QUICK PHOTOGRAMMETRIC SYSTEMS APPLIED TO DOCUMENTATION OF CULTURAL HERITAGE: THE EXAMPLE OF AOSTA ROMAN CITY WALL

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ABSTRACT

The critical process of reading the artefacts has been facilitated by the introduction of Computer Science in the field of documentation and survey of architectural heritage. Indeed, computer-based techniques have strongly modified the acquisition phase as well as subsequent operations such as computation and management of information coming from different fields. For instance, it is possible to add further information, such as qualitative data, morphology, colour information and so on, to photogrammetric acquisition.
This paper focuses on experimental results deriving from the application of quick photogrammetric stereoscopic systems to surveying and documenting the Roman city walls in Aosta, a circuit of five kilometres around the town (internal and external sides).
The final result is composed of metric *raster* stereoscopic strips, explorable in a stereoscopic environment, where it is possible to perform three-dimensional measures and to survey conservation status. In this way is possible to avoid the vectorial phase which often represents a subjective abstraction from the truth: the *raster* strips provide a corpus of information deriving from the geometrically controlled stereoscopic pairs, which are qualitatively and quantitatively richer than a traditional relief.
The innovative photogrammetric system tested is a digital mono-camera system which has the advantages of a bi-camera based system and allows stereoscopic acquisition that can be used directly for restitution. This system guarantees the same accuracy of geometric data acquisition as a traditional stereoscopic method, which is fundamental in the process of diagnosing the state of conservation. Although the system does not need topographical support, the latter was nevertheless provided in order to verify the reliability of the test system, the accuracy of the results obtained and to set the stereoscopic models properly in real space.
All the photographic stereoscopic pairs were processed using dedicated software that allowed control points to be added (natural and targets deriving from topographic survey) in order to minimize errors in overlapping stereoscopic models.

1. INTRODUCTION

Geometric survey is a fundamental stage in a correct approach to surveying, defined as the complex of actions required to obtain an “integrated knowledge” of the architectural artefact to be conserved and protected.
The innovation, introduced also in this sector by recent technology, has contributed to further enhancing the cognitive potential of the “measurement” phase.
Currently, the consolidated procedures of terrestrial photogrammetry draw considerable advantage from digital systems. These systems open up extremely interesting horizons 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 present article illustrates the methodology adopted and the results obtained during the testing of innovative systems of stereoscopic photogrammetric surveying used in 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, within the framework of the Protocol of Intent between the CNR and the Valle d'Aosta Autonomous Region (RAVA).
This project represented a good opportunity to test these innovative instrumental survey systems, which had been developed in recent years and are capable of optimizing acquisition time, simultaneously guaranteeing a reliable result.
Moreover, owing to the large scope and the characteristics of the consultation environment, it mostly may be considered unique as well as fully suited to satisfy Public Administration needs of protection and conservation.

1.1. The study case

The artefact investigated in the present study consists of the entire ancient Roman city walls of Aosta (*Augusta Praetoria*). The stereophotogrammetric coverage of this monument became necessary for the purpose of preparing a scientific basis of geometric data, finalized to evaluate the state of conservation and to plan the subsequent conservative restoration actions.
The city walls, still today almost entirely conserved, have a total length of over five kilometres between the external and the internal side; they are rectangular in shape, and their sides measure respectively 727.5 meters and 574 meters.

