OPTIMUM DIGITAL SURFACES MODELS GENERATED BY AUTOMATIC STEREO MATCHING OF CONVERGENT IMAGE NETWORKS.

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ABSTRACT:

In architectural photogrammetry, convergent geometry has some advantages over normal geometry. One of them is the reduction of the number of images needed for the full coverage of the object. This advantage simplifies network design and increases theoretically the accuracy of the method and internal reliability. However, the method has still not been widely used in practice because, probably the workflow has not been as consolidated as in the case of normal geometry.

In this article, we present and discuss the workflow to make a Digital Surface Model (DSM) of architectural façades semi-automatically and using convergent geometry. The accuracy of DSM is verified using and independent group of checkpoints, measured using conventional topographical methods. The influential parameters in the quality of DSM are discussed

This DSM generated includes a great number of 3D-points that come from diverse combinations of stereo-pairs. This points can have a very different accuracy and reliability, in addition to a great and nondesirable spatial redundancy.

We analized different methods to generate several synthesis DSM whose points are the result of a statistic process. The aim is to obtain a regular mesh of points whose Z coordinates are estimated from the whole set of data over the interpolating function. We choose the best of them using a random mesh of points whose coordinates were measured by multiple direct intersection.

RESUMEN:

En fotogrametría arquitectónica terrestre, la toma convergente tiene muchas ventajas frente a la toma normal. Una de ellas es la reducción del número de imágenes necesarias para el recubrimiento completo del objeto. Esta ventaja simplifica el diseño de la toma y aumenta la precisión del método y la fiabilidad interna.

Se presenta un flujo de trabajo para generar mediante toma convergente y procesos semiautomáticos, el modelo digital de superficie (MDS) de una fachada arquitectónica. La precisión del modelo es verificada mediante una malla de puntos de control, medida por topografía clásica. También se estudia la influencia de los parámetros variables en la calidad del MDS.

Un modelo Digital de Superficie generado mediante correlación automática a partir de imágenes convergentes, se forma gracias a un gran número de puntos con coordenadas tridimensionales obtenidos como puntos homólogos de las diferentes combinaciones de los modelos formados con cada dos imágenes que forman un modelo. Estos puntos tienen una precisión y fiabilidad diferentes.

Se analizan distintos métodos para generar un Modelo Digital de Superficies de síntesis cuyos puntos son el resultado de un proceso estadístico. El objetivo es obtener una malla regular de puntos cuya coordenada A sea estimada del total de puntos mediante una función de interpolación. Se elegirá el

mejor de ellos utilizando como comprobación una red de puntos de control medida mediante intersección directa múltiple.

1. INTRODUCTION

Architectural photogrammetry continues to be made with the strict limitations of aerial photogrammetry, in which the geometry is normal, the base is constant and the scale is uniform. These restrictions limit the flexibility now of recording data, increasing the number of images and requiring true acrobatics in order to resolve hidden areas. (See, for instance, [2]). The convergent geometry solves the problems of space and camera movement, the number of images necessary for the complete coverage is less than in the case of normal geometry and the multiple images assure that there will be a repetition, which may be taken advantage of in order to obtain results that are more precise.

The problem is in the data processing because the photogrammetric applications are designed principally for the treatment of aerial case, with normal geometry [8]. In this case an application is needed which will allow work to be done with a multi-images convergent network and photogrammetry in addition to implementing algorithms of stereo-matching for automatic Digital Surface Models (DSM) generation. The only commercial application that contains these characteristics is the extension Orthobase Pro of Erdas Imagine extension. Orthobase Pro allows for the adjustment of multiple networks with oblique images specifically designed for terrestrial photogrammetry. There are object programs that allow adjustments to be made with these types of networks but they are not able to execute a completely automatic DSM and you can work only with an outside of an ensemble of points marked on the object (see, for instance,[7]).

Once the net and the computer applications were defined, the work focused on a principal objective: achievement of a DSM with a maximum density of points and the best precision possible. In order to carry this out, experiments were performed in which various value combinations were tested for a group of potentially influential variables. The results will allow for a discussion concerning aspects such as the adaptation of the software to the type of geometry, which factors can limit the DSM precision and possible improvements or corrections in order to advance in the automatic architectonical generation of DSM.

