TRADITIONAL AND UNCONVENTIONAL PHOTOGRAMMETRIC TECHNIQUES FOR METRICAL DOCUMENTATION OF CULTURAL HERITAGE: THE EXAMPLE OF THE "ROLANDINO DEI PASSAGGIERI" TOMB (ST. DOMENICO SQUARE) SURVEY IN BOLOGNA

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ABSTRACT

The Geomatics techniques offer today very interesting opportunities for Cultural Heritage surveys. In this context the role of Photogrammetry is improved thanks to the development of new Image Matching algorithms and to the introduction of simplified digital tools that permit the realization of surveys for architectural or archaeological purposes, without stereoscopic skills, so not requiring expert photogrammetrists.
This paper deals with methodologies and problems encountered during the photogrammetric survey of the "Rolandino dei Passaggieri" tomb in Bologna; different solutions were experimented using digital photogrammetric systems, in terms of data acquisition (semi-metric and digital cameras), data processing (monoscopic and stereoscopic plotting, with and without the use of Control Points, automatic surface model reconstruction) and representation (e.g. orthophotos, VRML object).
The operative phases of surveying were described and solutions were compared in order to evaluate the accuracy and the reliability in restitution of the object shape.

1. INTRODUCTION

The methodology of terrestrial photogrammetry changed significantly in the last years thanks to the improvement of matching algorithms and to the introduction of simplified digital tools that easily permit the 3D object model reconstruction without stereoscopic skills.
In this work an experiment has been conducted on a real case, aiming to verify what accuracy may be reached at close-range photogrammetry when a semi-metric and a non-metric camera are in use, applying two strategies for image processing and two strategies to solve the orientation problems.
Object of the test is the Rolandino dei Passaggieri Tomb located in the famous San Domenico square in Bologna (Italy), adopted for its elevated historic-architectural meaning, for its ideal position to traditional photogrammetric survey realization purpose and for its dimension (length, height, width), representative of architectural and archaeological applications.
In the frame of this work, the following activities were realized:

- a topographic survey was performed to define the 3D coordinates of natural Control Points using a modern prism less Total Station (Topcon GPT 6001);
- direct object distance measurements were collected and accurate monographies were redacted;
- pseudo-normal, and horizontal, vertical or oblique convergent photos of the tomb with different scale factors were acquired by means of Leica R5 semi-metric camera and a Nikon Coolpix 5400 non-metric digital camera;
- a camera calibration work was performed using PhotoModeler v5.2 (EOS Systems Inc.) calibrator software tool in order to obtain the parameters of the inner orientation together with full lens distortion on the non-metric camera;
- images processing (orientation parameter estimation and restitution) using PhotoModeler's monoscopic system was realized by means of Control Points (method 1) and using Distance Constraints (method 2);
- images processing was even realized by means of a Digital Photogrammetric Workstation (SOCET SET v5.2, Bae Systems), that permits manual and automatic stereoscopic plotting;
- vector and raster outputs were produced by means of the monoscopic system and the DPW;
- a virtual 3D model was generated in the format VRML.

At the end, the different solutions were compared in order to evaluate the accuracy and the reliability in restitution of the object shape.

2. THE PHOTOGRAMMETRIC MATHEMATICAL MODEL

The basic mathematical model used to pass from a two-dimensional system (photo) to a three-dimensional system (object), can be represented by means of the following 3 equations:

$$\begin{vmatrix} \xi_i - \xi_0 \\ \eta_i - \eta_0 \\ -c \end{vmatrix} = m \begin{vmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{vmatrix} \begin{vmatrix} X_i - X_0 \\ Y_i - Y_0 \\ Z_i - Z_0 \end{vmatrix} \quad (1$$

Where:

- ξ_0,η_0 are the image coordinates of the perspective centre (Principal Point) with respect to the image plane;
- c is the focal length;
- m is the image scale factor;
- r_{ij} are the elements of the rotation matrix and are function of angles ω φ κ which describe the position of the camera in the ground-based reference system;
- X_i,Y_i,Z_i indicate the absolute coordinates of a generic point;
- X_0,Y_0,Z_0 are the absolute coordinates of the perspective centre;