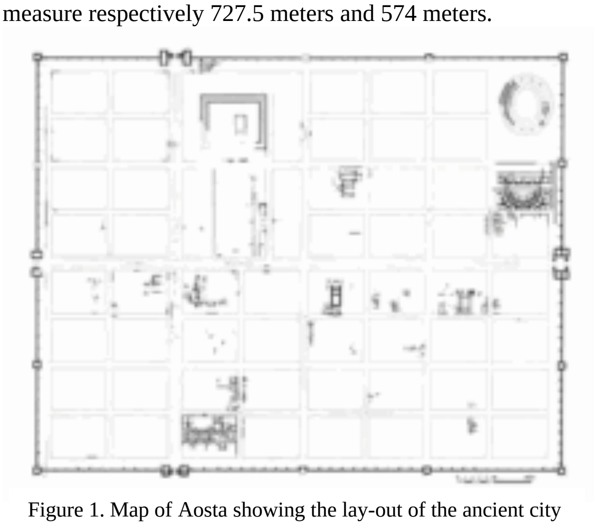

Figure 1. Map of Aosta showing the lay-out of the ancient city

The wall system, which dates back to the time of the foundation of *Augusta Praetoria*, appears with the classical lay-out reinforced by towers located at regular distances, some of which still well conserved despite the repairs carried out in successive periods. It is also interrupted, at the end portions of the *cardo* and the *decumano*, by four gates leading into the city, of which Porta Praetoria is a splendid example. From the construction point of view the walls are made of *opus caementitium* with a facing of squared travertine blocks that represent the external hanging of the internal cement conglomerate made of river pebbles covered with mortar. Today only a few sections remain, the conservation of which is essential for an understanding of the construction technique used and the outer configuration of the facing itself.

Figure 2. Portion of wall belonging to the Aosta wall perimeter that delineates its conformation

In spite of the planimetric continuity of the architectural lay-out, the current appearance of the walls is compromised by events occurring over time: collapses, alterations, and improper use have produced gaps in the *unicum* of the document.
Operatively, numerous different problems, also of a logistic nature, were encountered. These concerned above all the photographic coverage owing to the extreme morphological and geometric heterogeneity, due also to the different state of conservation, as well as the different conditions of interference with the surrounding urban texture.
The wall shape frequently changes: from relatively low (about 1.00 to 3.5 metres) to high height (about 6.5 metres), from sections in which the internal cement conglomerate is completely exposed to others containing remains of external facing made of travertine blocks, from situations involving the inclusion of long sections inside public gardens to others in which the wall is completely incorporated in new buildings (e.g. the Municipal Library) or with superimposed new constructions.

1.2. Guidelines

The project aim is to achieve the complete stereoscopic coverage of the entire city walls so as to allow it to be accessed using 3D navigation and exploration techniques by chaining together the created models. The successful achievement of such a vast and, in a sense, unique work programme, considering the size of the artefact and the quality of the documentation produced, has demanded and still demands* a considerable care in terms of human resources, time and materials.
It was necessary at the planning stage to schedule the work in accordance with precise technical and organizational criteria, aimed at rationalizing the management of the entire operation from both the scientific and the economic point of view, typically during the data acquisition stage.

This led to three essential choices:

1. the breakdown of the survey into sections by subdividing the entire wall perimeter into lots both during the design phase and during the operational phase;
2. the decision to use non conventional methodologies and techniques that, even in an experimental environment, would in any case guarantee optimized working times and thus cost optimization, without conflicting with the need for precision and quality of the survey product;
3. the preparation and design of an IT based management programme to order and immediately exploit the data acquired during the survey campaigns.

