DIGITAL ORTHOPHOTO AS A TOOL FOR THE RESTORATION OF MONUMENTS

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ABSTRACT

For the restoration of monuments it is now becoming normal practice to carry out a preliminary study of the monument before starting any kind of work. The metric survey is one of the main operations required. For this reason, photogrammetry applications already have a large bibliography. In particular, digital photogrammetry is currently an effective system, providing different solutions of both the vector and raster type.
For an 18th-century gate in the Malta fortification walls, many tests were carried out in order to establish a suitable procedure for the creation of digital orthophotos. A photographic metric product, showing maximum detail without subjective interpretation of the object and the conditions of the material, could be very interesting in supporting any restoration work. The use of automatic procedures is also particularly suitable where large-scale surveys have to be carried out on very large objects with homogeneous characteristics, as is the case with the Malta fortification Walls. The advantages of digital over manual processing lie in the possibility of measuring a very large number of points without fatigue and with a high level of productivity. Digital orthophotos require a digital surface model as input, but the production of a high-fidelity reconstruction of surfaces by automatic measurement of points in close range photogrammetry still remains an open problem. Particular difficulties are caused for instance by object details that are not imaged or with strong shadows, or by complete failure of the image matching algorithms. Discontinuities in the surface, very common in architectonic objects, complicate the generation of models and surfaces.
Within this work, several tests using commercial software were carried out, to define the best parameters for the automatic generation of DSM (Digital Surface Model) related to the monument being studied. The initial tests are based on the different dimension of the search window and the consequences of this choice on the accuracy and reliability of the matching procedure. Further tests are related to the number of points needed to start the matching procedure: firstly, points have been entered following a regular grid, then a greater number of points from the analytical plotting have been entered. The results are compared, also taking in account practical and economic considerations.
Finally, different aspects for the creation of representative surfaces of the object have been analysed due to the non planarity of the object, presence of linear discontinuities and noticeable overhangs.
The above-mentioned tests lead to several general considerations regarding strategies for creating orthophotos as a suitable qualitative and quantitative tool for the restoration of a monument.

1 INTRODUCTION

The increasing use of non-destructive scientific study techniques for the study and conservation of historical buildings, constructions and in general in the field of Cultural Heritage, is a symptom of how the operating procedure in such areas aims to use a modern scientific and technological approach, deciding beforehand, that is to say, before any work is started, which methods will be used, the sequence of procedures and their possible consequences.
Close range photogrammetry is essential in this context, since it allows metric-morphological reconstruction of the work examined, which can be documented and filed on paper or computer.
In the architectural surveying sector for the restoration of historical buildings, one of the most effective photogrammetric product may be the orthophoto derived from digital differential rectification techniques; the generation of a photographic image with metric characteristics constitutes a valuable tool for gathering information about the object, thanks to his characteristics of immediate implementation, accuracy and flexible usage (Baratin et al., 2000). A digital orthophoto is an orthographic photograph of objects which reproduces the photo-texture, colours or grey tones of the original photographs. It is derived from conventional perspective photographs by simple or differential rectification. Each pixel of the image is transformed by means of an orthogonal projection with scaling onto a horizontal

plane which represent an element of or the entire digital surface model of the object; image resampling is carried out using different kinds of transformations (Kraus, 1997).
The orthophoto support is given by the object DSM, which can be created with various manual or automatic methods.
Close range photogrammetry has been proven to provide significant cost savings over conventional measurement techniques. However, the photogrammetric processing stage has typically been slowed due to reliance on manual procedures. Introducing automation to photogrammetric processing is an obviously desirable advantage. However, varying scale, large depth of field, obstructions, kind of object surface and lighting differences can pose difficulties in automating photogrammetric processing in close range environments. The procedure followed for generation of the DSM directly influences the quality, in terms of precision, of the orthophoto produced. For better results, a preset procedure must be followed, considering that even if automatic DSM generation is currently a most interesting practice for replacing a repetitive and expensive stage of conventional photogrammetric production, its level of accuracy is not always clear (Achilli et al., 1998; Bitelli et al., 1999-a; Zanutta, 2000).
In the research described, which takes as its example an 18th-century gate in the fortification walls on the island of Malta (Zabbar Gate, at Cospicua; figure 1), a low cost digital photogrammetric station (StereoView Menci Software) was used to carry out a series of tests designed to identify the most suitable matching parameters for automatic generation of the DSM of the monument. Following generation of the DSM, several tests were applied to define the optimum procedure for construction of digital orthophotos. This optimised procedure would be used not only to identify the correct parameters which guarantee metric precision in the product obtained, but also a level of quality which makes it a valid support for the various analysis operations involved in the restoration of a monument: quality of the materials, analysis of their deterioration, etc.
The research is part of a project for the recovery of the system of fortifications on Malta, which arose as a result of co-operation between the University of Bologna and the Maltese government (Baratin et al., 1998).

