglecting documentation, study and valorisation of the artefacts, which raises ethical issues about the responsibilities involved in Cultural Heritage knowledge.

3. METHODOLOGY AND TECHNIQUES

The photogrammetry-based survey technology adopted was ZScan survey system (manufactured by Menci Software, Arezzo): it provides RGB point clouds and related 3D models at different levels of complexity, matching together 3 different high definition digital images through a specific algorithm for each 3D model obtained. This is a multi-scalar system because it handles objects in a wide range of sizes. For land-size survey 3 digital synchronized cameras are mounted on a bar 3 meters long (circa), bent under an aerostatic balloon. For artefact-size survey, considering a distance from the object in the range between 15 and 0,7 m, only one digital camera mounted on a 1 m bar with a tripod is required (Figure 5). In this case to obtain the 3 images it is necessary to slide the camera along the bar properly. Accuracy of the final 3D model is less than 1 mm. For small artefacts (up to 4x4 cm) or very detailed survey, a special 30 cm micrometric bar is required and a digital camera with macro lenses. The camera slides along the micrometric bar by means of an electric device. The distance from the object is less than 30 cm and the accuracy of the final 3D model is less than 1µ.

The 3 images must be be taken from the left to the right of the object, the left and the right being symmetric compared to the middle one, taken from the centre of the bar. The distance between the left and right image (“baseline”) must be carefully evaluated considering the optimal distance of the camera/s from the object, the survey accuracy and the level of detail required. Each sequence of 3 images (“triplet”) produces a single point cloud which represents a section of the final 3D model. There is no need for topographical support points even if they might be useful in registering all the single cloud points to obtain the final 3D model. The bar, the camera/s and the lens must be calibrated in a UNI certified laboratory.

Figure 5. ZScan System used for data acquisition, with 0,90 m calibrated bar for camera sliding

ZScan survey system consists of 2 specific programs: ZScan and ZMap. The first one is necessary for extracting from each triplet captured a single point cloud that contains both spatial and colour information, i.e. xyz co-ordinates and RGB values for colour rendering. After chromatic equalization of the triplet, it is sent to the program along with the relevant acquisition parameters (the baseline adopted and the calibration file of the lens used). ZScan procedure for RGB point cloud extraction consists of 4 main steps: images rectification, through the application of trinocular rectification and feature matching (to eliminate geometrical and optical distortions); selection of the image areas of interest (AOI) that must be processed; definition of the step resolution value, measured in pixel unit; production of a point cloud through the application of a specific algorithm. Moreover, the software allows to automatically create a texturized triangulated surface, through a triangulation process of the point cloud. After each point cloud is produced by ZScan, ZMap allows their registration in order to obtain the final complete 3D model.

The system satisfies characteristics of great flexibility and ease of use, and guarantees at the same time accuracy of the geometric data and colour information acquired. However, some application limits were detected. Colour homogeneity, repetitive patterns, reflective surfaces and high relief features (specially with deep shadows) can seriously affect the overall data processing.

4. SURVEY EXPERIENCES

The frescoes at Quart Castle were surveyed in two steps: from a distance of 1-2 m with a 24 mm calibrated lens with the 1 m bar for full coverage of the walls (a *10.2 megapixel CCD* digital camera). With a 80 mm calibrated macro lens (a *15.0 megapixel CCD* digital camera) within a distance of 24-30 cm from the painted wall to obtain 3,8 X 5 cm areas (Figure 6) at a very high LOD (780.000 points), using the micrometric bar, for close survey of the frescoes surface. The aim was to document the wall before and after the surface *descialbo* intervention (Figure 7, 7a, 7b) and to evaluate the quantity of “material” removed by comparing elevation values of correlated points before and after the restoration intervention (DEM).

