ANALYTICAL PHOTOGRAMMETRY AND COMPUTER GRAPHIC REPRESENTATION: COMPARATIVE ANALYSIS BETWEEN DIFFERENT SYSTEMS ON THE CITY WALLS OF CITTADELLA (Padova) ITALY

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The University of Architecture in Venice is involved in a research program on the walled city of Cittadella. A specific field of experiment has been tested to determine how to combine "classical" expertise with the "new" approach of computer vision, 3D models and cost-benefit analysis. The aim of this project is to establish a precise set of specifications for the technical approach to historical analysis and restoration. Here, photogrammetry must provide the cartographical support and constitute the basic reference for all future interventions. At issue is the graphic model which has to provide geometric information and architectural details at various scales while at the same time being compatible with personal computers and accessible to the research programs of many different disciplines. We will test instruments and procedures, comparing the results of photogrammetrical restituion of walls and towers.
Summarizing briefly, our attention will be dedicated to:
1 - analytical restitution at different scales with autocad editing,
2 - different restitution systems related to photograph-based bidimensional and tridimensional digitization programs (PHOX system, Elcovision, MR2 Rolleimetric system...)
Great attention will be dedicated to the search for graphic quality which is both precise and affordable.

The various experiments we have conducted in Cittadella have given conclusive results. Within the scope of this project we have responded to the needs of various disciplines involved in the analysis of the city walls by considering those procedures,costs and instruments relative to each field of experiment.

In addition to our conclusions, outlined in this paper, we have proposed a new set of experiments which will be conducted in the near future.

In brief, we can simply state that the photogrammetrical survey of city gates and towers has to be carried out in a different way from a survey of the city walls. The reasons for this variation are both technical and economical as different types of information are required for each type of survey.

Towers and gates will be investigated using "classic" photogrammetric methods, that is, using large size film and interchangeable lenses, because of their large dimension (from 14 to 20 meters in height), their number (36), and their several relevant architectural details. In addition, special attention has to be given to the area of connection between these elements and the walls since towers and gates are the statical support of the walls, and because the greatest number of disconnections, cracks, and deflections are concentrated here.

The photogrammetrical survey of these elements is aimed at producing analytical restitution at a large scale (1:50). Consequently, the format of the film has to be broad in order to both reduce the number of topographical points required and to create bigger models which can be explored stereoscopically. These large models are a marked advantage in a study of such elements because of the great amount of information which they provide.

For the walls, on the other hand, it is more convenient to use pseudometric cameras with interchangeable lenses that have restitution systems adequate to accept the use of monoscopical photographs. Because of the great extension of the walls (35 sections of approximately 40 meters each), the scale of the drawings will be 1:200. This scale is sufficient to create a comprehensive "general map" of the walls, but is inadequate for any detailed analysis, either architectural or archeological. Our goal is to simplify and to accelerate the procedures we rely on (outlined in the following pages) and to identify the photographical "treatment" most capable of providing all the information, such as cracks, stratification of the different layers of masonry, control of erosion, and placement of the guard walk, necessary for restoration interventions.

From the technical point of view, in order to reduce the number of photos necessary for this program we anticiapte the use of a lift truck. Not only will this decrease the number of shots needed, but it will also result in photos of the structure with the least possible degree of distortion.

One requirement of the targets is that their form and dimension be such that they are easily centered when the digitizer is used for the restitution process using printed photographs. Therefore they will have the shape of a square of approximately 20 cm. The usual information required for their correct classification (number, code, date, etc.) will also be transferred.

As far as restitution is concerned we have planned to use stero-analytical instruments in order to achieve a higher degree of efficiency and better results.

Every model will have to respect codified specifications in order to guarantee uniform and accessible data. All data will be recorded in an ASCII file and all the specifications of file format will be stored on disk to enable the most general use for CAD programs, particularly AUTOCAD.

Since the ultimate goal of this process is to produce a tridimensional "wire frame" model of the walls, the restituted form has then to be tri-dimensional. This means that every point has to have three coordinates related to the general system of reference set up by the principal topographical net. The lines connecting the various points of the model, or of any other graphical entity representing an object in the space, will then be lines in a three dimensional space.

In the general scope of this specific work we intend to process all the elements that are considered significant by the various disciplines (archeology, construction theory, chemistry, physics, etc.) into a three dimensional model which will constitute the "space archive" of the walls. Accordingly, all bidimensional drawings produced will be recorded in an Autocad (DWG) record. Particular attention will be dedicated to photographical rectification as it is necessary to have a continuous image of the entire measured object.