It is possible to eliminate the scale factor, that can be not uniform within the photo, by dividing the first and second equations of the system (1) with the third one:

$$\xi_i - \xi_o = -c\frac{r_{11}(X-X_o)+r_{21}(Y-Y_o)+r_{31}(Z-Z_o)}{r_{13}(X-X_o)+r_{23}(Y-Y_o)+r_{33}(Z-Z_o)}$$
$$\eta_i - \eta_o = -c\frac{r_{12}(X-X_o)+r_{22}(Y-Y_o)+r_{32}(Z-Z_o)}{r_{13}(X-X_o)+r_{23}(Y-Y_o)+r_{33}(Z-Z_o)} \qquad (2)$$

This is the easiest way to obtain the well known co-linearity condition, that expresses mathematically that the object point, the corresponding image point and the projection centre lying on the same projective straight line.
There are two ways to use the collinearity model: spatial resection and spatial intersection. In the first one problem, the goal is to detect the external and/or the internal orientation parameters; instead in the spatial intersection problem the purpose is to calculate the absolute coordinates of a point by means of image measurements realized, at least, on two photos, if the object can't be represented by plain.
Two equations can be collected for each measured image-point so, considering two images of the same object taken from different point of view, in total 4 equations can be written. If the internal parameters of the camera are known, 6 are the unknowns parameters which have to be calculated to resolve the plotting problem: the tree rotation angles ω, φ and κ, defining the matrix R, and the projection centre absolute coordinates (X_0, Y_0, Z_0).
To this aim, 3 common control points located in the overlapping area are enough to orient two photographs. If the object is visible on three or more photos, a bundle solution is possible including all available measurements at the same time.
The classical photogrammetry, based on the use of stereo plotters or Digital Photogrammetric Workstations, metric cameras and photos realized in pseudo-normal case to obtain stereoscopic models, permits to obtain very well results in function to the scale factor and the ratio of stereo base B/Z value (B = photo base, Z = object distance).
This technique requires expensive instrument to realize artificial stereoscopic view and often it is difficult to put into practice for the monitoring of cultural heritage, to preservation and restoration purpose.
Alternative photogrammetric systems, called "non conventional", are designed to monoscopic multi-image measurements in order to perform metric documentation; this methods are easier for surveying, for plotting and cheaper compared to the traditional instrumentation (stereo plotter, DPW). Such unconventional systems, utilizing modeling functions, permit 2D or 3D numerical and raster object restitution, base for further CAD elaboration or for Geographic Information Systems.
Photos can be acquired convergent, horizontally, vertically or oblique by means of different cameras (semi-metric or non-metric) or lenses, with the only recommendation that each unknown point should be intersected by at least two rays of satisfactory intersection angle.
More measurements obtained from different photos permit the application of a statistical least squares bundle adjustment in order to solve the redundant equations systems.
If the photos are acquired in normal case, the co-linearity equations (2) can be simplified and control points are not necessary for the restitution purpose. An alternative photogrammetric method provides for the application of a scale factor to the model by means of the introduction of direct object distances measurements.
This opportunity consents the execution of surveys in economy, employing no metric cameras, that have to be calibrate at the moment of the survey, without the requirement of expensive Total Stations and, in particular, consents errors acceptable for architecture survey, in archaeological fields and in general appear the ideal method for the documentation of the Cultural Heritage.
These alternative photogrammetric methods enlarge the use of photogrammetry even to person without culture of the geomatic disciplines; nevertheless empirical verifications concerning the real accuracy of the elaboration realized are still necessary to better understand the effective performance of the systems.

3. EXPERIMENTATION PHASE

The object interested by the experimentation is the "Rolandino dei Passaggieri tomb" in Bologna, situated in the San Domenico place (figure 1), built in the XIV century A.D. and restored successively after the heavy damages suffered during the 2^{nd} World War.

Figure 1. The San Domenico place, with the "Rolandino dei Passaggieri tomb" on the left.

Rolandino dei Passaggieri (1215-1300) was the founder of modern notary practice and for centuries his texts "laid down the law" in all countries governed by Latin law.
Rolandino was not only the author of the acclaimed "Summa totius artis notarie" and expert in Bolognese teaching circles, but also a politician. Bologna, at that time, was gripped by the continuing disputes between the Guelf and Ghibilline factions, and Rolandino led the transfer of power from the established aristocracy to the new, educated middle classes - the "common people". He did so with determination, managing to firmly control the city for a decade, as well as creating and commanding a militia, known as the "Society of the Cross". When Bologna came to be controlled by the papacy, Rolandino bowed out of the political arena to take up teaching again at the university, which had since undergone great changes and whose prestige was becoming world-renowned, particularly in legal circles.