2 SURVEYING THE FAÇADE OF THE ZABBAR GATE

The Zabbar Gate (figure 1) was built after 1706 by the Roman architect Fortunato Carapecchia. The gate's design is one of a vast series of "ideas for great churches" and "military defence works" for Malta which Carapecchia perfected during his stay on the island. For this gate, a survey of the façade was carried out: firstly, artificial control points (retro-reflecting signals) juxtaposed with the walls were topographically measured, then the photographs were taken and, finally, 1:100 vector plotting of the façade was carried out.

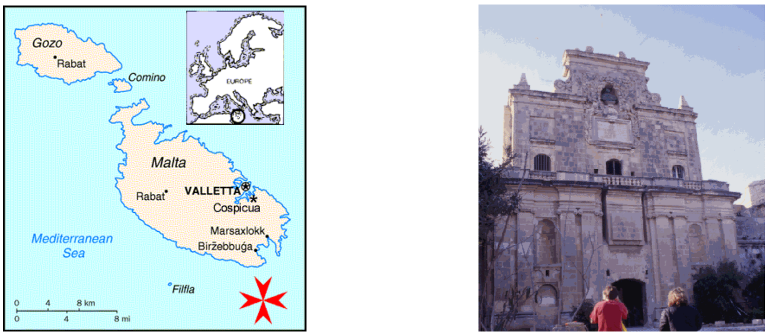

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Figure 1 – a) Map of the Malta Island; b) Zabbar Gate façade along the Cottonera Lines.

The topographical survey was realised by a Leica TC2000 total station. The space resection method was used starting from two stations located at the same distance from the façade, with measurement of the azimuthal and zenithal angles and, where possible, inclined distances. The least squares adjustment of the network produced the object coordinates of the signalised control points with error ellipses (95% confidence level) of just a few millimetres.
The nadiral photogrammetric images, acquired using a Wild P31 metric camera with lifting truck at various heights, were taken in such a way as to cover the entire object with sufficient stereoscopic overlap. The shooting distance of approximately 20 m gave the photograms a scale of 1:200.
The plotting, carried out using the Galileo Siscam Digicart 40 analytical plotter, produced conventional graphical and numeric results such as prospects, sections and profiles in a scale of 1:50, suitable for restoration of the structure (Bitelli et al., 1999-b).
The structure examined is entirely represented by four stereoscopic models obtained from orientation of the nadiral or psuedonadiral photograms. In order to generate an image of the façade with metric characteristics easily manageable in a CAD environment, the errors linked to the use of simple perspective rectification of a photogram were evaluated. The object surveyed has a maximum overhang of around 2.5 metres in the balcony area. In the models there are various shadow zones in which the stereoscopy is null or of poor quality. Generation of a pure perspective rectification would

introduce unacceptable errors due to radial image point displacements (up to theoretical values of $\Delta\rho \approx 10.9$ mm on the image): differential rectification is required, which leads to creation of the orthophoto. In such cases, it is essential to have 3D mesh models of the façade, on which carry out differential projection of the individual elements of the image. The 3D model of the object may be made manually, in semi-automatic or fully automatic mode. The following section describes a set of tests for automatic DSM generation.