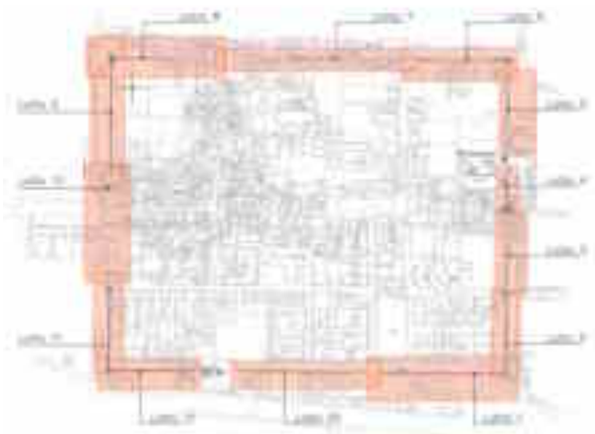

Figure 3. Map of the Aosta roman city walls divided into lots

Specifically referring to point no. 1, the criterion used to break the work down into individual lots was guided also by the natural configuration of the wall perimeter in the urban texture that, as mentioned earlier, displays an interruption of the various features characterized both by the presence of the towers and gates and by more recent situations of impairment (abutting rooms, buildings and other kinds of interruptions). This subdivision criterion thus led to a definition of lots with widely varying characteristics and degrees of difficulty owing to: differences in length or height of wall sections, presence of wall spurs orthogonal to the perimeter, different degrees of accessibility to the spaces in front of them.
After a detailed preliminary inspection, during which a photographic documentation was carried out, finalized to provide an immediate view of the morphologic-geometric characteristics of the construction, 13 lots were identified, further subdivided into outer and inner part.

2. METHODOLOGY AND TECHNIQUES USED

A quick non-conventional stereo-photogrammetric system** was applied. It guarantees reliability from the point of view of measurement rigour, as well as satisfying characteristics of considerable flexibility and ease of use (Menci, 2000). This consists of a single camera system that transfers into digital form the majority of bicameras advantage, the lay-out of which corresponds to the settings of traditional stereocamera systems. The relative calculations and basic survey principles are applied without the limitations peculiar to conventional instrumentation and techniques.

*The acquisition of the documentation isn't yet completed; actually as about 90% of the entire wall perimeter has been covered (May 2005).

**The *Cyclop II* stereo-photogrammetric system produced by Menci Software of Arezzo.

The system applied on a small scale and to architectural objects of limited size[*] should not require topographical support points. However, in order to verify the system itself, at the same time also a topographic survey of coordinates of significant points was carried out with a total laser station, supported by a system of local polygonals linked to the main datum points of the topographic network of the city[**]. This control operation has been important considering the difficult survey conditions and the length of the wall sections to cover, that is, in view of the fundamental need to boost the metric control of the construction over its considerable length.
The surveying of the topographic points was also essential in order to perform the chaining of the individual stereoscopic models and obtain a unitary view of whole wall sections (lots) that could be explored in a specially configured 3D navigation environment.
The stereoscopic acquisition was performed using a special calibrated aluminium bar, mounted on a topographic tripod, on which is applied a sleigh, realized in special steel, supporting the photographic camera, which was also calibrated (in this case a Nikon D-100 digital photocamera, with a 24 mm lens was used).

Figure 4. Calibrated aluminium bar on which the digital photocamera used for the photogrammetric survey is positioned

The sleigh, bound to flow on a rectilinear guide, allows the photocamera to be moved and secured in specific positions by being blocked using special holes drilled at fixed intervals on the bar (photogram dx and photogram sx), representing the base of the stereoscopic pair.
Considering the specific nature of the object investigated and the need to make geometric and qualitative assessments (characteristics of the component materials, forms of degradation, state of conservation of external facing and internal cavity, etc), the decision to use a digital photocamera, rather than a conventional film camera, made it possible to avoid numerous intermediate development and printing steps. Moreover in this way it is possible to avoid the subsequent scanning phase which would have caused considerable dimensional distortion and chromatic alterations to the photograms, with a significant loss of image definition, thus preventing a correct reading and interpretation of the construction.
As mentioned above, in order to construct stereoscopic navigation environments (i.e. in 3D and thus with meaningful x,y,z coordinates) suitable for managing all the derived body of information, the entire stereoscopic covering was processed using an *ad hoc* software preset for photogram orientation in order to obtain a geometrically controlled 3D raster model[***].

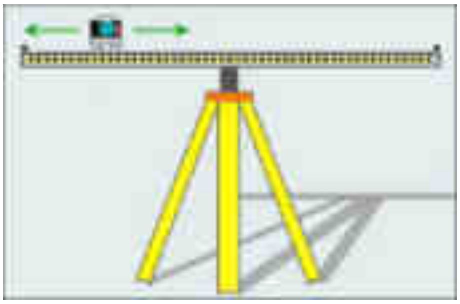

Figure 5. Scheme of the quick photogrammetric system utilization

3. THE SURVEY PHASES

In order to obtain the "finished" survey product, several specific operating phases were performed. These phases were carried out in a strictly progressive order and a detailed description of them is given in the following sections. They may be subdivided as follows:

- data acquisition;
- data processing;
- data organization and ordering.