This restitution is problematic, however, because the walls are not aligned rectilinearly from tower to tower and the crenellation is not on the same plane as the main body of the walls. The first problem can be solved by taking a photo for every single element of the broken line. For the second we are trying to find an interesting solution thanks to new instruments provided by the Galileo firm which we will discuss shortly.

The phase of restitution is divided into two parts:
1) Three dimensional restitution carried out at different scales of representation: one for the wall's gate and towers, and one for the masonry panels.
2) Photographic restitution (rectification) of all the boundary walls - the aim of this experiment.

Three Dimensional Restitution

The restitution of the photograms for the gate and the towers is carried out with a stereoscopic analytic instrument (Kern DSR1) at a scale of 1:50. This graphic representation is expressed as an orthoganal projection viewed on a vertical plane and obtained through the analytic interpolation of targets. Within this geometric representation of the observable solid the average parallel plane to the front view of the optical model contains all the numerical information belonging to the survey (targets, elevations, contour lines, etc.).

The residual error on this plane of representation is maintained at +\-0.3 mm at the scale of design. Diverse analytical systems were tested for restitution of the masonry panels starting with a photograph taken with a semi-metric camera rather than a stereoscopic one.

In addition to the summary described above, the general characteristics of these systems should be as follows:
a.) the capability of using simultaneously a number of photographs from 2 to 8;
b.) the use of a digitizer as an instrument able to measure the two plate coordinates;
c.) the use of a personal computer as a tool of calculation;
d.) the possiblity of interfacing with Cad programs, preferably AutoCad;
e.) the restitution of three dimensional points.

The representation has been established at a scale of 1:200 and the graphic information is stored both in the system of general reference and as an orthogonal projection on the vertical plane parallel to the single segments of the fragmented line.

In the case of Cittadella, in order to guarantee a great degree of control and precision in the restitution of these points, a minimum of three photographs is necessary in order to formulate the model. In general, this model consists of a number of "n" photographs covering the same segment of wall or part of that same segment. This representation includes the crenellation contours, all holes, targets, and the most evident bands of stratification in the wall's diverse layers of masonry. At a scale of 1:200, the graphic error of this representation is always maintained below 4 cm.

A comparative analysis of the diverse systems available on the market (Rollei System MR2, Phox, Elcovision 10 is part of a series of tests we are developing with the Insitute of Topography of the University of Bologna, on several buildings and under different conditions), the characteristics of which will be described later, has been performed on a very limited area on the internal "masonry panels" using six targets with a (RMSE) root mean square error of 3 mm in absolute value.

One aspect of this process still under consideration regards the stereoscopic photos. These are always taken with a semi-metric camera which permits a "classic" analytic restitution. This "classic" restitution then acts as a control against which are compared those results obtained with other systems.

Within this experiment, not only has the restitution of targets and of the values of orientation parameters been evaluated, but these targets and parameters have also been singled out as a series of characteristic geometric points related to the structure of the object from which we have extrapolated three dimensional coordinates. In particular, for the Phox

system, photographs are taken with a Pentax camera format 24 x 36 mm and focal length of 50 mm. The average scale of these photograms fails between 1:500 to 1:750 with an average scale of enlargement about five times greater than that of the negatives.

For the restitution, if three prints are used possessing targets lying on different planes which have been partially surveyed topographically, the number of photos required by the program, between 10 to 15 when using a non-metric camera and from 7 to 10 when using a metric camera, can be derived photogrammetrically from the stereoscopic photos of the same section of wall. These photos contain significant points identified as coordinates which are used for the analytic restitution.

The phase of orientation is executed in two stages: in the first phase the calculation of orientation parameters is conducted ignoring the resulting distortions, as all images are distorted to a certain extent; in the second phase all parameter distortions are accounted for and corrected. The value of the "sigma 0" indicates the orientation's degree of precision and the residuals of observation expressed in digitizer units. In general, the lower this value, the more reliable the orientation.

After creating the orientation without taking distortions into account, the second phase of calculation proceeds in a manner similar to the first one, but in an interactive mode with a ratio of convergency that tends towards 0. To continue, one proceeds by establishing the constitutent elements of the subject through a coincidence of corresponding significant points. Related to these restored points are the three dimensional coordinates X,Y,Z. In correspondence with the coordinate digitizer, these points are assigned specific values pertaining to the residuals of observation and the value of "sigma 0" relative to these same residuals.

