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# MONITORING AND ASSESSING STRUCTURAL DAMAGE IN HISTORIC BUILDINGS

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*Abstract*

*In the cultural heritage field, the monitoring of the integrity of structures can greatly benefit from 3D digitising techniques. The aim of deformation analysis and structural surveillance is the early detection of damage in order to be able to react appropriately and in good time. The devices that have been traditionally used in the measurement of fissures, cracks and fractures are contact tools whose application depends on accessibility; moreover, they only provide discrete point measurements rather than giving a continuous record of the damage dimension in the whole affected area, as modern 3D modelling techniques can do. Among these techniques, close range photogrammetry is still the most complete, economical, portable, flexible and widely used approach in architectural applications. This paper is focused on the application of close range photogrammetry in the detection and monitoring of structural damage. The following procedure is proposed: the gathering at different epochs of 3D point clouds in the neighbourhood of cracks; the comparison among the successive point clouds by means of shape parameters; and the application of a bootstrap test for the detection of the significant statistical results. This procedure is applied to the analysis of structural damage detected in a masonry structure of cultural heritage interest: Basílica da Ascensión, located in the north-west of Spain.*

Keywords: bootstrap test, close range photogrammetry, heritage conservation, structural monitoring

## Introduction

Monuments and heritage sites provide structures of great value, since they are proof of historic forms of life and the history of modern societies, and show the existence of a tangible cultural identity. The architectural heritage gives a distinctive aspect to its environment, constitutes one of the essential elements of the rural and urban landscape, and, furthermore, a tourist resource of great importance for many rural communities. Nowadays, the architectural and cultural heritage is recognised as a fragile and irreplaceable resource that should be preserved and transmitted to future generations (UNESCO, 1972). However, protection policies are not always as efficient as they should be, to which could


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be added lack of interest on the part of individual citizens and an adverse socio-economic climate in rural areas. As an example, on many buildings the passage of time has caused a great deal of damage to the materials, including partial or total degradation of the structure as a whole.

One of the causes of the partial or total degradation of a structure is the result of stresses that exceed the resistance to flexion, traction or compression of the construction materials. The consequence of an overload is the appearance of fissures, cracks or fractures. When this type of damage is detected, it is necessary to carry out monitoring and control procedures in order to check the stability of the area and quantify the development of the damage. This then assists decisions about the urgency of restoration work necessary to avoid further structural decay.

Techniques that have been traditionally used in the measurement of fissures, cracks and fractures normally involve contact tools that incorporate on the one hand an attachment system to be fixed to the structure and, on the other hand, a measuring system—usually one-dimensional—through a graduated bar or potentiometric measurements. These systems can achieve high precision (better than a few millimetres) but they have a great inconvenience, that is, their application depends on accessibility, and in any case, they provide discrete point measurements in place of giving a continuous record of the extent of damage in the whole area affected, such as can be provided by modern 3D digitising techniques.

The effective use of non-contact 3D modelling techniques in industry (for example, by Tucker and Kurfess, 2006; Ruan et al., 2007); medicine (Malian et al., 2005); computer vision (Dias et al., 2006) and other fields has also engendered a spectacular advance in the geometrical documentation of heritage assets. An archive gathered over time provides valuable information when restoration is required. Furthermore, high resolution models can assist formal studies of individual properties; in the case of damaged works of art or monuments, the digital model can provide reference data as an exact guide to the restoration needed. In recent years, numerous research papers have been published that deal with the documentation of heritage assets using 3D modelling techniques. Guidi et al. (2004) focused on creating a methodology to monitor fragile wooden sculptures over the years giving special attention to modelling accuracy and quality control procedures. Pereira et al. (2004) cover the acquisition of architectural archives using different techniques and instrumentation and the comparison of results in terms of accuracy. Valzano et al. (2005) and El-Hakim et al. (2006) accomplish the virtual reconstruction of heritage sites, the former for interpretation and entertainment purposes while the latter focuses on inferring the original appearance of a site. Recently Alves and Bártolo (2006) developed a novel system for the rapid generation of 3D computer models from existing buildings that allow a direct link to rapid prototyping systems. Finally, in Arias et al. (2007b) low-cost photogrammetric techniques are compared to traditional methods in the graphic and metric documentation of traditional buildings.

In the cultural heritage field, the monitoring of the integrity of structures can also greatly benefit from 3D modelling techniques. The main aim of deformation analysis and structural damage surveillance is the early detection of damage in order to be able to react appropriately and in good time. Much effort has been devoted to investigations of deformation analysis and of structural testing and monitoring by non-contact techniques. Pieraccini et al. (2001) reviewed the state of the art of 3D acquisition and digitising techniques applied to heritage monitoring. Mills et al. (2001) described the measurement of deformation of a pavement from stereoscopic imagery using both analytical and digital photogrammetric instrumentation. Dare et al. (2002) accomplished automatic crack detection and measurement in single digital images. Maas and Hampel (2006) discussed the major hardware and software modules of a toolbox for civil engineering materials testing and large structure monitoring. Ergun and Baz (2006) addressed the use of a digital photogrammetric expert measurement system for deformation measurements on concrete surfaces. Arias et al. (2007a) showed a multidisciplinary approach to structural analysis of historic masonry bridges involving close range photogrammetry and ground-penetrating radar techniques, as well as the development of structural models based on finite elements. Despite these interesting approaches much work remains to be done.

## MEASURING AND MONITORING THE GROWTH OF CRACKS: STATEMENT OF THE PROBLEM

In order to establish an adequate system for measuring and monitoring cracks in heritage monuments, which should be non-destructive and involve long periods of time (Woodhouse et al., 1999), it is necessary to take into account the environment in which such measurements are required, establish an adequate procedure for the comparison of 3D models and finally determine the value of the results obtained.