This kind of work structuring, today, allows even an operator that has not performed the survey operations to use the data and work on the stereoscopic images in a "facilitated" way.

3.1. Data acquisition

To perform the survey a working group composed of four persons was set up: two architects for the coordination activity, the photographic acquisition and the monographies of all the field data needed for the subsequent processing operations; a professional topographer for topographic data acquisition; a qualified technician for support and ancillary activities.
Briefly, each field campaign regarding each single lot involved the following operating phases:

- framing by means of a series of local topographic networks suitably related and linked to each other and coupled, by means of the necessary survey and computation procedures, to the general topographic network of the whole city;
- photographic coverage of elevations with a minimum overlap of 30% between individual stereo pairs[****];
- total station acquisition of space coordinates of the support points represented by targets specially positioned on the artefact in sufficient numbers to allow the anchorage of the subsequent stereomodels (note that

[*] In this sense, the present method was widely tested by the authors in other research projects. Reference is made to a four-year research contract covering the "*Construction of a computerized data base of monuments in the Appia Antica Park*", signed by the ITABC - CNR and the Superintendence of Cultural Heritage of Rome (Salonia et al., 2004).
Further experimentation related to the survey of the entire cycle of late mediaeval frescoes in the Collegiata of S.Orso in Aosta, again within the framework of the Protocol of Intent between CNR and RAVA (Salonia et al., 2005).

[**] The necessary topographic support was provided by Mario Mascellani of ITABC.

[***] *Stereo View* software produced by Menci Software of Arezzo.

[****] The innovative system adopted, as far as the overlapping of models during the acquisition phase is concerned, does not necessarily have to fit the parameters laid down for conventional stereophotogrammetry, consisting of 55 - 65% overlap (Kraus, 1987).

for each pair of photographs a minimum of four known coordinate points, shared with the preceding stereomodel, must be surveyed. Nevertheless two or more additional points were surveyed so as to avoid, in the case of possible error, not being able to perform the next processing phase);

- topographic survey of the planimetric development and summital profiles of the individual parts of wall in order to define the wall sections.

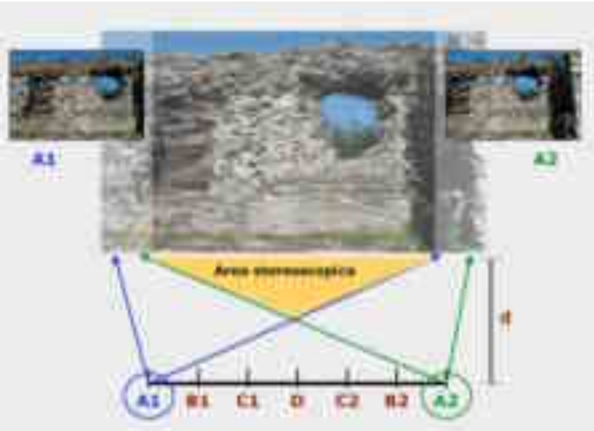

Figure 6. Stereoscopic model of a portion of Aosta city walls

In order to optimize the quality of the overall stereoscopic view, during the acquisition phase several procedures of a practical and general nature were adopted.

It was therefore attempted to shoot the sequences in homogeneous lighting conditions. Inspections were used to determine the best time for shooting for individual wall sections.