The purpose of photogrametric methods basing on automatic correlation is to generate massive clouds of points (figure 3). This paper demonstrates that these data can undergo selection regarding the value of the correlation coefficient. Selection eliminates bad quality data and simplifies matters, in spite of which, the amount of resulting points is still huge. In this paper, a method to filtrate these points is introduced, in order to achieve a model of synthesis surface without appreciable loss in accuracy.

Several methods have been used; for example, Kriging, broadly used in other disciplines and based upon sound statistical principles, since it ensures an optimal interpolating function. The aim is to obtain a regular mesh of points whose Z coordinates are estimated from the whole set of data over the interpolating function.

2. DATA

This work was carried out on one of the churches of the historical centre: San Mateo Church, sited in Cáceres (Western Spain, city declared World Heritage by UNESCO in 1986). The Southern façade has a complex design due to the presence of one tower and some reliefs that frame the main gate. All these elements make this church ideal for our study (Figure 1)

Figure 1. Southern façade of San Mateo Church.

The points of photographic exposures form a convergent network of 11 images. The central image is perpendicular to the façade and the rest of them are taken with an increment of 5º at both sides up to a maximum of 25º (figure 2).

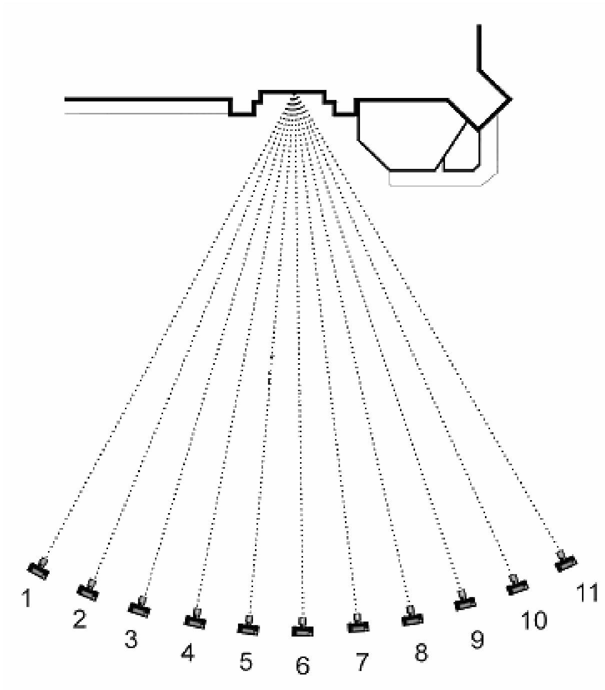

Figure 2. Design of the convergent geometry

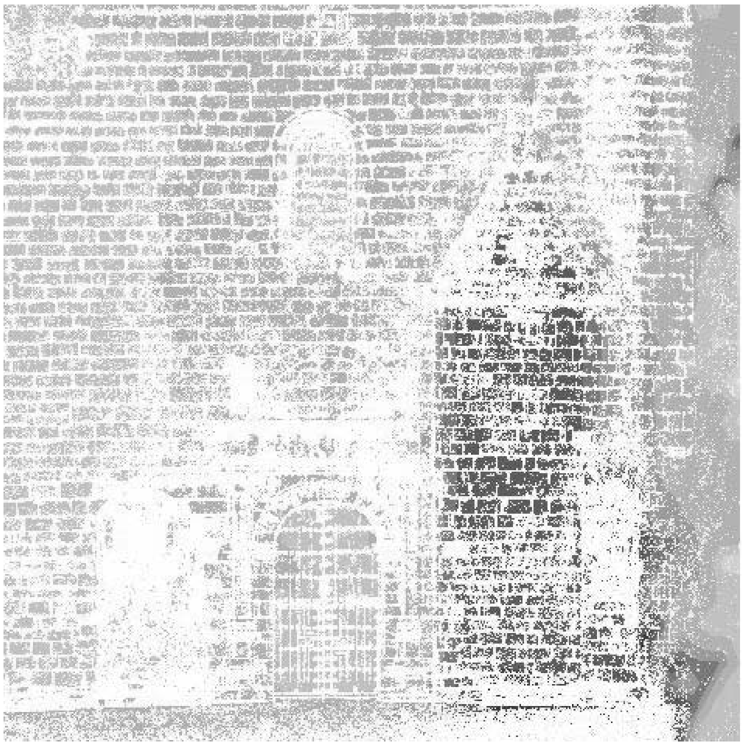

Figure 3. Correlated clouds of points.