3 AUTOMATIC DSM GENERATION TESTS

The aim of matching in photogrammetry is to define the three-dimensional object coordinates from images. The points in the object-space are related to the points in the image system by means of the collinearity condition.
However, to solve image matching, that is to say, to establish correspondence between images or between images and a model, there is not one solution, but a variety of strategies which are often combined (Hahn, Förstner, 1988; Heipke, 1996; Helava, 1988; Kraus, 1997). Yet the matching problem cannot always be solved and even the most sophisticated algorithms recently produced may fail or supply ambiguous solutions. For example, for a given point on an image the corresponding homologous point on other image(s) may not exist or may be in an ambiguous position due to repeated geometric patterns or poor image information content (texture).
A variety of matching algorithms presented in literature is implemented in digital photogrammetry stations. The research in question made use of the low cost StereoView software, running on PC platform, made by Menci Software srl (*http://www.menci.com*) and distributed by Nikon Instruments spa. The software uses for the image matching a mixed area/feature based algorithm with the matching method known as VLL Matching (Vertical Line Locus; Kraus, 1993). Thus, the program can create a 3D model of the object studied, starting with a pair of digital stereoscopic images and known object coordinates. However, automatic point positioning does require a minimum user intervention. The images are matched on a regular grid of the model, defined in advance by the user. First, at least 3 three-dimensional points must be positioned manually, to allow definition of a reference surface for the start of matching. The automatic matching process starts from the starting point, that is to say, from the three-dimensional point located in the working area which has the greatest correlation coefficient. It may be a control point or a three-dimensional point entered by the operator (therefore, with maximum correlation coefficient). The final product of matching is a DSM, which is easily manipulated to create a 3D raster model of the object, of which the orthophoto constitutes a special view (orthogonal).
To create a good quality DSM, suitably defining the automatic matching parameters and minimising editing before and after, the photograms are first scanned using a DTP (Desk Top Publishing) scanner with 1200 dpi resolution, guaranteeing a object pixel size of approx. 4 mm (table 1).
The scanned images (figure 2) are corrected to remove the geometric deformation errors introduced during the acquisition stage, using a special calibration module (SVScan), supplied in addition to the StereoView software.
After the internal orientation, the photograms are externally oriented by means of bundle adjustment, simultaneously, on the basis of the control and observation points. The orientation residuals in the various models show an average standard deviation value in the three coordinates of 2.8 mm.

Camera	P31 Wild	Image resolution	1200 dpi
Lens	99.39 mm	Image scale	1:190
Film size	90 x 120 mm	Pixel image	(25400:1200)≈21.67μ
n. images / n. stereomodels	4 / 2	Pixel on the ground	(21.67*190)≈ 4mm

Table 1 – Main characteristics of primary data acquisition and scanning.

Figure 2 – Photograms of the Zabbar Gate, test object.

The area tested, measuring approximately 10 m^2, is the lower right-hand part of the structure. It is reproduced in two photograms (bottom in figure 2) and, therefore, a single photogrammetric model.
7 DSMs were automatically generated, on a square grid with grid interval 5 cm, changing some matching parameters each time. To start the matching, the same grid of 334 basic points manually acquired at the digital station in stereoscopic mode was employed, with grid interval of 50 cm. In order to validate the models generated in this way, a reference DSM of 8428 points was created using the Digicart 40 analytical plotter, with the same coordinates of the origin and grid interval 10 cm.
Comparisons were made by subtracting the models generated using StereoView point-by-point from the reference DSM. The initial tests were carried out by varying the half-width of the search matrix ($\Delta X = \Delta Y$ = 7, 9, 11, 15, 21, 31 pixels) and repeating automatic matching, starting with the same basic information (same model, orientations and set of basic points). The half-width is related to the horizontal and vertical dimension of the search matrix, expressed in pixels: a value of $\Delta X = \Delta Y = 10$ pixels defines an area of size 20x20 pixels on each image. The matrix size, expressed in the object reference system, can be calculated by multiplying the size of the search window in pixels by 4 mm (pixel size in the object system).
The results of the comparisons and some statistical parameters for the differences between the model produced by the analytical plotter (D) and those generated automatically (7÷31 spot pixels), are indicated in the following table.

	Search window size		DSM points	Mean	Std. Dev.	Min/max	percentage frequency of point differences						
	Image (pixels)	Object (cm)	(n. and % Cc≥0.7)	(mm)	(mm)	(mm)	-400 ÷ -10 cm	-10 ÷ -5 cm	-5 ÷ -2 cm	-2 ÷ 2 cm	2 ÷ 5 cm	5 ÷ 10 cm	10 ÷ 200 cm
D-7	14	5.6	4748 (56)	-23	230	-3479/1554	15.50	8.80	10.80	*30.00*	16.00	10.00	8.90
D-9	18	7.2	4872 (58)	-14	180	-3479/1738	11.40	7.50	11.80	*36.90*	17.70	8.40	6.30
D-11	22	8.8	5015 (60)	-14	138	-2171/1653	10.60	6.70	12.40	*40.40*	17.60	7.50	4.80
D-15	30	12.0	5277 (63)	-11	127	-2035/1669	9.50	6.30	11.10	*45.40*	17.30	6.60	3.80
D-21	42	16.8	5513 (65)	-17	133	-2013/1732	9.50	6.50	11.30	*49.00*	16.20	4.40	3.10
D-31	62	24.8	5547 (66)	-19	132	-1095/1622	12.2	9.3	9.0	*45.90*	14.0	4.9	4.7