3.1 Surveying activity

Firstly a surveying plan phase was performed in order to determinate the most appropriate image scale for the wanted accuracy; particularly the aim was a restitution scale of about 1:100, which associated accuracy is, in according with graphicism-error, ±2cm.
Due to the object height, the acquisition of images at the necessary scale (1:400) should required two strips, but for

logistic reasons, it was preferred to adopt a little inclination of the optique axis: consequently the photos present a lightly lower scale in the top part. The medium image scale for each object side, with the associated restitution scale and accuracy, are reported in the table 1.

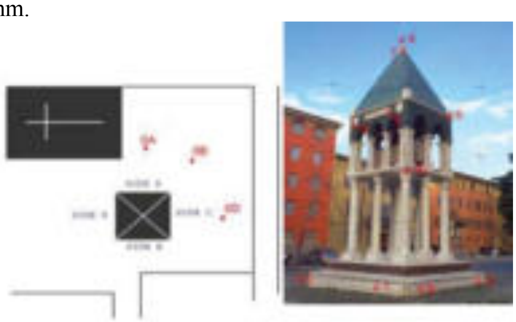
	Medium image scale	Restitution scale	Accuracy
Side A	1:550	1:140	2.8 cm
Side B	1:550	1:140	2.8 cm
Side C	1:480	1:120	2.4 cm
Side D	1:340	1:85	1.7 cm

Table 1. Medium image scale for each object side, associated restitution scale and accuracy.

The plan foresaw photos both in pseudo-normal and convergent trim, suited respectively for a stereo-scopic and a mono-scopic restitution.
For the image acquisition a 24 mm semi-metrical Leica R5 film based camera and a non-metrical Nikon CoolPix 5400 digital camera were adopted, whose inner orientation parameters were successively obtained by means of a self-calibration procedure.
The images were then digitized by KODAK Photo CD system.
To define the 3D coordinates of 10 natural control points, a topographic survey was performed using a modern prism less Total Station (Topcon GPT 6001). It was preferred to use natural points in spite of a loss of accuracy in the collimation phase, because of the aim of simulate common conditions of a cultural heritage application and so in order to simplify on the whole the survey procedure .
The adopted surveying scheme was the three-dimensional spatial intersection from three vertex; the control points are localized on two tomb facades.
Figure 2 A and 3 B show respectively a San Domenico square plan with in evidence the position of the tomb and the three topographical survey vertex (0A, 0B, 0C), and the scheme of chosen control points.
Besides, direct object distance measurements were collected by means of a metric ribbon, in order to evaluate the possibility of carrying out a speditive model orientation using only distance constraints.

3.2 Data processing

The data processing started with the adjustment of the photogrammetric control points net, carried out by the StarNet software. The accuracy associated at the distance measurements has been assumed equal to 1 cm, being the control points only natural points. The adjusted coordinates obtained are characterized by an associate root mean square in the order of 1 mm.



a) b)

Figure 2. a) San Domenico square plan; b)Scheme of the Control Points.

The calibration of the non-metric digital camera was performed as well, in order to find the inner orientation parameters together with full lens distortion; for this purpose was used the PhotoModeler v5.0 self-calibration module, that perform the bundle adjustment analytical model by using several images of a plane test-field, supplied with the software. Of course, photos must be taken with the same focusing condition of the application case and, due to the planarity of the test-field, by a convergent scheme of acquisition (figure 3); moreover, to successfully recover the principal point position, it is recommended to take some photos with the camera rolled through 90° (Bitelli et al., 2003).

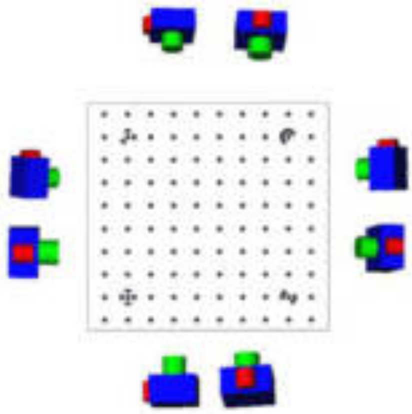


Figura 3. The calibration test-field and the images acquisition position.

