ON THE USE OF LASER SCANNER AND PHOTOGRAMMETRY FOR THE GLOBAL DIGITIZATION OF THE MEDIEVAL WALLS OF AVILA

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Commission III, WG III/1

KEY WORDS: 3D laser scanner, cultural heritage, close-range photogrammetry, computer vision, image analysis, surface reconstruction

ABSTRACT:

The new technologies are playing a main role in the preservation and restoration of the architectural heritage. In this paper, a digitization of the walls of Avila process, by means of laser and photogrammetric technologies, is described. This process includes the acquisition of data, the processing and integration of both data sets and finally, the generation of a photographic texture model of the wall. More specifically, a terrestrial – time of flight – scanner laser is used besides a low cost aerial imaging device attached to a captive blimp. In this way, two earth technologies are integrated successfully while attaining, for the first time, a global digitization of this World Heritage monument.

1. INTRODUCTION

The techniques for the architectural heritage documentation have traditionally been based on topographic surveying and photogrammetry. The developing of new sensors and new data processing techniques allows us to state that these conventional documentation procedures are becoming rather obsolete. (Cannatacci, 2003; Barber, 2004). Within the surveying techniques based on the use of Total Stations, measures can be obtained without the use of a prism while only acquiring the most relevant points that define the object geometry. These data are then imported to CAD software to render a 2D design. The advantage of this method is the accuracy of the model. The quality of the results prevails over its quantity. This is due to the fact that the data volume aims only at the goal of obtaining a sketch of the object, enough to define its structure, and a detailed representation of complex or hard to process forms is usually neglected.
With photogrammetric techniques, object restitution can be obtained from images taken from a calibrated camera beside some surveyed points to ensure the geometric control of the model. (Arias et al., 2006; Arias et al., 2007). In spite of the fact that it implies a rather complex and tough work, the results are usually better than those provided by the surveying techniques as the object is rendered with a more level of detail.

Nowadays, the trend is to accomplish the 3D documentation with a terrestrial scanner laser (Gonzalez-Aguilera et al., 2008; Yastikli, 2007) as millions of high fidelity points can be acquired. In a simple fashion, the laser stations are adjusted to the object shape avoiding to cope with the highly demanding topographic stations. A sequential group of point clouds is obtained which must afterwards be unified to a single and coherent set.

Nevertheless, this point cloud is only a simple acquisition of points with XYZ coordinates and, in some cases, with IRC intensity values or RGB colour. In this way, to achieve a surface model or a vector model can be a complex task (Remondino, 2003). In addition, this step will demand the application of optimization strategies (Cignoni et al., 2004) in order to obtain models that can be handled by modern CAD/CAE.

The goal of this work is to obtain a 3D model with high metric accuracy of the outer part of the walls of Avila. This model is the result of the integration of the non destructive technologies of laser scanner and low cost aerial photogrammetry. In addition, the 3D model will permit the generation of some by-products such as cross sections, profiles, perspective views and orthophotos, very useful to technicians and experts related to the damage diagnose, the preservation and the restoration of this monument, regarded as a World Heritage Wealth.

The Walls of Avila are the best example of military architecture of the Romanesque style in Spain and a unique model of the European medieval architecture. (Serna, 2002). The construction of its walls and towers is perfectly adapted to the relief. The southern parts have little heights as they are built upon a cliff that acts as a natural defence. The western and northern parts grow higher to reach the highest and thickest parts at the east. At this zone, the “Alcazar” fortress and the strongest doors were raised (named of the “Alcazar” and of “San Vicente”) and the defence system was reinforced with a barbican and a ditch. It must be stressed that it is the only case of a medieval wall in which one of its towers is a part of the cathedral itself. Some references state that the building took place around 1090. Some other researches, instead, point out that the works should have persisted over the XII century and that the walls were build over and older one.

This paper consists of three parts: after this introduction, in chapter 2, a detailed description of the methodology will be developed. In chapter 3, the results will be described and finally, chapter 4 will deal with the main conclusions and the expected future developments.