Table 2 – Assessment of the differences between the reference model generated with the analytical plotter (D) and the seven surface models (spot size 7÷31 pixels) generated by matching procedure: search window size, number and percentage of points with correlation coefficient ≥*0.7,* main statistical parameters, percentage frequency of point differences.

The point comparison between the DSM created using the Digicart 40 analytical plotter and the DSMs produced digitally using the StereoView software, allowed the following conclusions to be drawn:
- the table indicates that the percentage of generated points, a function of the matching coefficient value used, is always lower than 70% and rises in direct proportion to the size of the search window;
- the residuals divided into classes shows that of the various tests carried out, the best solution is that in which the search window measures 16.8 cm (spot size = 21 pixels). In this solution, the frequency of residuals which belong to the central class of ±2 cm is the highest and the percentage of residuals relative to the extreme value classes is at a minimum. The solution is worsened by bringing the search window to 24.8 cm (spot size = 31 pixels);
- the statistical parameters for the depth differences, such as standard deviation, reveal that, in contrast to the previous conclusion, the best solution seems to be that obtained using a 12 cm (spot size = 15 pixels) search window. Said statistical parameters, calculated on the entire population of depth differences, are not sufficient to validate a DSM, since this requires a spatial evaluation of their trend on the object to identify local deficiencies on the model. It must be emphasised that the extreme incorrect values (outliers) have a significant influence on the depth difference statistics. Therefore, it is sufficient for the stereoscopic model to have occluded or shadow zones to automatically generate points with large errors.
The tests carried out revealed how the size of the image block, that is to say, the size of the search window, is a fundamental parameter in the image matching effected with the software.
Further tests, localised in the balcony area and, therefore, with the greatest depth difference (approx. 2.5 m), showed that the spot size of 21 pixels used was optimum for automatic imaging of the entire façade, both for flat zones and for zones with sudden depth changes.
The depth difference graphs (figure 3) show that on the flat areas of the object, increasing the search window visibly increases the points plotted correctly. The "salt and pepper" appearance is reduced, increasing the areas of homogenous distribution and the solution becomes more stable overall.