For each lot it was endeavored to maintain a constant distance between the camera and the object, in many cases proceeding with a coverage of vertical strips as well as horizontal ones in particular situations in which the vegetation concealed portions of the wall and where it was impossible to access with the equipment. This procedure made it possible to have similar useful coverage surfaces in order to avoid annoying “scale jumps” during 3D navigation and allowing a more fluid viewing of the object. The distance between the shooting station and the object was often practically compulsory and, above all, in the case of limited areas, were suitably adjusted in order to obtain a precise scale ratio for the photogram. As a general rule distances between 3 and 12 metres were used precisely in view of the volumetric articulation of the individual sections.

In the cases in which the height of the wall profile to be covered was found to be greater than the area covered by the model itself, a larger number of shots were taken with an axis inclined towards the bottom and/or the top, with a rotation respect to the vertical of not more than 15° in order to make the several overlapping strips needed to cover the whole wall. In any case the alignment of the photographic stations was fixed so as to be parallel to the plane of reference, and thus to the construction itself, in order to avoid any deformation.

As mentioned in the preceding section, the lots identified during the design phase totaled 13 and, at the present time (May 2005), since the beginning of the survey work (July 2004), the stereophotogrammetric coverage has involved 9 complete lots: summing the various campaigns, in the approximately 60 working days (corresponding to about 510 working hours), data corresponding to a total of *1070* stereoscopic *models* (and thus 2140 photograms) and about *9000 topographic support points*, merely for the subsequent chaining of the pairs, have been acquired. The file referring to the work today measures 30.3 GB.

The number of stereoscopic models developed to cover each lot varied in the extreme, depending on the different situations and degrees of difficulty of shooting.

Several lots, although having an extensive linear development, were surveyed with a total number of about 60 models , thanks to the free space in front of them.

Other smaller lots, on the other hand, had a limited free area in the street in front of them or were characterized by visual obstacles due to the vegetation. For this reason they required a stereoscopic coverage consisting of hundreds of horizontally and vertically overlapping models with closely spaced photographic stations (e.g. for lot 7 alone some 240 models were performed as the road width in front of the wall was reduced to about 3.5 metres).

Finally, other lots, in order to obtain stereoscopically complete coverage, required a large number of models because of the presence of numerous wall spurs for which also elevations orthogonal to the wall were obtained using special stations.

During the phase of stereophotogrammetric acquisition it was necessary to make a very detailed monography containing all the information referring to the photogrammetric survey. This monography was characterized mainly by:

- an eidotype of the wall section investigated both in elevation and plan, on which the models linked together respectively by means of shared points (minimum of four) with the approximate position of the targets defining these topographic support points and the position of the various photographic stations;
- a card referring to the eidotype on which all the information is marked, required on the one hand, to organize a large number of data (date of acquisition, the lot investigated, the number of photos defining the stereoscopic model, the model number and the relative acquisition station, etc.), and on the other, to create the stereoscopic model (the position chosen for the digital camera on the bar, i.e. the width of the base, the distance between the photographic station and the wall, the camera focus, etc.).

This monography, useful during the survey campaign in order to have a continuous verification of the data acquisition phase, was necessary above all for the subsequent processing of the data to obtain a rapid recognition of the photos belonging to the different models and the relative topographic point and the organization of the work of documentation in the ad hoc computerized management software.

3.2. Data processing

Once the field data had been acquired using the stereophotogrammetric photographic system described above, the digital images comprising the stereoscopic couple were loaded into an *ad hoc* software in order to obtain three-dimensional management (control, measurement and rendering) of the work under examination.

This software actually displays all the characteristics and functions of a digital photogrammetric renderer, but does not require any preparatory phases of photogram orientation. The software allows the pair of images of each stereomodel to be loaded immediately; the only data required, in addition to the couple of images chosen, are the photographic base used (distance between two shots), the distance from the object and the selection of the calibration parameters of the lens used.