3. PRECISION AND IMPROVEMENT OF DSM

3.1 *DSM Precision*

Experiments have been performed in order to check the effect of these variables and select the best possible combination to generate a DSM of greater precision. The variables analysed are the following:

- Convergence Angle. Our experiments showed that the error increases significantly with that angle (see figure 4).

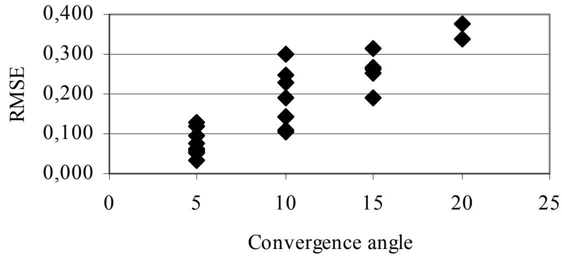

Figure 4. Relation between the convergence angle and the precision of the DSM expressed as RMSE in meters.

- Size of the search windows and correlation. Different analyses were carried out fixing the coefficient values of the threshold correlation (0.85) and the correlation window (7×7) but varying the size of the search window. The results demonstrate that the tie point number increases and the adjustment error descend if the search window is reduced.

- Elimination of gross errors. When the improvement curve reaches an inflection point the DSM is considered to be purged of large errors. The highest value (0.122 m) corresponds to the whole sample. By eliminating the greatest error point, the RMSE descends to 0.105 m. The purging of gross errors finalized when the 5 points with the greatest errors are eliminated. At this point, the curve shows an inflection and the error slope is shallow. The values of the confidence interval were estimated according to the formula proposed by [5]. Figure 5 shows an example in which the RMSE value is related to the check points. The method has different steps: First put in order the errors, then calculation of RSME without the biggest error, after that draw the graphic, calculation of reliable distance (I) depend of number of points (n) and its RMSE (expression 1), finally detect inflection points and delete the necessary points.

$$I = \frac{1.96 \cdot RMSE}{\left[2 \cdot (n-1)\right]} \tag{1}$$

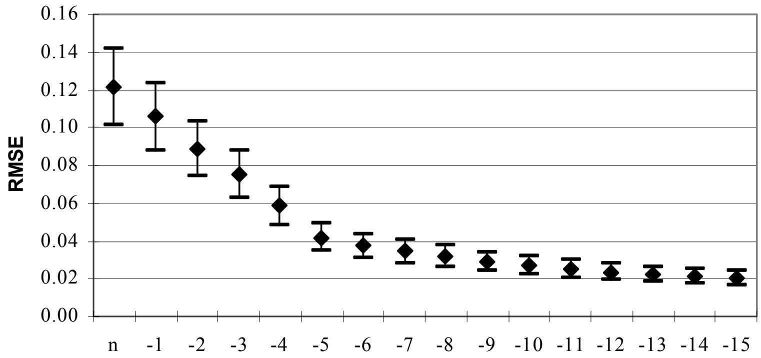

Figure 5. Improvement of the precision of the DSM with the elimination of the check points with the greater errors. The vertical strokes show the value of the confidence interval at the 95%.

- DSM Errors. Selecting the best values for the search and correlation windows and by eliminating gross errors, the DSMs are constructed for each pair of stereoscopes with a 5º convergence.
- Correlation coefficient value. The tests of error control show that the elimination of points with a worse correlation improves the results. Conserving the points with a correlation coefficient (r) >0.85 exclusively improvements are obtained in almost every case.

3.2 *Improvement DSM*

It has already been indicated that the DSMs are constructed from a sole stereoscopic pair. Since the application does not construct a DSM by using all the data on the network, a synthesis has been carried out which follows the steps hereafter:

- Elimination of gross errors and hidden points in each DSM
- Elimination of all points with correlation coefficient < 0.85
- Union of individual DSMs
- Error control in the synthesis DSM

MDS (pair)	All points	r>0.85
M1-2	0.044	0.031
M2-3	0.043	0.036
M3-4	0.055	0.033
M4-5	0.031	0.033
M6-7	0.016	0.016
M7-8	0.017	0.015
M8-9	0.010	0.009
M9-10	0.028	0.019
M10-11	0.023	0.020
Mean	0.030	0.023

Table 1. . RMSE (m) values for the individual DSM and the average.