It was possible to reconstruct all the frescoes through the single area merging, or geo-referencing small areas to bigger wall portions, highlighting at the same time the wall curvature

(Figure 8), alteration, degradation and surfaces/fresco detachments (Figure 9).
The 3D RGB point cloud recording gives the position, the shape, the form and the exact dimensions of the whole and the parts of the frescoes, documenting, at the same time, a number of architectural and artistic information for conservation and protection purposes. The actual status of the frescoes then can be periodically verified and recorded, along with the pathology and the probable causes of possible future decays.

Figure 6. Quart 3D fresco and detail at different LOD

The 3D reconstruction was also useful to analyze the complex relationships between materials and different alteration phenomenologies, as well as to quantify decay pathologies variability in relation to the influence of the environmental context (Salonia et al., 2007).

Figure 7. Before and after *descialbo* intervention.

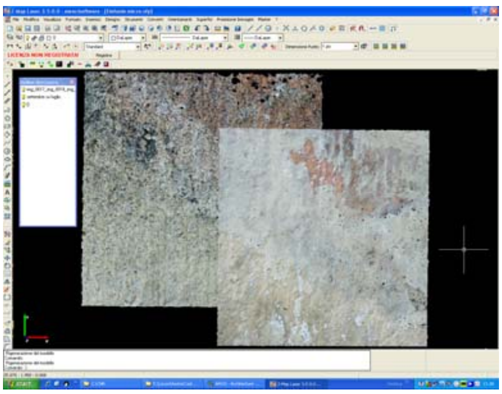

Figure 7a. 3D *descialbo* intervention detail and analysis

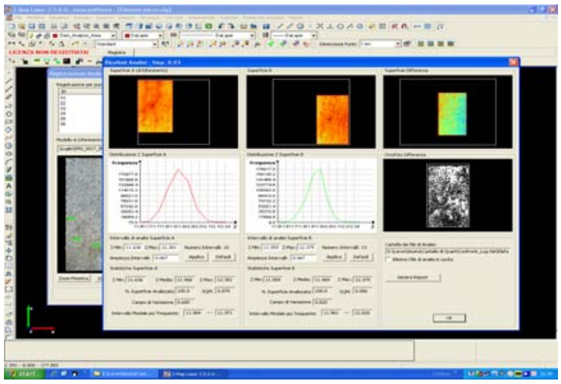

Figure 7b. Comparison and quantification of elevation values of correlated points before and after *descialbo* intervention

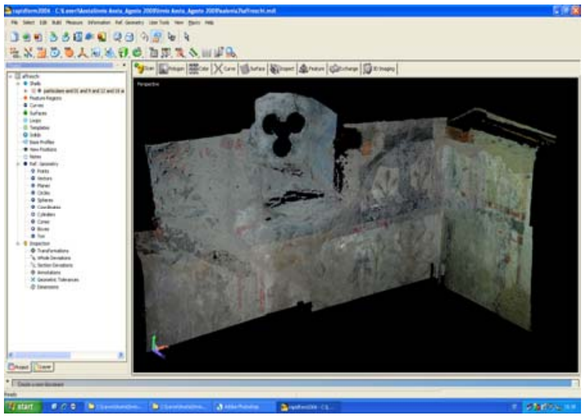

Figure 8. Merged singles frescos, giving the wall geometry with more than 10 million 3D RGB points

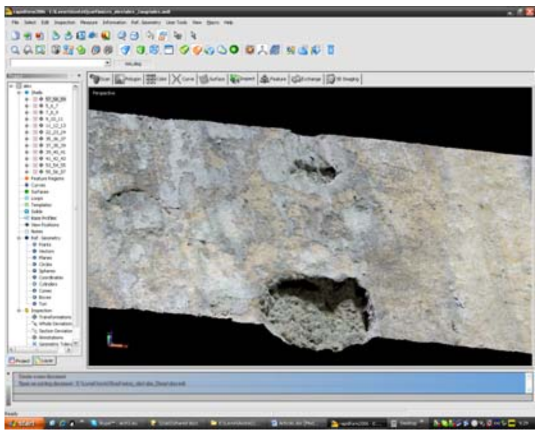

Figure 9. 3D point cloud, of about 780.000 points, giving a fresco degradation detail

Survey of the capitals of St. Orso cloister represented a chance to enlighten some critical aspects of the application of ZScan system. Capitals represent a challenging task for 3D photorealistic modelling, given their complexity both from a geometric and colorimetric point of view: the presence of recesses and partially occluded surfaces makes hard to complete the reconstruction of their shape. Both dark patina on capital surface and high light contrast between the cloister galleries and the small square courtyard, hinder the homogenous photographic capture of the triplets necessary for the output of a realistic 3D model texture.