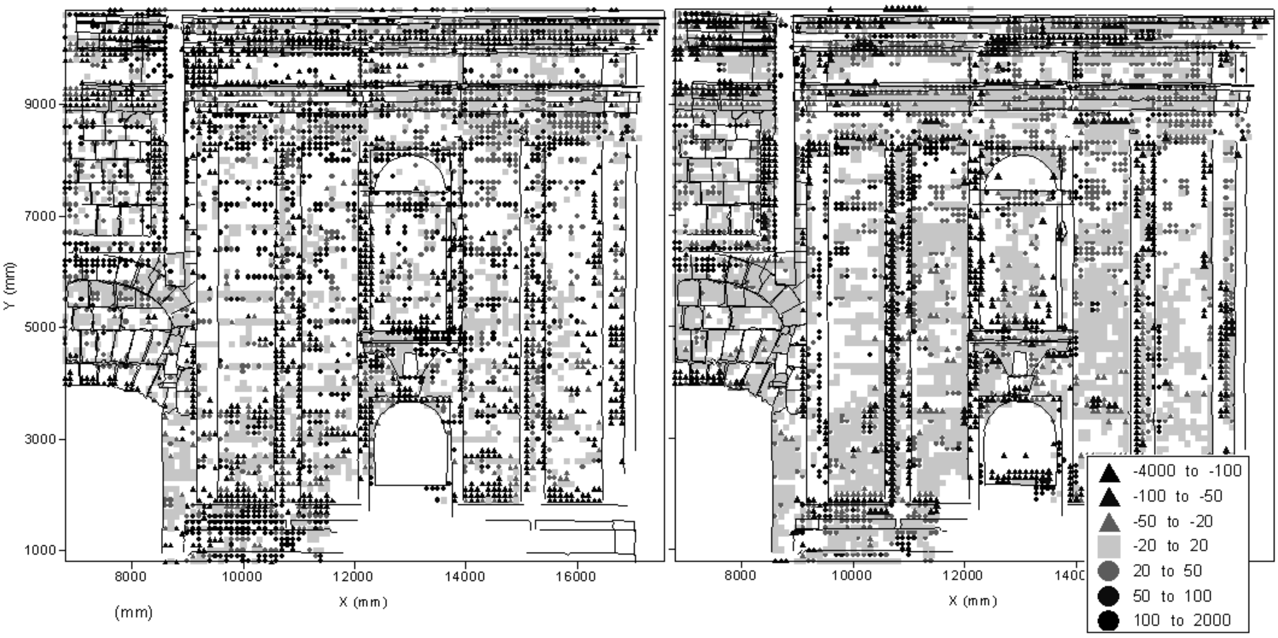

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Figure 3 – Differences between DSM generated with analytical plotter and automatic matching: a) spot size = 7 pixels; b) spot size = 21 pixels.

The classes of the residuals corresponding to the extreme values of the differences are relative to the shadow zones, with poor stereoscopic view and in correspondence of sudden changes in object depth.
The difference graphs reveal furthermore that there are numerous blank spaces due to the absence of data. Such gaps are caused by various factors: the correlation coefficient used (Cc=0.7) produces that not all points on the grid are plotted, but only those with Cc ≥ 0.7; the hidden zones were not plotted by the operator in the analytical environment and, as a result, were excluded from the comparison. In many cases, the blank spaces coincide with empty areas on the object surveyed (windows, doors).
Another test on the façade was carried out with the aim of checking if and how automatic matching is improved by introducing, in addition to the 334 basic points manually plotted according to a regular grid with side 50 cm, further points obtained by vector analytical plotting. Therefore, entering 2606 3D points obtained with manual vectorisation of the main features of the object, a DSM was automatically created on the entire right-hand part of the façade. A comparison with the reference surface model did not reveal any significant changes. It was observed that increasing the manually entered points to a disproportionate degree did not benefit the search for matches: it is sufficient to enter a set of points distributed evenly over the surface in order to cover all possible depths.
A final test carried out on the façade relates to the matching coefficient. The minimum acceptable value for this parameter is set before starting automatic matching and is used by the program to carry out data screening at the end of matching. A correlation coefficient is calculated for each point on the grid; the pairs of homologous points with a coefficient greater than the limit value set are plotted, whilst those with a lower value are rejected. As a result, the DSM produced often has areas without points. The use of such limits, therefore, presupposes that all points with high correlation coefficient values are correct. In the graph in figure 4, the matching coefficient calculated for each point is represented with a different colour, juxtaposed to the correct planimetric position. Gaps are represented by blank spaces and, as already indicated, can often be attributed to empty zones or lack of information, but not only this. The matching excludes points with a coefficient below 0.7: many blank zones can be explained by the absence of these data.
The graph in figure 4 and the graph of point differences (figure 3b) show that not all points with a high matching coefficient are correct and vice versa. The matching coefficient used as the limit in this case is not an effective parameter for measuring the quality of the points plotted.

4 ORTHOPHOTO GENERATION

Once the inner and outer orientation of the digital images is known, creation of an orthophoto requires representation of the surface of the object using faces (mesh) on which the individual portions of the images are projected.

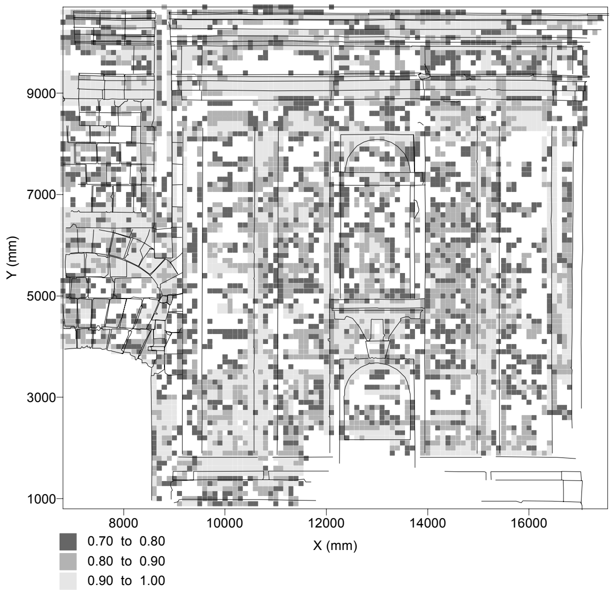

Figure 4 – Point values of the matching coefficient for the DSM generated with spot size = 21 pixels.

