

Damage quantification and monitoring in masonry monuments through digital photogrammetry

P. Arias^a, J. Armesto^b, C. Ordóñez^c, H. Lorenzo^d, N. Caparrini^e

Department of Natural Resources and Environment Engineering, University of Vigo

Campus Universitario As Lagoas Marcosende C.P. 36200 Vigo, Spain

^aparias@uvigo.es; ^bjulia@uvigo.es; ^ccgalan@uvigo.es; ^dhlorenzo@uvigo.es; ^enataliac@uvigo.es

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Abstract. The measurement and monitoring of structural damages in masonry monuments is an important task in the field of conservation and restoration of architectonic heritage. Traditional surveying devices provide punctual measurements of the damage size and usually are contact-demanding, being an important limitation since risky systems are needed when structural problems appear in no accessible locations. In this field close-range Photogrammetry depict a valuable option. In this paper the dimensional analysis and temporal monitoring of crack is accomplished. Accurate 3D clouds of points defining the crack boundary are obtained in different dates. A quantification of the crack size in each date is obtained by shape parameters. This procedure allows detecting any displacement in ashlar and obtaining a feasible knowledge of the crack growth even when no fixed references are available to align 3D models obtained in different times.

Introduction

Nowadays it is well-known that the architectonic cultural heritage is a fragile and irreplaceable resource that it must be preserved and passed on to future generations. Nevertheless, heritage protection policies are not always as efficient as expected. The course of time has contributed in the deterioration of the materials and the degradation of part or the whole structure in a great amount of building, monuments and constructions. One of the causes of partial or total degradation of a structure is related to the concurrence of forces that exceed flexion, strain and compression resistance of the natural construction materials. Differential displacements, fissures, cracks or fractures appear on the structure as visible signs of such problems. When they appear, a monitoring and control system should be installed to determine if the damage is still increasing or not, as well as the knowledge of the urgency of accomplishing restoration actions.

Different devices have been traditionally used to survey and monitor displacements and cracks, usually being manually placed on the cracks; they include fixing systems to be placed on the structure and measuring systems like a scaled bar or potentiometric sensors. These devices are accurate but they lack in being accessibility dependant, further on, they only provide measurements at punctual places of the damaged area instead of a complete register of the total damaged area.

Non-contact 3D digitalization techniques, greatly used in industrial, medical and computer fields, have allowed a spectacular progress in the field of graphic and geometrical documentation of cultural heritage. The possibility of obtaining long-lasting and unalterable files of the condition of a building is a useful documental resource as a reference when it is needed to do restoring activities. Formal properties studies can be done using high resolution models as a starting point. In case of damage, masterpieces or monuments can be restored taking the digital model as a reference. Several studies have been published describing the application in this field of laser scanning and close range photogrammetry [1,2,3].

Within the cultural heritage field, the structural damage control can greatly benefit from high accuracy 3D digital imaging and processing techniques. Further than allowing detecting structural damage [1], the periodic survey can be useful to accomplish 4D control of observed damages; hence, restoration intervention could be planned accordingly.

In this article, a complete procedure to survey structural damages in heritage monuments and 4D control is described; it is based on obtaining 3D clouds of points defining the boundary of a crack in a wall given by digital close range photogrammetry and subsequent comparison among the clouds of points dating from different years by shape parameters. This procedure is applied in the assessment of a structural damage detected in a heritage monument, *Basílica da Ascensão*, in the Northwest of Spain.

Crack monitoring by close range photogrammetry: a 3D shape analysis problem

Digital Close Range Photogrammetry is a non-contact digitalizing technique to measure the size and shape of objects, in this case a crack, from photographs instead of by direct measurements. The last goal of a photogrammetric process is to obtain a set of 3D coordinates of points in the surface of the object in order to build 3D digital models of the object accurately representing its geometry. The standard procedure to survey an object through Digital Photogrammetry is described in [4]. The main steps are: data collection, data processing, restitution and 3D modelling.

In the case of the dimensional analysis of cracks, two stages can be established: the photogrammetric process, in order to obtain 3D models of a crack taken at different dates beginning from the restitution of those points on the ashlar's boundary that enclose its shape and wideness; and a second stage of model comparison, to evaluate the damage stability. The first stage requires a suitable design of the photogrammetric process, according to the magnitude of the damage to be analysed, the limits derived by the condition of the environment, the precisions to be obtained, etc. A representative quantitative value of the size of the crack at each moment to allow the comparison among successive models constitutes the aim of the second stage.