For each capital 24 sequences of triplets had to be taken for full coverage (a *10.2 megapixel CCD* digital camera, 24 mm calibrated lens): 8 triplets with the lens orthogonal to the surface (1 triplet for each face and 1 for each angle). Another series of 8 triplets keeping the lens at an angle of + 15° and -15° with respect to the axis orthogonal to the surface, for undercuts coverage. An overlap of about 30% between subsequent triplets was adopted in order to allow the global registration of the single point clouds obtained from ZScan.
In order to obtain a high survey precision and a high representation detail, the shots were taken with a camera distance of only 70 cm from the capitals, with a baseline of only 10 cm; this configuration allows to achieve a theoretical depth accuracy of approximately 0.4 mm.
According to the research aim, a final global 3D model of each capital was provided. Each 3D digital model (Figure 11) can be interactively explored through the use of an appropriate software that displays different types of model (RGB point clouds, grey shaded models, wireframe rendering, photo-realistic rendering), becoming a very useful tool for analysis, investigation, and scientific control.

Figure 10. Different types of 3D model visualization: RGB point cloud (top and bottom left); photo-realistic (top right) and grey shaded models (bottom right)

Survey on "Balteus" was an occasion to experiment this technology at the very edge of its limits, as the artefact has a reflective bronze surface and the figures of the fight scene are developed over the belt in high relief. For a complete coverage, more than 600 high resolution pictures were taken, in one and a half days of work, with a Nikon D-200 digital camera (*CCD sensor of 10.2 megapixel*, 35 mm and 24 mm calibrated lens used). Shots were taken with a camera on the 1 m bar, at a distance of only 70 cm from the artefact, with natural and artificial light, with a subsequent baseline of 10 cm, as this configuration allows to achieve a theoretical depth accuracy of approximately 0.5 mm (Salonia et al., 2008). After the equalization phase, only the pictures taken in artificial light were used for best results. Due to the extreme complexity of the belt structure and the homogeneity of bronze surface, a step resolution of 1 pixel was adopted (meaning a 0.13 mm point to point sample spacing on the output point cloud) to facilitate the final registration of the partial point clouds obtained from ZScan, because no target had to be placed on the belt during photographic capture.
The most difficult step was the registration of the 36 partial point clouds using ZMap, for the morphological complexity and the discontinuities of the bronze reflecting surface produced by data processing. After the registration, a final 3D photorealistic model was produced (Figure 11).
The model come up to the system specifications and project requirements, even if presenting several data lacks ("holes") and surface discontinuities, due to the extreme complexity of artefact morphology, rich of recesses, cavities and partially occluded and reflecting surfaces, that would probably be a difficult challenge for every other range-based survey technologies. As a part of the whole documentation produced, an exhaustive and articulated web presentation, integrated with VRML models from the final 3D model, was realized to provide a full fruition and deployment tool for this artefact.

Figure 11. Final 3D photorealistic model of "Balteus"

St. Maxim Church survey aimed to document both the apse and triumphal arch frescoes. The digital Zscan technology gave a good response to the survey even at a first quick inspection executed in natural lighting conditions (*CCD sensor of 10.2 megapixel*, 24 mm calibrated lens used).
Shots were taken from a distance of 12 meters from the apse for an overall documentation, and from a closer distance of about 6 meters to shot single frescoes. After the phase of image post processing, point clouds of the apse and the arch (Figure 12) and for some single frescoes (Figure 13) were obtained. A series of paintings of particular interest was then merged together into a single strip (Figure 14). To avoid distortions, the single curvature parts of the arch were shot from a distance of about 5 meters and the focal axis of the camera was kept perpendicular to the mid-point of the framed fresco portion. The resulting registered point cloud consists of portions with different point density, because the ones being surveyed from a closer distance obviously have a higher one.
According to the survey precision and to the detail needed for representation, a step resolution value of 3 pixels was adopted for the elaboration of each triplet, corresponding to 1.65 mm point to point sample spacing on the created point cloud.