The object surfaces can be reconstructed by a set of points constituting point entities (DSM grid) and/or linear entities. The latter allow the identification of object elements such as discontinuities or special geometric features.

In close-range applications, the a priori description of the object must be carefully developed, to avoid gaps in the data which are reflected in the final orthophoto as surface deformations. During the plotting stage, ensure that all main discontinuities are represented by inserting points, lines and polylines, having a clear advance idea of the type of interpolator that will be used to create the DSM, support for the orthophoto.

In order to obtain a grid with user defined interval, an interpolating function determines the height value at the nodes on the basis of the heights of the adjacent known points, assigning each point a weight which is proportional to the inverse of the square of the distance from the node on the grid. The search can be limited to a surrounding area which is a function of the curvature of the object surface, calculated on the basis of the starting points.

Otherwise, particularly if the available information includes lines and polylines, Delaunay triangulation is a model widely used. This model is applied to the original data and leads directly to the construction of the object surface using triangles. These triangles are generated in such a way that they have equal angles as far as possible and the smallest possible sides, and the triangular Delaunay mesh passes through all of the object points.

Considering the two different approaches, and in order to identify the best procedure for creating an orthophoto of the object surveyed, taking care to limit deformations on the image and the operator’s work time, three methods for orthophoto production have been tested on the study object.

Orthophoto I (figure 5aA): DSM in automatic mode according to a grid spacing 5 cm; search window size 7.2 cm on object, correlation coefficient = 0.7; basic points 334. A full 5 cm DSM is obtained by interpolating values where not previously automatically calculated and finally the model is resampled to a 50 cm mesh for orthophoto production.

Orthophoto II (figures 5aB, 5bA): the DSM is interpolated according to a grid spacing of 5 cm, taking in account vector object plotting (points, lines and polylines) and resampled to 50 cm mesh for orthophoto production.

Orthophoto III (figure 5bB): the surface model is realised by a triangular mesh, directly from vector plotting data (lines, polylines).

An examination of the results allows some conclusions to be drawn, although they do not apply in general, being linked to the software platform used:

- the most effective procedure for creating an orthophoto of an architectural object, characterised by a number of planes and by discontinuities, is to vectorise the main breaklines and create the surface which represents the object using triangulation; projecting portions of the rectified image onto the surface generated in this way;
- a dense grid obtained from the interpolation of vector plotting does not always give an object surface without deformations and, as a result, a metrically valid orthophoto. The problem arises from the interpolation used which, on the basis of any algorithm, chamfers discontinuities such as boundary edges, indentations, etc. As a result, the surface derived from the DSM thus obtained cannot be used to model the object correctly, generating visible deformations on the orthophoto created;
- during the plotting stage, subsequent use of the numeric database must be clear, in order to adopt the most effective plotting method (profiles, sections, grids, isolines, polylines). It is essential to know whether or not the data will be interpolated and, if so, which model will be used. For example, if Delaunay triangulation is to be applied to the vector plotting data, the edges of all surfaces must be identified, by entering lines and polylines. The only use of points can create interference and must, therefore, be avoided. The lines and polylines must be accurately entered in order to

delimit planes with different depths, shadow zone limits and rounded geometric features. The number of points to be acquired depends on the complexity of the surface to be described. An undulating surface requires the insertion of adjacent profiles or sections with a sampling step directly dependent on its curvature. In the presence of surfaces with different depths, simply delimit the edges, bearing in mind that, with triangulation, each of the polylines plotted will become the side of a triangle which is, as far as possible, equilateral, forming an object surface consisting of triangles.