If the Elcovision system is used for restitution, a semi-metric Leica R5 camera with a format of 24x36 mm and a focal length of 24 mm can be used. The average scale of photograms, as found in the stage of the "masonry panel" experiments, exists here at a scale of 1:500 and 1:750 with an average scale of enlargement from about 5 to 7 times greater than that of the negatives. The dimensioning and positioning of the models is established by means of targets as pointed out previously in the phase of the topographical survey (6 points in total).

The preliminary phase of orientation allows one to control the data's reliability, first providing the residuals of the sights on the grid (Dx and Dy), then the points of orientation relative to parallax Py and absolute (Dx, Dy, Dz), and finally the (RMSE) root mean square error of the calculated parameters. It is also possible to identify the three dimensional coordinates of the retained, significant targets of the object and to compare them with the stereoscopic restitution by means of a graphic editing program developed within this system. According to the scheme of photos necessary for restitution, those three taken using the Rollei MR2 system are executed with a semi-metric Rollei 6006 camera with a focal length of 40 mm. Here, two convergent takes are aimed towards a central point containing the six targets identified previously using the analogic photographic points in the three takes. Although this increases the number of points necessary for the solution of the photogrammetric problem, a maximum of eight different points, between which all distances must be known, and a maximum of twenty observations must always be maintained. The average scale of the photograms remains equal to that used in the preceding case although the restitution is performed at an enlarged scale three times greater than that of the negatives.

The phase of orientation occurs in different stages: initially the model develops from two photograms to which are then linked all the others following a pre-established sequence until finally this set of models is processed and placed on an average position on the targets. The final orientation of this synthesis of models is calculated photogram by photogram according to the parameters of the shots, the orientation, and the residuals of observation.

The Rollei apparatus uses the same number of points derived from images for the acquisition and treatment of data as those used in the preceding experiment. The control of the design is obtained, also in this case, by identifying and combining points. Control of the outcome of the layout, however, is entrusted to the sigma of the coordinates of single points (minimum three photos) and is automatically processed. This qualitative evaluation of the diverse systems with which we've experimented, which are differentiated primarily in the final stage of the photogrammetric process, is based on the use of simplified systems and efficient software, but surely suitable for objects of ordinary morphology.

The quantitative analysis which appears in the enclosed table confirms the evaluation made previously on the described aspects of the system keeping in mind that one must compare separately the planimetric aspect X, Y from the altimetric Z., However planimetric values match those values intrinsic to the graphic tolerance of the scale of representation and change considerably when depth is also introduced. If, on one hand, the metric data is obtained with sufficient approximation, the semantic aspect is often quite deceiving, although we must consider that we have compared two diverse methodologies, the first being very experienced and the second completely new.

Photographic Restitution

The masonry curtain under consideration, as was mentioned previously, remains the object of this test of photographic restitution at a scale of 1:100 then reduced to a scale of 1:200 with the proceeding photo mechanics. The shots necessary to obtain photographic rectification of the masonry panels presented problems as they are not rectilinear. In fact, a shifting of pararellism with the plane of reference creates errors in the coordinates on the printing plane which affects the corrected orthogonal projection. For

this reason we have photographed separately every fragment of the segmented line in such a way that the optical axis of the lens was perpendicular to the wall.

The operation of rectification is carried out with an analogic technique reproducing the original image under particular optical and geometric conditions on an appropriately inclined plane using the same targets of the restitituion. The plane of projection always corresponds to a vertical plane parallel to the segment ignoring the plane of crenellation. Fortunately we have today the possibility to transfer information from photographic prints into a numerical form which can be stored in and manipulated on a personal computer. Furthermore we have also the capability to test a numerical system of rectification through digitial information. In fact, the Orthomap system, produced by Galileo Siscam and tested by us, permits the rectification and orthogonalization of numerical images.

Various types of tests have been carried out:
- the creation of a digital photoplane of the same segment of wall tested in the preceding case;
- the creation of a digital photoplane including diverse shots in order to test the patchwork of photogrammetry;
- the creation of a digital photoplane of a particular shot with a semimetric camera with a focal length of 150 mm and successive vectorialization of each segment of the wall texture at a scale of 1:25;
- the creation of a digital ortophoto always of the experimental segment.