2. METHODOLOGY

It is important to stress the difficulties that arise from the particular features of the walls of Avila, mainly its size. The wall towers have an average height of 15 m (up to 20 m in some of the doors) and this feature influences the position of the laser stations in order to guarantee an adequate covering of the object having in mind the device vertical field of view. In addition, the length of the perimeter is 2516 m and so, a high number of stations become necessary. This, in time, demands a careful design of the framework to guarantee the adequate coherence and soundness in the results.

Figures 1 and 2 show the procedures and methodology followed in both the laser scanner and the camera work flows.

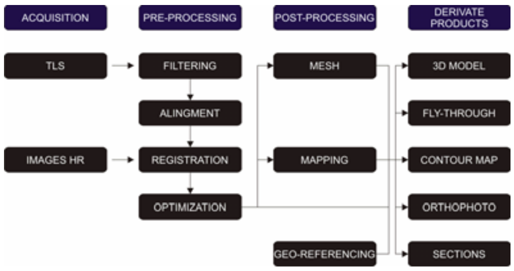

Figure 1. Scheme of the laser data flow

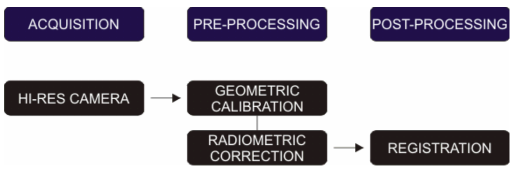

Figure 2. Scheme of the camera data flow

2.1. Field Work

Data acquisition with laser scanner: The instrument used is a time of flight laser scanner from Trimble. This instrument collects data with a horizontal field of view of 360º and a vertical field of view of 60º. This poses an important limitation when rendering a high object from a close distance as in the present case. So, a special head must be used to cover the higher parts of the wall. A previous analysis was carried focusing on the main obstacles, occlusions and restrictions of the environment. The goal of this analysis is to reach a balance between the maximum coverage of the object and the minimum number of stations (figure 3). It is of the major importance to note that a large number of stations can easily spoil all the work because of the cumulative fashion of error propagation when orientation is transmitted from one laser station to another. On the other side, an adequate spatial resolution is set to obtain a good level of detail of the object. Last but not least, a local coordinate system is fixed that permits a precise reference of all the data in a unique and straightforward way.

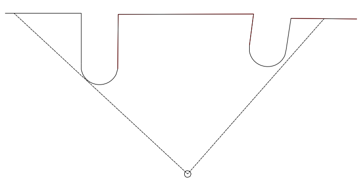

Figure 3. Example of laser station with adequate overlap

High resolution images: The taking of high resolution images (both terrestrial and aerial) completes the data acquisition phase. This data overcomes the main laser scanner drawback, that is, the lack of radiometric information. The reflex camera is a Nikon D80, previously calibrated at the laboratory. The planning must ensure a complete acquisition of the radiometric information of the walls. Some guidelines must be followed to achieve the best results: to avoid every cast shadow produced by any object in the surroundings; to choose cloudy days and to use a tripod to obtain the best illumination conditions. It is recommended to use a low ISO number and a diaphragm aperture that meets a compromise between image quality, noise and depth of field. Another relevant issue is to acquire the images in a raw format because it happens to work as the conventional negative film, collecting information with the lowest level of noise. In this way the image may contain as much as 12-14 bits per channel. In addition, while processing the digital developing, the radiometry may be optimized by modifying parameters such as the vignetting, the exposition, the white balance,... The images must provide a pixel size projected on the object (GSD-Ground Sample Distance) between 5 and 10mm to achieve the optimum resolution on the final results, as stated by the equation:

$$GSD = \frac{D \cdot s_x}{f} \qquad (1)$$

where D is the distance between the camera and the object, s_x is the pixel size and f , the camera focal length. Multiple overlapped images are taken trying to ensure the same object registration of that of the laser scanner. To render the side part of the towers, some additional images are taken pursuing to avoid major perspective effects. (Figure 4)