3.2.1 The monoscopic restitution: The monoscopic restitution of the object was performed by means of PhotoModeler v5.2; this software is very user friendly and characterized by a very intuitive interface; in fact the operator is supported in the whole project setup phase, and many are the tools at disposal, for example the epipolar geometry that helps homologous points collimation. Besides PhotoModeler offers the important option of using in the same project images acquired by different cameras; in our application this task was fundamental, because a complete monoscopic object restitution couldn’t have been possible without using also the non-metric digital images.
Certainly this software can be easily utilized also by operators not endowed with a photogrammetry learning, even if offers many final products useful to technicians, as vectorial drawning, orthophoto and model in VRML (Virtual Reality Model Language) format. On the whole, Photomodeler seems to be particularly advisable for cultural heritage applications.
As said before, on the same photos were performed two photogrammetric elaborations different for the exterior orientation approach. In the first case, the exterior orientation was performed by using control points and the process achieved a global root mean square of 1.5 cm.
In the second case, it was adopted an easy and quick method to obtain a not-oriented scaled object model without topographic survey, based on the use of distance constraints directly taken on the object. Figure 4 shows the PhotoModeler window to define the distance constraints in the model scale arrangement.
The monoscopic restitution of some architectural particulars, as columns and capitals, was very difficult, because working with “flat” images, misses the stereoscopic effect necessary for the reconstruction of curve surface; so for this objects has provided for their modelling by special tasks of the software.
Actually PhotoModeler offers in these cases the possibilty of defining spatial geometry on the base of operator defining points.

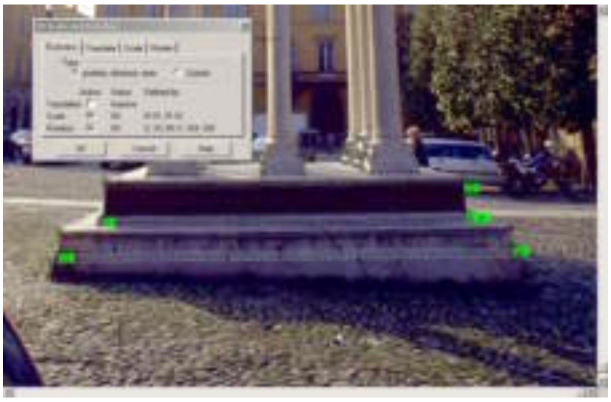


Figure 4. PhotoModeler model scale arrangement window

For example the column definition happens corresponding on two oriented images 4 points on the column, as reported in figure 5.

The “marking curves” command has permitted the modelling of the capitals and the column basement; in this case the operation starts from a 3D known point, then, following the object morphologie, are defined many curve nodes.

Unfortunately, if the column modelling has came to a very good result, the modelled capital is quite different the real one (figure 6).

Figure 5. Column modelling.

Figure 6. The modelled capital and the real one, with the used marked nodes.

One of the obtained products is the textured object model in VRML format.

The VRML format is a standard format of three-dimensional scene description on Internet. Unlike the HTML pages, with VRML world is possible to provide a virtual three-dimensional environment, where the user can move and navigate changing the point of view by opportune commands.

Figure 7. Textured object model exportable in VRML format.

3.2.2 The stereoscopic restitution: The stereoscopic restitution was carried out by a SOCET SET v5.2 digital photogrammetric workstation (Bae Systems).

The managing software SOCET SET consists of almost 60 application functionalities that mainly allow data import (images, DTMs, coordinates files etc.), inner orientation, automatic or manual aerial triangulation, automatic DTM extraction and manual editing and, finally, ortophoto and true-othophoto production and mosaicing.

For the case of study were processed the C-D sides stereo-pairs, because of the presence of control points.

The inner orientation was performed by an affine transformation and the resultant root mean square (r.m.s.) was about 0.7 pixel.

The triangulation procedure, realized by a bundle adjustment analytical model, has presented a global elaboration r.m.s. of 0.4 pixel and a medium residual of some millimetres on control point coordinates.

It’s important to point out that the topographic reference system is not suited to the use in a stereoscopic close-range photogrammetry processing, where even building facade requires a proper reference system, with the X-Y plane on the facade and Z axis coming out. Therefore it was necessary to rotate the control points coordinates to go in the new reference system. Obviously at the end this operation has to do again backwards to conduct again the whole restitution in a unique reference system.