The digital photo plane has been created from a digital image of a shot from the knowledge of the coordinates of the object and the corresponding coordinates of a certain number of points of the image plane.

The procedure does away with the errors due to the inclination of the camera but does not eliminate the deformations due to the different inclination of the photographed object. For this reason we have decided to have two different planes, one for the crenellation and one for the wall panel, both integrated with the coordinates given by the targets surveyed photogrammetrically.

The quality of the photomap is determined by the control of the residual error resulting from the calculation of the parameters of the homography. If the object is similar to a plane and the coordinates of both the object and the photo map are correct, the residual error is close to zero.

The experiment for the digital orthophotography has been treated on the digital image taken with the corresponding targets and a DTM created on a regular grid of 20 cm. This procedure eliminates the various errors of inclination, both of the object and the camera integrating the DTM with a file of restitution where the lines of the elements with different depth (such as holes, embrasures, etc.) are clearly delineated. The measures on the orthophotography being correct we have been able to confront these results with the previous ones.

Drawing a conclusion at the present stage we can state taht we do not have great differences between the various instruments and softwares: all of them as far as the problem of Cittadella is concerned present tolerable errors for the scale of restitution.

The use of Rollei 6006 and MR2 system has the advantage of a larger size of film therefore reducing the number of photos and topographical targets. Given the extension of the walls this is a device that will cut down the cost drastically.

We will develop in the near future the experiment with Galileo Siscam in order to set up correct specifications for the use of Orthomap system: it looks in fact the best solution, the quickest, the most agile and definetly adequate to the demand of the scierntific committee governing the conservation of Cittadella.

CITTADELLA SECTION 4	QUADRANT SOUTH-WEST

	TOPOGRAPH. TARGETS		
VERTEX	X	Y	Z
2	124,9212	121,9879	16,9872
3	117,5905	120,7668	16,6198
4	111,1214	119,4932	17,0205
15	125,2616	120,7467	4,7362
16	117,6119	119,426	4,7127
17	111,6196	118,2052	4,4077

	RESTITUTION KERN DSR1		
	X	Y	Z
	124,9181	121,9966	16,9899
	117,5905	120,7664	16,6160
	111,1227	119,4988	17,0248
	125,2700	120,7500	4,7279
	117,6126	119,4267	4,7106
	111,6200	118,2019	4,4036

ORTHOMAP PHOTOPLANE	
X	Z
124,9200	16,9900
117,5400	16,5500
111,1200	16,9700
125,2500	4,6900
117,6100	4,6700
111,6100	4,3600

ORTHOMAP ORTOPHOTO	
X	Z
124,9100	16,9800
117,6100	16,6000
111,1300	16,9900
125,2800	4,7000
117,5900	4,6800
111,6000	4,3900

PRECISION CONFRONTED WITH TOPOGRAPHICAL TARGETS

VERTEX			
2			
3			
4			
15			
16			
17			

Dx	Dy	Dz
0,0031	-0,0087	-0,0027
0,0000	0,0004	0,0038
-0,0013	-0,0056	-0,0043
-0,0084	-0,0033	0,0083
-0,0007	-0,0007	0,0021
-0,0004	0,0033	0,0041

Dx	Dz
0,0012	-0,0028
0,0505	0,0698
0,0014	0,0505
0,0116	0,0462
0,0019	0,0427
0,0096	0,0477

Dx	Dz
0,0081	0,0072
-0,0195	0,0198
-0,0086	0,0305
-0,0100	0,0362
0,0219	0,0327
0,0196	0,0177

medium	
rmse	

-0,0013	-0,0024	0,0019
0,0038	0,0043	0,0047

0,0127	0,0423
0,0191	0,0241

0,0019	0,0240
0,0171	0,0110

PRECISION CONFRONTED WITH KERN DSR1

VERTEX			
2			
3			
4			
15			
16			
17			

Dx	Dz
-0,0019	-0,0001
0,0505	0,0660
0,0027	0,0548
0,0200	0,0379
0,0026	0,0406
0,0100	0,0436