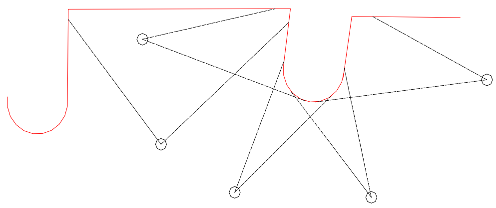

Figure 4. Adequate positions of the reflex camera

Images from the blimp: The aerial images are taken from a captive blimp. A self stabilizing platform attached to the blimp lodges de camera. This camera provides images that complete those acquired from the ground. The aerial view permits to access a privileged "bird point of view" that completes the means of object exploration. As in the case of the terrestrial images, a previous planning must be accomplished in order to guarantee a thorough documentation of the object. A critical factor in this case is the wind: if its velocity is above 5km/h problems arise (Figure 5).

Figure 5. Blimp (left) and aerial image of the northern wall (right).

2.2. Laboratory Work

The main difficulty in the laboratory tasks resides on the data geometrical fitting. The large size of the object as well as its closed shape poses a major challenge on the use and optimization of the alignment and adjustment of the point clouds (Chen and Medioni, 1992).

2.2.1. Alignment and adjustment of the laser scanner data. The alignment is done on a basis of an independent models orientation approach. Each consecutive pair of point clouds is oriented to each other in order to provide a set of relative orientation parameters. These parameters are then used as initial solution in a block adjustment procedure. More specifically, the alignment of each of the individual data sets is based on the solution of a rigid body transformation. As each set is expressed in its particular local system, at least three homologous points with the neighbouring sets must be provided. With this initial solution in which each cloud is referred to the first one, the original 3D transformation may be simplified, resulting the following equation:

$$\begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix} = \begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix} + \begin{bmatrix} 1 & -\Delta\kappa & \Delta\varphi \\ \Delta\kappa & 1 & -\Delta\omega \\ -\Delta\varphi & \Delta\omega & 1 \end{bmatrix} * \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{2}$$

where (X',Y',Z') are the coordinates in the new frame, (X,Y,Z) are the coordinates in the input frame, ($\Delta X,\Delta Y,\Delta Z$) and ($\omega,\varphi,\kappa$) are the parameters of the relative orientation, translations and rotations, respectively.

Afterwards, the alignment (2) will be refined by an iterative least squares adjustment in which all the points of the overlapping area will be involved. In addition, and with the idea of minimizing the closure error to half its value, two completely opposite clouds are used as original references in the initial alignment. The clouds are divided into two subsets instead of using a unique initial cloud as a reference for whole lot of them.

Finally, once the independent model adjustment is completed, a block adjustment is launched. This procedure is completed by a network of GPS control points that has been designed and measured on the upper part of the walls.

2.2.2. High resolution images registration. This phase consists on solving the outer orientation of each of the high resolution images. The parameters are referred to the laser scanner frame. It is a manual process in which the so called DLT (Direct Linear Transformation) (Abdelaziz and Karara, 1980) is used. This model is based on the popular collinearity equations (3). In it, a eleven parameter model relates the image coordinates (x,y) to the object laser coordinates ($X´,Y´,Z´$) (see equation 2). In this way, all the images are referenced to the laser scanner data frame.

$$x = \frac{(x_p r_{31} - f r_{11})X' + (x_p r_{32} - f r_{12})Y' + (x_p r_{33} - f r_{13})Z' - (x_p r_{31} - f r_{11})X_S' - (x_p r_{32} - f r_{12})Y_S' - (x_p r_{33} - f r_{13})Z_S'}{r_{31}X' + r_{32}Y' + r_{33}Z' - (r_{31}X_S' + r_{32}Y_S' + r_{33}Z_S')}$$

$$\tag{3}$$

$$y = \frac{(y_p r_{31} - f r_{21})X' + (y_p r_{32} - f r_{22})Y' + (y_p r_{33} - f r_{23})Z' - (y_p r_{31} - f r_{21})X_S' - (y_p r_{32} - f r_{22})Y_S' - (y_p r_{33} - f r_{23})Z_S'}{r_{31}X' + r_{32}Y' + r_{33}Z' - (r_{31}X_S' + r_{32}Y_S' + r_{33}Z_S')}$$