By using the SOCET SET image correlation algorithms, DTMs of the oriented stereoscopic models were automatically extracted. In particular, the “adaptative” method was selected, leaving the software the opportunity of choosing the suitable correlation strategy, and a TIN format because it makes easier

the manual post-editing operation.
Totally about 18000 points, with a medium post-spacing of 4 cm, were measured on the two chosen facades.
The DTM manual editing was consistent particularly in those zones, as the columns, where the homogeneous photographic tone makes very difficult the correlation procedure.
Then the orthophotos of the two facades were generated using bilinear transformation as resampling strategy; a ground sample distance of 0.01 m was chosen.
For a correct orthophoto generation was necessary the introduction of numerous breaklines along all the discontinuity lines, as archs, basements, columns, pitches.
One of the obtained orthophotos is shown in figure 8.

3.3 Results presentation

For the purposes of this experiment, to not have problems concerning coordinate systems registration, differences among distances measured by means of Socet Set and PhotoModeler (Method 1 and Method 2) have been calculated, as well as the main statistical parameters (see table 10).
With the aim to evaluate the range of acceptability of the residuals, we have tacked in account the following expressions that permit to evaluate theoretically the distance accuracy measured by means of close range photogrammetry:

$$\sigma_D = \pm\sqrt{\sigma^2_{XYZP_1} + \sigma^2_{XYZP_2}} \quad (3)$$

Where:

σ_D is the root mean square of the distance between two generic points P1 and P2 detected on the photos;
$\sigma^2_{XYZP_1}$ and $\sigma^2_{XYZP_2}$ are the variances of the points plotted.

Considering $\sigma^2_{XYZP_1}$ and $\sigma^2_{XYZP_2}$ equivalent in the stereoscopic model or within the block of photos, results

$$\sigma_D = \pm\, \sigma_{XYZ} \sqrt{2} \quad (4)$$

On the basis of the mean scale factors of the Tomb's photos and to experimental evaluation of the root mean square of the points plotted, we have assumed the size of the differences without significant within the range of ± 2 cm.
Observing the table 2, what is most evident in the results is that the residuals are mainly comprised in the range of ± 2 cm in agreement with the mean scale factor of the photos.
The differences of distances further than appear to be dependent from the advised direction (figure 9). They highlight a systematic extension in the geometry of the object along the vertical bearing in respect of the Socet Set solution, considered like Datum for these comparisons.
The reasons of this systematic error may be that the accuracy in the restitution by means of monoscopic systems is restricted using photos taken at ground level with limited intersection angles. To confirm and quantify this effect, further studies with additional camera positions may be necessary for the test.

Figure 8. Orthophoto of the tomb C side.

Differences of distances		A-B	A-C	B-C	B-C
N° of values		84	84	84	24
Type of natural points		check	check	check	control
Minimum (cm)		-4.0	-5.1	-1.7	-5.7
Maximum (cm)		2.3	2.0	0.6	0.0
Mean (cm)		-0.2	-0.8	-0.6	-1.7
Standard Deviation (cm)		1.3	1.4	0.4	1.6
Range (cm)		Frequency (%)			
min	-3	5	5	0	5
-3	-2	1	9	0	14
-2	2	89	84	100	81
2	max	5	3	0	0

Table 2. Statistical values concerning distances comparisons: A = Socet Set source; B = PhotoModeler source, Method 1; C = PhotoModeler source, Method 2.

Check points Control Points

Figure 9 – Some distances measured by means of Socet Set and PhotoModeler (Method 1, 2). The coloured arrows show the significant discrepancy detected

4. CONCLUSIONS

The Rolandino dei Passaggieri Tomb has been surveyed following traditional and unconventional photogrammetric techniques. Numerical restitutions in monoscopic and stereo mode have been produced, orthoimages have been created and a virtual 3D model has been generated in VRML format. The distances between check and control points have been measured by means of two photogrammetric systems, adopting control points and distances constrains to calculate the external parameters or to scale the object model.

The distances, compared to those obtained be means of stereoscopic skill and the topographic network, are characterized of standard deviation contained by ± 1.6 cm, in agreement with the photos scale factor.

The results from the experiment confirm, that simple and fast photogrammetric techniques are able to completely meet the requirements of cultural heritage documentation being inexpensive and efficient in comparison to the traditional ones.

These alternative methods enlarge the use of photogrammetry, even if elementary geomatic knowledge are still necessary to solve problems related with the survey, the data processing, the coordinates transformations etc. Besides verifications concerning the real accuracy of the elaborates are always necessary to complete the restitution works and to understand their effective accuracy.

Virtual models can be easily generated even from unconventional photogrammetric systems. These photo models easily divulgate on the InterNet, permit animation and 3D visualization, therefore today are fundamental tools for the Cultural Heritage knowledge and documentation.

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