The comparison of 3D models is essentially a 3D shape analysis problem. This is not a new subject of research. Various methods have already been reported in the literature of computer graphics, space database systems, industrial quality control systems, etc. These methods might be classified into the following three groups according to [5]. The first group is based on geometric features extracted from the shapes. Various types of features have been used to characterize the shapes, including volume, surface area, and moments respect to coordinate axes. The second group is the one that normalizes a shape into a canonical form; the main problem of these methods is that the coefficients are not invariant with respect to (even simple) transformations, such as rotation and shearing. The third group is based on a procedural representation of a shape, like constructive solid geometry; they are not always applicable to any class of shapes.

The method selection to be used depends on the characteristic of the object to be measured, the environmental conditions when the measurements are carried out, etc. In our case, that is the comparison of the 3D forms of a crack in a heritage building documented at different dates, the time interval that can pass between the successive measurements can be of months or years. This is why, besides the esthetical and functional reasons, makes it unfeasible to place reference signs that will remain unalterable during this period in a facade on a building. This is why we consider that the method based on getting the geometrical parameters is the most adequate for this type of research. Concretely, the use of the area defined by boundary points as the parameter for the temporal-dimensional control is proposed, since the calculation of this parameter starting from coordinate points is relatively simple and easily to automate. On the other hand, any partial displacement of the ashlar's that forms the frame of the crack might imply an area value variation of the described surface.

Survey and monitoring cracks

Theoretic grounds. A multistation convergent system is proposed for cracks survey, since it is considered the most feasible, affordable option. As it is known, this system is based on the collinear equations (1), which expresses the geometrical fact that a point in object space, $A (x_A, y_A, z_A)$, its corresponding point in the image plane, $a (x_a, y_a, -f)$, and the camera perspective centre $O (x_0, y_0, z_0)$ lie on a straight line, although in practice, deviations from the collinear condition occurs. If enough numbers of ground coordinates are measured in the object space and the image coordinates of these points are defined in two or more convergent images, the parameters of the exterior orientation for each camera (co-ordinates and rotation angles) can be accurately approximated by a least-squares bundle adjustment. In the same way, the collinear condition allows the ground coordinates estimation for any point in the object space, starting from the image coordinates in a minimum of three convergent photographs. Details can be found in [6].

$$\begin{aligned} x_a &= -f \frac{r_{11}(X_A - X_0) + r_{12}(Y_A - Y_0) + r_{13}(Z_A - Z_0)}{r_{31}(X_A - X_0) + r_{32}(Y_A - Y_0) + r_{33}(Z_A - Z_0)} \\ y_a &= -f \frac{r_{21}(X_A - X_0) + r_{22}(Y_A - Y_0) + r_{23}(Z_A - Z_0)}{r_{31}(X_A - X_0) + r_{32}(Y_A - Y_0) + r_{33}(Z_A - Z_0)} \end{aligned} \quad (1)$$

In the multistation bundle adjustment system, all measured photoco-ordinates are processed simultaneously, using (iterative) linearised least quadratics methods. An important advantage of this system, now that digital cameras are being increasingly used in close range photogrammetry, is that it permits the evaluation of elements of camera calibration and interior orientation, together with the exterior orientation parameters and the object space co-ordinates [7]. Additionally, this system incorporates automatic estimators of adjustment quality.

As a result of this process, spatial coordinates estimations of all the points defined in the object space are obtained, in this case, the points in the surface of those ashlar which define the boundary line of the crack. This way, from clouds of points, scaled 3D wire frame models can be built representing the object shape and size.

The photogrammetric survey of cracks. This stage might be sequenced as follows.

- Multistation network design. The placement of sensor stations might avoid obstructions in the working environment and ensuring visibility of the ashlar in the contour of the analyzed crack. Maximum distance from camera to the wall might be estimated as a function of the expected average precision of feature measurements, the expectable image measurement coordinate precision, the number of photographs at each station and the principal distance of the camera (see [8] for details). The former factor might be established in accordance to the ashlar displacements that can be expected in the interval between successive surveys. The second parameter might take into account that points that are defined in the object space to perform the crack boundary restitution are rock features (mainly crystals); these are not punctual elements, so a low precision in the image coordinate measurement might be expected.
- Topographic support: control point measurement. Measuring the co-ordinates of control points enable to level the model in space and draw to scale. Paper targets might be placed and fixed in the wall surface to make the identification of such points more accurate.
- Taking the photographs: the principles of photography and the requirements of the digital monoscopic photogrammetric systems might be considered:
 - Adequate lighting of the photographed object. Avoiding shadows, reflections, overexposure, etc. A camera with high values of depth of field should be used, so as not to run the risk of these shots being out of focus.