The rest of the parameters of (3) are the singular elements of the rotation matrix (r_{ij}), the image coordinates of the principal point (x_p,y_p) and the laser coordinates of the point of view (X_S',Y_S',Z_S'). In (3) the distortion parameters are not expressed, as these parameters have been computed previously in a laboratory procedure and can be applied to correct the input image coordinates. Six homologous points, on each image and on the laser scanner point cloud, are identified and so, the exterior orientation of each image can be computed. More precisely, images captured from the blimp are registered taking singular elements (battlements) as homologous points in both dataset: point cloud and aerial images. This step is solved manually since the baseline and perspective between both dataset are radically different and thus the automatic registration could does not work at all. When these parameters are known the radiometric information of the image can be projected over the point cloud or over the triangle mesh by means again of the collinearity equations (3).

2.2.3. Georeferencing. Finally, the whole data set is geo-referenced to the ETRS89 system. The chosen geodetic projection is UTM in the zone 30. In this way, it becomes feasible to integrate, in a simple way, cartographic and photogrammetric data. This last stage requires a field campaign to acquire the GPS observations but it is always possible to perform it at the same moment of the photographic or laser scanner campaign. Through the observation of three geodetic vertices and the geoid undulation model EGM08, the 7 parameters of the Molodensky-Badekas (Welsch and Oswald, 1984) can be computed,

$$\begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix} = \begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix} + \begin{bmatrix} X_C \\ Y_C \\ Z_C \end{bmatrix} + \begin{bmatrix} 1+d\lambda & \varepsilon_Z & -\varepsilon_Y \\ -\varepsilon_Z & 1+d\lambda & \varepsilon_X \\ \varepsilon_Y & -\varepsilon_X & 1+d\lambda \end{bmatrix} * \begin{bmatrix} X - X_C \\ Y - Y_C \\ Z - Z_C \end{bmatrix} \tag{4}$$

where $d\lambda$ is the scale variation, ($\varepsilon_X,\varepsilon_Y,\varepsilon_Z$) are the elementary rotations and (X_C,Y_C,Z_C) are the coordinates of the centroid which is the origin of the rotations.

3. RESULTS

Table 1 gives a general vision of the large size of this project and the difficulties related to the acquisition and processing of the walls of Avila. We may stress that the wall heights range from 14.5 m at the east to 10.5m at the south; the towers height vary between 14 and 17 m. The towers of Puerta del Alcázar and Puerta de San Vicente exhibit a height of 20 m (Mariano Serna, 2002).

Length	2.516 m
Nº of towers	87
Nº of Battlement elements (nowadays / original)	2113 / 2379
Nº of doors	9
Width of the wall	Between 2.6 and 2.8 m
Average height of the wall	11.5 m
Average height of the towers	15 m

Table 1. General information of the walls of Avila

The ideal laser station is that in which the horizontal scan span covers two towers, the wall between them and part of the wall at the outer part of the towers so the alignment with the adjacent stations can be ensured (Figure 3). The stations must be placed at the middle of the distance between the two towers. In this way, the laser rays would be as perpendicular as possible to the walls and also to the sides of the towers. This constraints lead to the fact that the ideal station is that in which the laser is at a distance of between 15m and 20m from the wall. At the apse of the Cathedral and at the doors, a special attention must be paid to the shadows. The process is repeated until the whole wall is surrounded completely. In those zones where the vegetation occludes the wall, some additional stations have to be done to overcome the lack of information. The overlap between adjacent stations is of about 20%. This will guarantee and adequate alignment between the point clouds. The resolution is set to a value between 15mm and 20m for the average distance from the scanner to the object (Figure 6).

Figure 6. Acquiring the data with de laser scanner.