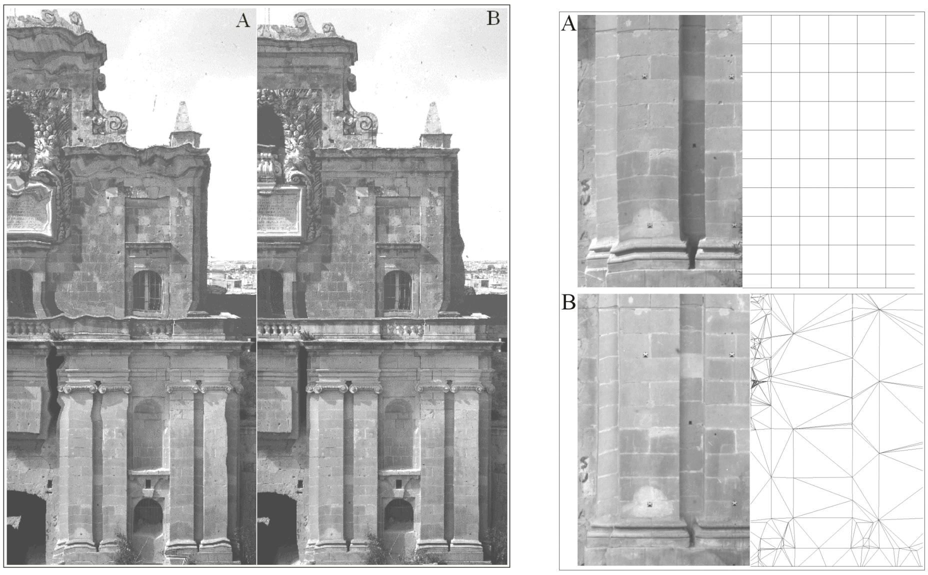

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Figure 5 - Orthophoto of a portion of the Zabbar Gate façade; a) with DSM generated automatically, without a posteriori editing (spot pixel 9; A); with DSM generated by interpolation of the analytical plotting (B); b) Detail of the colonnade and original DSM with regular mesh (A) and with triangular mesh (B).

A visual comparison of the result obtained by a traditional architectural plotting product versus the adoption of orthophoto can be obtained by figure 6, where the right side shows the orthophoto previously described in figure 5aB with superimposed the main features.

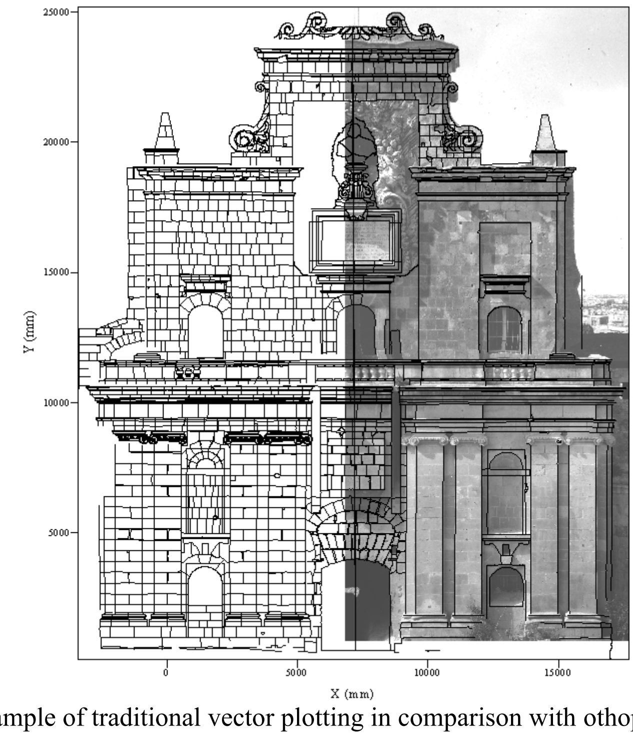

Figure 6 – An example of traditional vector plotting in comparison with othophoto for the façade.

5 CONCLUSION

More than other classic photogrammetric products, in the restoration sector orthophoto has the advantage of combining image metric quality with the possibility of obtaining information about the type of material, state of conservation and deterioration (for example, the presence of humidity, wall surface erosion, etc.).
The validation tests carried out on the digital photogrammetry station used revealed the current limitations of fully automated procedures and their sensitivity to the definition of some parameters.
If automatic DSM generation is now definitely an interesting practice for substituting a repetitive and expensive stage of conventional photogrammetric production, it is evident that the DSM generated requires accurate editing in order to correct errors, sometimes particularly large, which are introduced by automatic matching.
One very interesting point which emerged is linked to the possibility that an accurate photogrammetric survey, by using digital processing techniques and with integrated manual-automatic vectorising procedures, can constitute a valid support for decision-making procedures and the operative stages of restoration. In this context, the generation of digital orthophotos opens the way to new methods for approaching photogrammetric data, considered an open archive which can be accessed to directly carry out metric surveys.

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