- Each area of the crack must be contained in a minimum of three photograms. The convergence between photograms taken from different positions might be kept between 90° and 60° , so that the beam adjustments are carried out well. The precision of the coordinates estimation depends on a great number of factors, but specially, on the geometry of the take system and the level of the measurements redundancy [9].
- There must be at least 50% overlap between photograms. The shots must be taken in such a way that the element covers the majority of the photogram surface.
- Relative orientation of the photograms: the position and aiming direction of the camera in each shot is calculated starting from the image coordinates of target points in convergent images by bundle adjustment.
- Absolute orientation of the model: levelling and scaling. The 3D coordinates of the target points are introduced in the photogrammetric model and a new adjustment is performed that adjust it to the ground's co-ordinates system, granting correct levelling, orientation and scaling of the three-dimensional model.
- Restitution of points. The reliability of the final 3D model lays in this step. The image coordinates in convergent shots must be obtained for a number enough of points to approximate the shape of the crack, for a subsequent computing of the corresponding coordinates in the object space from the collinearity and coplanarity conditions and least squares adjustment.

Cracks monitoring. Once the cloud of points that define the shape of the empty space among ashlar in the damaged wall is defined, a quantitative value representing the size in each survey is needed. In order to do so, a Delaunay triangulation is performed to obtain the surface whose boundary limit is given by the cloud of points. The area of each triangle is computed as a function of the length of the triangles sides by the Heron's formula. The estimation of a whole surface area is then obtained by addition of the compounding triangles area. Finally, an indicator of the stability of the analyzed crack can be obtained by arithmetic subtraction of the computed areas in each date.

A case study

The described procedure was applied to the *Basílica da Ascensión*, an important element of the Spanish patrimony placed in the Allariz Council, in the Northwest of Spain. The construction of the *Basílica da Ascensión* began in the 14th Century, but the building remains unfinished at present. There is a height of up to stand six layers of granite ashlar in some parts of the nave. Supposedly, the building was designed to receive a wooden roof in the nave. Unfortunately this monument is an example of unsuccessful Spanish protection policies: the eastern wall shows an important crack from the bottom to the top.

This damage was documented and surveyed through digital close range photogrammetry in two different dates: 2001 and 2003. A Rollei Flex 6006 analogical semi-metric camera was used in the former survey with a Kodak Professional Ektachrome E100SW 6 · 6 cm film; the interior orientation values were determined by a prior calibration process. A standard scanner HP SCANJET 7400 C, with 2400 x 2400 dpi optical resolution was used. Details of this survey can be found in [3]. For the second survey different camera was used but similar procedures were followed. A digital calibrated camera, Canon EOS 10D of 6,291,456 pixels CCD resolution was employed. A set of nine paper targets were fixed to the wall and the co-ordinates (X,Y,Z) of the mid cross point were determined with a Leica X-Range 1102 laser total station. They were used in the orientation process and further in the levelling and scaling stages. The photogrammetric network is shown in figure 1. 11 photographs were taken. The restitution of 80 points within the ashlar surface in the crack boundary was performed in both surveys keeping the major correspondence between the former and second sets of points. The table 1 shows the errors, 95% confidence level, in the 3D co-ordinates estimation for both models 2001 and 2003.

Table 1. Average accuracy results in successive control surveys.

Control surveys	Object accuracy 95% confidence level [mm]			Image RMS error [pixels]
	X	Y	Z	
Model 1 (2001)	0.2	3.6	6.5	0.76
Model 2 (2003)	4.4	4.2	4.9	0.17

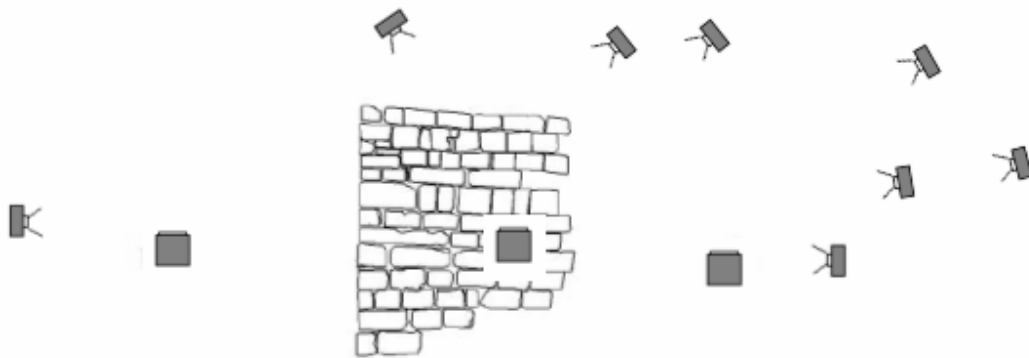


Fig. 1. Multistation network design.