While acquiring the data, an arbitrary datum is set for each station. These sets of datums have one thing in common: the accurate determination of the vertical direction. This is possible because of the existence of a double axe compensator attached to the instrument. In addition, a network of about 50 control points, placed in the towers and the upper part of the wall as well as in its base, was observed with the GPS. This network was also used to define a reference frame in UTM coordinates (zone 30) in the ETRS89 reference system for the whole wall (Figure 7). To compute the transformation parameters the closest geodetic vertices were observed. The model of geoid was EGM08 adjusted to the REDNAP (High Precision Levelling Network) by the IGN (National Geographic Institute).

Figure 7. Acquisition of GPS data.

The terrestrial images are taken with an 18-70mm lens and are corrected both geometrically and radiometrically for the posterior work. The average distance from the camera to the walls ranges from 15 to 20m.

Regarding the equation (1), if we consider a pixel size of 0.00605 mm (obtained by laboratory calibrating procedure) and using a focal length between 18 and 35mm, we obtain a GSD of between 5 and 10mm, good enough for the final product.

In the aerial images taking, a platform in carbon fiber is used. This platform embraces a reflex camera that is remotely controlled from the ground. In addition, the platform has a vertical and a horizontal axe, with gyroscopes and servos that permit tilt and pan rotations. This rotational degrees of freedom lead to the possibility of designing both oblique or stereoscopic vertical configurations. In our case, we are interested especially on the second type of geometry due to configuration of our object: a vertical plane or a vertical cylinder from which we are interested in obtaining its radiometric information (see figure 8). More details about the system and the platform may be found at (Gómez-Lahoz and González-Aguilera, 2009)

Figure 8. Attachment of the camera to the aerial platform.

In the aerial taking, the northern part of the wall is the easiest to perform as there is plenty of space to work. On the other side, the eastern part is the most difficult since the streets are narrow and there are electric cables that hinder the movements of the blimp.

Table 2 shows a synthesis of the most relevant issues of the field work.

Nº of laser stations	98
Resolution	15mm x 15mm at 20m
Geodetic reference system-Projection	ETRS89 and UTM30
Geoid undulation model	EGM08
Overlap	15-20%
Nº of points	300 000 000
Nº of points in optimized model	240 000 000
Scanned area (aprox)	30 000m^2
Nº of images	215
Nº of hours (laser + camera)	150h + 4h
Nº of hours GPS	5h

Table 2. Synthesis of the field work.

At the laboratory, we proceed to the alignment of all the laser data obtaining a raw product of about $300 \cdot 10^6$ points. Afterwards, this model is cleaned from all the noise due to people, urban objects, cars, etc, with a spatial filtering of 1cm the model is optimized and all redundant data is eliminated from the overlapping zones. Due to the large size of the project (both in data volume and geometry extension) the wall is divided in four parts: north, south, east and west.

When the model is unified and optimized we proceed to register the images. The next step is the creation of a surface model based on the generation of a triangular mesh. This surface leads to an improvement of the photo-realism of the results.

The last phase of the project is the generation of by-products such as (Figures 9-12):

Total and partial 3D Model: this is the final result of work flux described above.

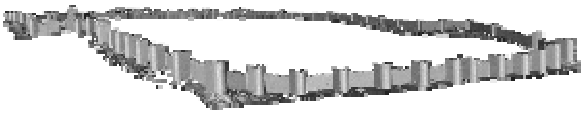

Figure 9. Complete 3D laser model of the Wall of Avila.

XY map: easily derived from the 3D model. Since the model is geo-referenced in a geodetic national system it can be easily exported to other cartographic data bases. It leads to metrical analysis and comparison.

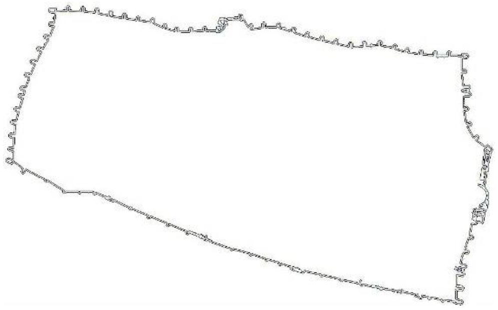

Figure 10. XY map of the wall from laser data.