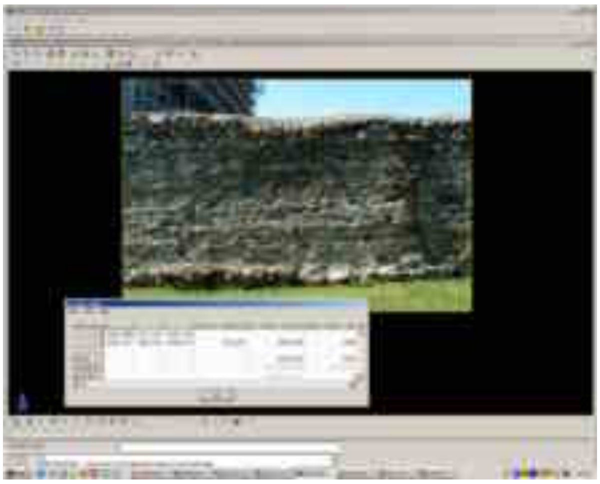

Figure 7. The *Cyclop* software, produced by Menci Software of Arezzo

In brief, the main functions of the software are as follows:
- immediate loading of the couple of photograms ready for 3D measurement without any preparatory phase;
- dynamic stereoscopic exploration of the model;
- interactive measurement with the production of tables;
- rendering of 3D entity in stereoscopy.

The system, thanks to the use of a single photocamera, has numerous advantages: cheapness, accuracy (a single calibration), constructive homogeneity (same response to colour and same defectology in general).
For the processing of the stereoscopic models another digital photogrammetry software* was used that was suitable for the case in question, but above all having a very large size.
This software allows the stereoscopic couples to be linked together in such a way that they can be explored successively and with the possibility of passing from one model to another without a break (Menci et al., 1999).

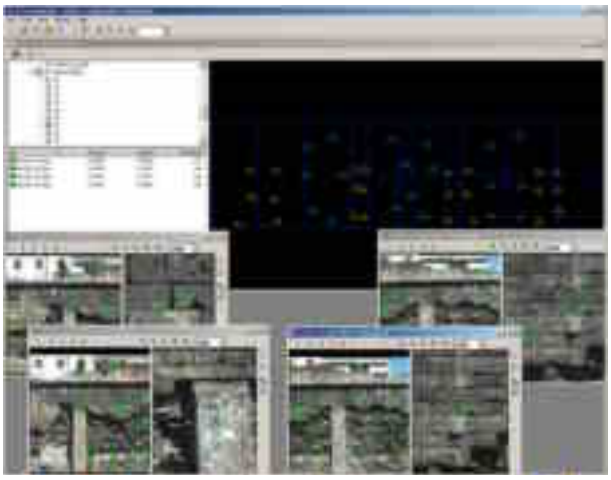

Figure 8. The *SV Triangulation* module of the *Stereo View* software produced by Menci Software of Arezzo

The software consists of three modules, each of which corresponds to given needs of photogram processing which may be summed up as follows:
- creation of internal, automatic or semiautomatic orientation of the photograms (Image Builder);
- creation of the absolute orientation of the photograms (SV Triangulation);
- creation of the model and stereoscopic rendering of the couples (SV Plotter).

For each photogram, both with orientation by couples and with block chaining, a corpus of specific data is created for each image. In addition to the image and orientation files it is also necessary to store a reference map (*.dxf file) which represents the unified framework of the photograms that is based on the evaluation of the results of both orientation by couples and triangulation.
This chaining file can be imported into AutoCad and, in any subsequent graphics rendering phase, allows chaining of the 3D vectorializations of the construction.

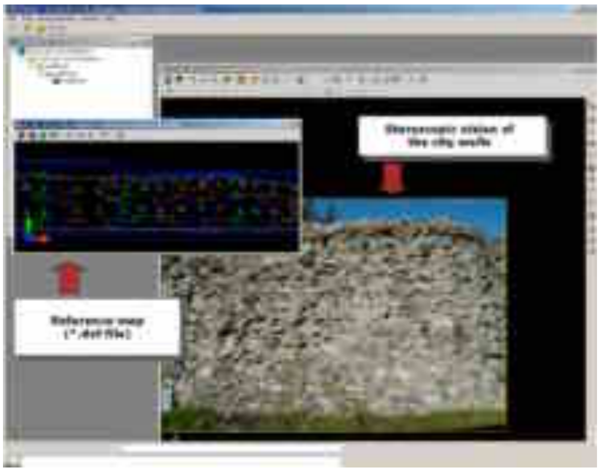

Figure 9. The *SV Plotter* module of the Stereo View software produced by Menci Software of Arezzo