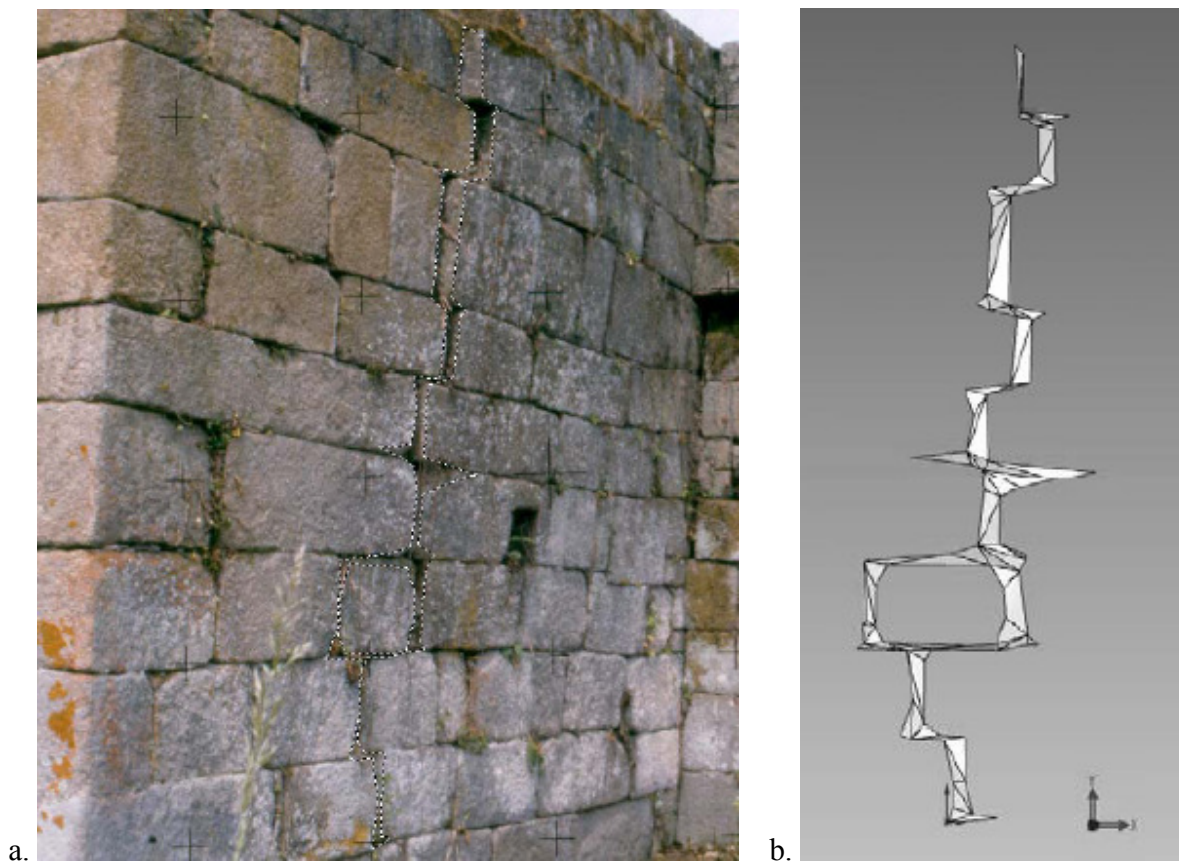


Fig. 2. a) Cloud of crack boundary points; b) triangulated surface.

Starting from the points that limit the boundary of the crack in 2001 and 2003, (see figure 2a) the corresponding surfaces are generated through Delaunay triangulation (see figure 2b), and the area of each one of them is calculated. The resulting values are the following: the surface area of the crack in 2001, the value was of 0.366m^2 , while for 2003 was 0.412m^2 . A crack size increase of 12.6% was obtained.

Conclusions

A systematic method is shown that allows measuring the structural damage and inferring the stability evaluation of them, using digital photogrammetry as a measurement technique, and obtaining parameters in a way to quantify the damage. The 3D measurement of a crack is carried out through the restitution of points over the edge of the ashlar that form the frame of the crack, the definition of the surface that is enclosed by clouds of points and the calculation of the area of such surface. The use of this parameter as a bi-dimensional parameter allows us to compare the photogrammetric models taken at different dates without the need to refer to successive models at a common coordinate system; consequently, it is not needed to supply permanent references to buildings nor apply alignment systems. An essential advantage of this technique as a dimension-temporal control system of cracks is that it does not require a direct contact with the structure, and allows the measurement of cracks with access difficulties needed in traditional contact techniques.

The main limitation of this methodology is that it provides a global dimension of the studied damage and it does not allow the identification of the turning axis. In any case, we consider that this methodology can be of great use in the follow up and diagnosis of the deterioration state of the building on the interest of heritage, as it provides a measurement of the stability of the damage. Definitely, it can be a tool of great help in the decision taking related with the planning of the urgent restoring measure.

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