Videos and virtual fly-through: with the 3D model impossible points of view may be accessed. A variety of fly-through can be rendered aiming at the dissemination and promotion of the cultural heritage.

Figure 11. 3D laser photo-realistic model (Western wall)

Height maps and contours: is an easy derived product from the laser geo-referenced model.

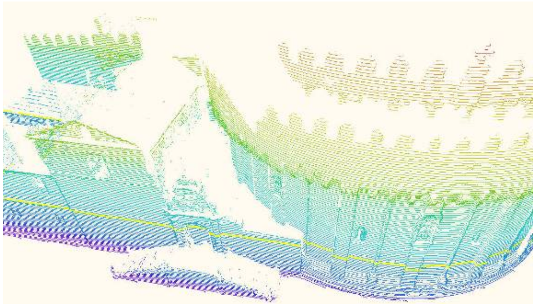

Figure 12. Contours of the cathedral apse, integrated in the wall (equidistance: 20cm).

True Orthophotos: This product allows realizing dimensional analysis such as measuring the distances and computing the area of cracks, humiditys and towers. These measures sustain the development of control and monitoring tasks in zones that are under risk.

Cross sections and profiles: We can obtain a series of longitudinal and lateral profiles from the original model. These documents permit thorough analysis of the geometric dimensions of the wall.

Accuracy control: one of the most important aspects of this project considering the large-size and closed shape of the object is the achieved accuracy of the global model, especially the accumulative fashion of error propagation which involves a lot of laser scanner stations. To this end, a network of control points distributed along the battlements of the medieval wall has been designed and measured by RTK GPS. These control points have allowed us to guarantee the global adjustment convergence. Finally, in order to control the accuracy of the global model several distances have been checked in favourable cases (distances measured over the same wall) and unfavourable cases (distances measured between different walls). The following expression has been used to this control:

$$df = \sqrt{\sum_{i=1}^{N}\sum_{j=2}^{N}\left[(d^{j}{}_{i})_{LS} - (d^{j}{}_{i})_{GPS}\right]^{2} / n}, \qquad i < j \tag{5}$$

being $(d_{ji})_{LS}$ the distance between laser control points, and $(d_{ji})_{LS}$ the distance between GPS control points.

As a result, discrepancies of 2 cm have been achieved in the favourable cases, since discrepancies of 5 cm have been obtained for the unfavourable situations.

4. CONCLUSIONS AND FUTURE PERSPECTIVES

In this paper a real work is reported in documentation of a large-size and closed shape historical site. Several practical methods, such as terrestrial laser scanner and low-cost aerial photogrammetry have been integrated and applied in this project.

The results attained are due to the sustained effort of a large number of students, researchers and teachers from the University of Salamanca. The size of the work is clearly expressed on the figures related to the data volume and dimension of the object. Nevertheless, this numbers must not eclipse the huge work and effort of the processing task. Even though laser technology is already completely developed and extended, the size of the object conveys a special meaning to

this work and thus, not much similar works may be found in the Cultural Heritage literature.
From another point of view, the person responsible of the heritage in the local city council with the experts that work at his office can now sustain their work on a complete, accurate and detailed model of the wall. Consequently, the preservation and restoration of this object is better assured than ever before.
The possibility of deriving novel graphic and infographic products amplifies the set of applications further than the effective decision taking to protect the monument and including aspects such as historical analysis, tourism or dissemination in the Internet.

Regarding to future perspectives and trying to reinforce the quality control of the global model, a precision and reliability control should be added. To this end, the cofactor matrix of the parameters and residuals should be estimated based on the error propagation law.

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Acknowledgements

The authors of this work would like to thank all those persons that worked in this project and contributed in a major or minor way to the accomplishment of this "pharaonic" project. From the students of the University of Salamanca that worked at the data acquisition and processing to the Fire Brigade of Avila that facilitate the access to difficult or risky parts of the wall. We would like to specially thank the city council and particularly, its Heritage and Urbanism department, for their active and permanent contribution to sustaining our most precious public wealth: the Wall of Avila.