The results are clear, (table 1)the synthesis DSM shows a better precision than the individual DSM. The right column shows the improvement after the elimination of points with *r*<0.85

4. FILTRATE METHODS

Different estimates have been given, all of them validated afterwards, letting us know the mean square error and compare models' accuracy.

4.1 *Inverse Distance Weighing (IDW)*

The z coordinates of the point to interpolate are estimated allocating weights to environment data in inverse relation to distance; nearest points thus getting more weight in calculations. It is an exact method that estimates the value of the variable for a point not belonging to the sample, using the following expression (2):

$$z_j = \frac{\sum_{i=1}^{n} \frac{1}{d_{ij}^{\rho}} \cdot z(x_i)}{\sum_{i=1}^{n} \frac{1}{d_{ij}^{\rho}}} \tag{2}$$

where dij is the euclidean distance between each data item and the point to interpolate, and p is the weighting exponent. The least mean square error of the prediction (rmspe) is calculated in order to determine the optimal exponent value. The optimal power (p) value is determined by minimizing the root mean square prediction error (rmspe). The rmspe is the statistic that is calculated from cross-validation. In cross-validation, each measured point is removed and compared to the predicted value for that location. the rmspe is a summary statistic quantifying the error of the prediction surface [4]

4.2 *Radial basis function (RBF)*

Radial base functions comprise a wide group of exact and local interpolators that use an equation with its base dependent on distance. Generally speaking, the value of the variable is given by the following expression (3):

$$z_j = \sum_{i=1}^{n} a_i \cdot F(d_{ij}) \tag{3}$$

where F(dij) is the radial base function, with d being the distance between points; a_i, the coefficients that will be calculated solving a linear system of n equations, and n, the number of neighbouring sample points involved in obtaining z_j.

In this case, we will use a radial base multiquadratic-type function (4) [1], which comprises an r parameter: the softening factor. This value should be previously tested according to the data in each case; a very high value will generate a very softened surface, far from the real surface.

$$F(d_{ij}) = \sqrt{d_{ij}^2 + r^2} \tag{4}$$

4.3 *Kriging*

It is an exact and local interpolation method [6] that sets the weight of each sample point according to the distance between the point to interpolate and the sample points.
Kriging's procedure estimates this dependence over the semivariance, which takes different values according to the distance between data items. The function that relates semivariance to distance is called semivariogram and shows the variation in correlation among the data, according to distance. The basic expression is (5):

$$\gamma(h) = \frac{1}{2n} \sum_{i=1}^{n} (z_i - z_{i+k})^2 \tag{5}$$

where n is the number of value pairs separated by a distance h.

Theory demands the semivariogram to be of general validity for the whole digital model's area. This means that data interdependence should be the exclusive function of the distance among them, and not of its absolute space location, because of which it doesn't allow for the treatment of discontinuities that lead to abrupt changes, such as slope ruptures.

5. RESULTS

To evaluate the effectiveness of the interpolation methods, the data were validated through a random mesh of points (figure 5), whose coordinates were measured using multiple direct intersection by classic topography.

Figure 7. Distribution of the validation points.

For the statistical evaluation of the effectiveness of each method, the model we obtained was checked with the real model, using the root mean square error (RMS) over the 72 validation points, which is defined by the following expresion(6)[3]:

$$RMS = \sqrt{\frac{\sum_{i=1}^{n}(z_i^{estimated} - z_i^{real})^2}{n}} \qquad (6)$$