3.3. Data organization and treatment

As mentioned at the beginning of this section, in order to facilitate team work and allow use by any operator of the Administration, and above all for any subsequent updating of the work, all the field information were merged in an ad hoc database which thus represents a rationalized archive of the work performed.

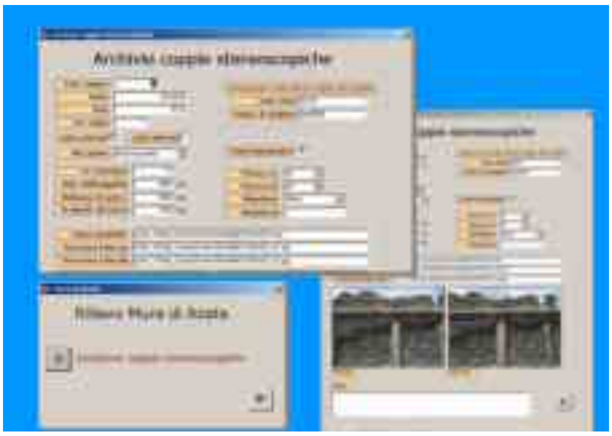

Figure 10. Example of database window implemented in MSAccess environment containing the photographic image archive, the stereoscopic pairs and of all the other identifying data of the single model

The database was implemented in an MSAccess environment and contains the photographic images of the stereoscopic

* This is the *StereoView* stereophotogrammetric system produced by Menci Software of Arezzo.

pairs and all the other data identifying the individual model; using a suitably designed interface it is possible to consult the images referring to the stereoscopic couples and to a whole range of data related to the shooting conditions and the technical parameters.
For each stereoscopic model also all the other indications comprising the full information corpus were stored: data, lot, photographic station number, distance from the preceding base and from the object, serial number of the original photos and shot position on the bar (corresponding to the base, photogram sx or dx).

4. CONCLUSIONS

The experimentation carried out and still under way suggests a number of general observations and at the same time ideas for further experimentation in the sector.
The many difficulties encountered in the field work phases suggested fresh stimuli and ideas for the integrated applications of innovative techniques and methodologies. It has actually been postulated that 3D models obtained by laser scanner could be chained in order to survey several final wall sections for which the system used so far proved impracticable and uneconomic in terms of time and costs.
The image database constructed represents an information archive of great scientific and documentary interest considering also the high definition of the photographic acquisitions themselves (digital images with 6.2 million pixels).
Moreover, with an eye to further development, it is hoped that this database can, if suitably implemented, be used as a support for the management of data obtained from miscellaneous and future activities by the Superintendence (survey updates, analysis of actual conditions, conservative restoration projects, etc.).
The specificity and peculiarity of the work consist not so much in the application of an innovative system that, as mentioned in a preceding note, has already been widely tested in a wide range of other contexts, as rather in the application of this fast 3D survey system on a large urban scale as is well represented in this case by the town walls of Aosta.
Complete stereoscopic coverage of this construction, because of its large size, would alone represent a unique task; if we add to this the rapid availability of a 3D raster document and the ease of management for users of this product, the final outcome of the experimentation, which has been underlined constantly in the present article, certainly finds its fuller completion and total satisfaction.
It should indeed be emphasized that the attainment of the pursued objective has resulted in the creation of a powerful documentation tool. This tool makes it possible to investigate the whole construction with a very high degree of accuracy and with certain geometric rigour and, at the same time with levels of subsequent zooming to “approach the object” made possible by the high definition of the photographic apparatus which would be inconceivable in a visual inspection of the real object.

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