Dx	Dz
0,0081	0,0099
-0,0195	0,0160
-0,0073	0,0348
-0,0100	0,0279
0,0226	0,0306
0,0200	0,0136

medium	
rmse	

0,0148	0,0398
0,0217	0,0250

-0,0012	0,0238
0,0166	0,0105

CITTADELLA	QUADRANT
SECTION 4	SOUTH-WEST

	TOPOGRAPH. TARGETS		
VERTEX	X	Y	Z
2	124,9212	121,9879	16,9872
3	117,5905	120,7668	16,6198
4	111,1214	119,4932	17,0205
15	125,2616	120,7467	4,7362
16	117,6119	119,426	4,7127
17	111,6196	118,2052	4,4077

	RESTITUTION KERN DSR1		
	X	Y	Z
	124,9181	121,9966	16,9899
	117,5905	120,7664	16,6160
	111,1227	119,4988	17,0248
	125,2700	120,7500	4,7279
	117,6126	119,4267	4,7106
	111,6200	118,2019	4,4036

RESTITUTION	SYSTEM	PHOX
X	Y	Z
124,9012	121,8898	17,0026
117,5875	120,7559	16,5869
111,0999	119,4759	17,0005
125,2589	120,7159	4,7525
117,5896	119,3985	4,6989
111,5876	118,1189	4,3987

RESTITUTION	SYSTEM	ROLLEI MR2
X	Y	Z
124,9250	121,9830	16,9870
117,6030	120,7460	16,5960
111,1210	119,4990	17,0260
117,6020	119,4240	4,7130
111,6100	118,2120	4,4080

RESTITUTION	SYSTEM	ELCOVISION
X	Y	Z
124,9120	121,8930	16,9770
117,5970	120,5910	16,5440
111,1530	119,3960	16,9580
125,2170	120,7340	4,7200
117,5470	119,3700	4,7080
111,6100	118,2040	4,4120

PRECISION CONFRONTED WITH TOPOGRAPHICAL TARGETS

VERTEX			
2			
3			
4			
15			
16			
17			
	medium		
	rmse		

Dx	Dy	Dz
0,0031	-0,0087	-0,0027
0,0000	0,0004	0,0038
-0,0013	-0,0056	-0,0043
-0,0084	-0,0033	0,0083
-0,0007	-0,0007	0,0021
-0,0004	0,0033	0,0041
-0,0013	-0,0024	0,0019
0,0038	0,0043	0,0047

Dx	Dy	Dz
0,0200	0,0981	-0,0154
0,0030	0,0109	0,0329
0,0215	0,0173	0,0200
0,0027	0,0308	-0,0163
0,0223	0,0275	0,0138
0,0320	0,0863	0,0090
0,0169	0,0452	0,0073
0,0117	0,0373	0,0197

Dx	Dy	Dz
-0,0038	0,0049	0,0002
-0,0125	0,0208	0,0238
0,0004	-0,0058	-0,0055
0,0099	0,0020	-0,0003
0,0096	-0,0068	-0,0003
0,0007	0,0030	0,0036
0,0095	0,0111	0,0115

Dx	Dy	Dz
0,0092	0,0949	0,0102
-0,0065	0,1758	0,0758
-0,0316	0,0972	0,0625
0,0446	0,0127	0,0182
0,0649	0,0560	0,0047
0,0096	0,0012	-0,0043
0,0150	0,0730	0,0275
0,0348	0,0644	0,0332

PRECISION CONFRONTED WITH KERN DSR1

VERTEX			
2			
3			
4			
15			
16			
17			
	medium		
	rmse		

Dx	Dy	Dz
0,0169	0,1068	-0,0127
0,0030	0,0105	0,0291
0,0228	0,0229	0,0243
0,0111	0,0341	-0,0246
0,0230	0,0282	0,0117
0,0324	0,0830	0,0048
0,0154	0,0405	0,0056
0,0085	0,0381	0,0234

Dx	Dy	Dz
-0,0069	0,0136	0,0029
-0,0125	0,0204	0,0200
0,0017	-0,0002	-0,0012
0,0106	0,0027	-0,0024
0,0100	-0,0101	-0,0044
-0,0018	0,0091	0,0048
0,0101	0,0096	0,0104

Dx	Dy	Dz
0,0061	0,1036	0,0129
-0,0065	0,1754	0,0720
-0,0303	0,1028	0,0668
0,0530	0,0160	0,0079
0,0656	0,0567	0,0026
0,0100	-0,0021	-0,0084
0,0176	0,0909	0,0324
0,0405	0,0596	0,0340