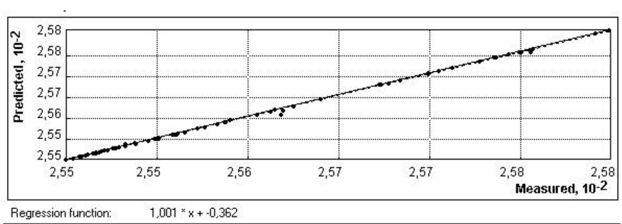

Figure 8. Result of points' validation

There are different search types among which we must choose to select those neighbouring sample points that will take part in the numeric determination of the "non-sample" point. This can be performed taking quadrants, octantes or the whole circular sector into account. So as to research the influence we performed the IDW interpolation using the three types of neighbour selection for 30 neighbours of which at least 12 within a search circumference of a 10cm radius, obtaining the following final RMS (table 2):

Selection	RMS (m)
all	0.025
quadrants	0.028
octantes	0.030

Table 2. Model's error according to different search types by sectors.

5.1 *Optimal number of neighbouring points*

The number of neighbouring points that take part in the interpolation was calculated evaluating the RMS, using IDW as a method.The method without quadrants has been selected for being the one with best results, as seen in the previous section.

Number of neighbours	Minimum number of neighbours	RMS (m)
45	15	0,026
30	12	0.025
15	10	0.026
8	8	0.032
6	4	0.033

Table 3. RMS according to the number of neighbours selected

According to the table 3, there is a certain threshold above which the interpolated model's precision doesn't improve, no matter how high the number of points considered. For this reason, the options of 30 neighbours with at least 12 within and that of 15 neighbours with at least 10 are considered valid, since having more points without improvement in precision only increases the volume and time of calculations.

5.2 *Determination of search radius*

Tests were carried out choosing neighbours within a circular area of variable radius, keeping the number of neighbouring points fixed at 30 with at least 12 within, using selection without quadrant, over the whole sector (table 4).

Method	Semiaxis	RMS
IDW	0.50	0.025
	0.10	0.025
	0.05	0.025
	0.01	0.028
Kriging	0.50	0,041
	0.10	0.041
	0.05	0.042
	0.01	0.021

Table 4. RMS according to neighbours' selection radius.

In the light of results, we can affirm that the method most homogeneous to the selection circumference is IDW, knowing that varying the radius, the model's mean square error remains constant.

It can be due to the fact that all points that take part in the interpolation have already been selected within a 5-cm radius; thus an increase in radius doesn't alter the interpolation at all. Hence the RMS varies when the radius decreases to 1 cm.

5.3 *Choice of optimum exponent*

The use of the IDW method implies choosing the optimum exponent of the weighting functions. In our case -having analysed all the data- the exponent with minimum RMSPE (i.e. the optimum) has a value of 1.257; which not only means that it is not a linear relationship, but that more importance is given to far away points than is this exponent is quadratic.

5.4 *Statistical evaluation*

Comparing among models using the value of a 10-cm radius without quadrants, we obtained (figure 9):

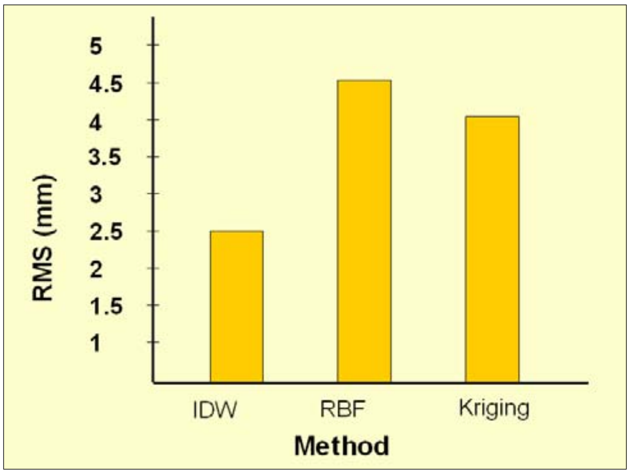

Figure 9. Comparison among the different models.

6. CONCLUSION

Results have shown that these methods can be used to accomplish an effective filtering of massive clouds of points generated by means of automatic photogrametry. The values of accuracy are reasonable for the model studied, although different methods yield different results. It is remarkable that the simplest method (IDW) is also the one that reaches smaller RMSE values of just 2.5 cm. There is therefore no need for more sophisticated methods, which have almost duplicated the previous RMSE in the cases analysed. Likewise, the IDW method is more robust in the face of changes in selection area and in the number of points used in the interpolation.

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