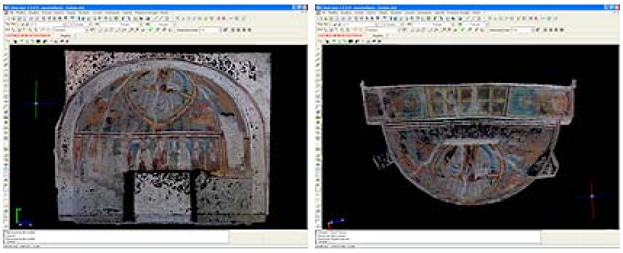

Figure 12. 3D model of the apse and triumphal arch from a single triplet

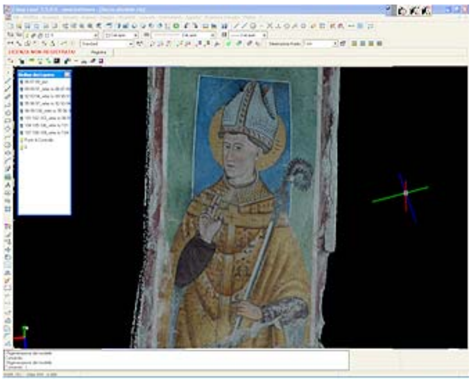

Figure 13. 3D point cloud of a single fresco on triumphal arch

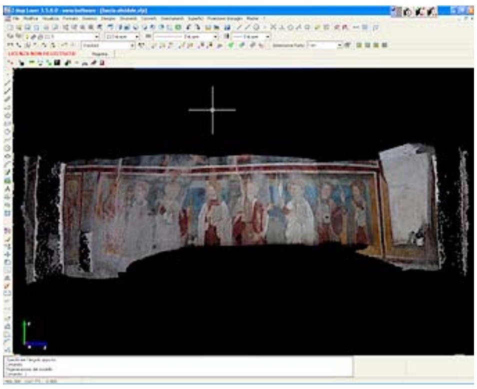

Figure 14. 3D point cloud of merged high LOD single fresco point clouds

5. CONCLUSIONS

This paper remarks how systems based on image capture and processing for digitization and 3D model reconstruction can be widely applied to different scale artefacts of historic-artistic interest, despite the fact that "traditional" ways can still be pursued and enforced as valid applications to survey Cultural Heritage (Martinelli, 2006).
Digital scanning of high quality images through the application of photogrammetric principles has given satisfactory results in terms of surveyed number of points, and precision in locating the acquired surfaces. Moreover, it is more convenient than scanner laser technology, which cannot be applied to a multi scale project survey without shifting from a time of flight sensor to the optical triangulation one, being more affected by the scale of the artefact in terms of LOD. In addition, it captures at the same time both geometric and colorimetric data (point clouds with RGB colour information), so that photo-realistic 3D models can be easily produced on a high quality level like the ones created from laser scanner dataset trough a longer post-processing and texturing elaboration.
Wide range of usability, from land-size to centimetre, high accuracy, reduced processing time, colorimetric information directly associated to geometry, ease of practical usage, in addition to the flexibility and comparative low cost of the equipment required (both HD and SW), make this innovative technology very attractive and interesting.
Being most of the limits relative to the software employed in the digital scanning of the triplets step, it seems reasonably to suppose that in a closer future they will be overwhelmed by new versions of the software, extending the field of application of this survey system even to more complex morphologies and to more extended size ranges.

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