Conventionally, for detecting deformations, estimated coordinates obtained from least squares adjustment of observations of the same points made at different epochs are compared with each other by using statistical tests, commonly congruency testing (Welsch and Heunecke, 2001). Therefore, this procedure is called conventional or geometrical analysis, and requires the alignment of successive models into a common coordinate system or referring measurements to a common fixed reference. Some examples of the feasibility of this system can be found in Mokarrami and Ebadi (2004), Robson et al. (2004) and Parian et al. (2006). Alternatives to this system based on estimation of coordinates are the comparison of matched surfaces (Gruen and Akca, 2005) and shape signatures (Cardone et al., 2003).

When measuring structural damage to heritage monuments, it is convenient to take into account that:

(a) It cannot be assumed that all or part of the structure or any other element of its surroundings will not move.
(b) Natural or artificial features with a definite defined geometry are not always available to provide a precise reference frame.
(c) Because of the time intervals between successive measurements (months or years) it is undesirable for both aesthetic and functional reasons to use fixed targets as check points.

A viable alternative is to compare point clouds or surface shape signatures that do not vary in relation to the coordinate systems used, such as the geometrical parameters taken from the shape of the object (Cardone et al., 2003).

This paper is focused on the application of close range digital photogrammetry in the monitoring of structural damage to heritage monuments. This technique has been chosen since it still remains the most complete, economical, portable, flexible and widely used approach in architectural applications, as pointed out by Remondino and El-Hakim (2006). A close range photogrammetric procedure is proposed based on gathering 3D point clouds for a given crack at different dates, the comparison among the successive clouds of points through shape parameters and the application of a bootstrap procedure for the detection of the statistical significance of the result. This procedure is applied to the analysis of structural damage detected on a historic masonry structure, the *Basílica da Ascensión*, in the north-west of Spain.

## METHODOLOGY

A crack constitutes a particular case in the measuring of objects since it is not a physical feature, but a free space between the stones or ashlars that form a wall, in the case of masonry constructions. The first step in order to measure a crack lies in its definition as a concrete geometrical form, and a way of doing it is to define the points of the borders of the ashlars that limit the form and width of the crack. Close range photogrammetry allows the spatial coordinates of these points to be obtained, in a precise manner, such that the crack is perfectly defined in the three-dimensional space. The temporal analysis is then reduced to two key matters: on the one hand, obtaining quantitative values of the dimensions of the crack, starting from a cloud of points on its border; the other important task to be solved lies in comparing these quantitative dimensional values adequately, having regard to the statistical significance of the comparison. While the first task is indispensable for an objective assessment of the dimensions of the damage, the second is essential to interpreting the results of the comparison.

To measure cracks, the use of the surface area defined by the border points as a shape parameter to the temporal–dimensional control is proposed, since the computation of this parameter, starting from the information given by a photogrammetric measurement, is simple enough and does not require a great volume of calculations. On the other hand, it can be expected that any relative displacement of the ashlars forming the frame of the crack implies a variation of the value of the surface area described.

Thus, the difference between the area values obtained for the surface of the crack defined from the border points in successive epochs can be considered as a valid quantity parameter for the temporal analysis of a crack. However, a differential value between areas obtained by comparing two 3D models cannot be taken as a base to give a solid diagnosis, since the spatial coordinate estimation of the outline points of these models involves a calculation error, an error that is transmitted to the area calculation and, consequently, to the final differential value between areas. Thus, it is essential to assess the statistical significance of the result obtained. To do so, bootstrap methods are used. They are computer-intensive methods of statistical analysis that use simulation to calculate standard errors, confidence intervals (CI) and significance tests. These methods have been widely applied by quantitative researchers in the life sciences (Figueiras et al., 2005; Cadarso-Suárez et al., 2006; Manly, 2006), environmental sciences (Anderson and Thompson, 2004; Fernández de Castro et al., 2005; Roca-Pardiñas et al., 2005), ecology (Pla, 2004), econometrics (Sperlich et al., 2002) and other areas where statistics are used.

In this section the basis of the proposed procedures for the temporal–dimensional analysis of cracks in heritage monuments is presented. It is organised as follows. In the first section, the basis for the construction of a photogrammetric model of a studied crack is shown. The surface defined by the cloud of points is obtained and its area calculated. This process is common for each of the successive measurements. In the last section, the application of the bootstrap test for the calculation of the statistical significance of the results is described.

### *Photogrammetric 3D Modelling of Cracks*

As is well known, close range photogrammetry provides 3D coordinates of any given point located on the surface of the measured object, in this case, the outline of a crack in some part of a structure. The result of the photogrammetric measurement of a crack at two different dates is two clouds of points, being $\{(\hat{X}_{i1}, \hat{Y}_{i1}, \hat{Z}_{i1})\}_{i=1}^{n}$ and $\{(\hat{X}_{j2}, \hat{Y}_{j2}, \hat{Z}_{j2})\}_{j=1}^{m}$ the estimated 3D coordinates of the points dating from the first and second measurement, respectively. It is to be expected that these points are distributed randomly around the crack and in theory define the boundary of the same region but cannot in practice guarantee a match between pairs of points.

One of the advantages of current digital photogrammetric work stations based on collinearity equations and iterative linearised least squares methods (Cooper and Robson, 2001), is that they introduce automatic estimators of the adjustment quality, and thus the accuracy of coordinate estimation (Mason, 1995). The estimation precision of $\{(\sigma_{i1}^X, \sigma_{i1}^Y, \sigma_{i1}^Z)\}_{i=1}^n$ and $\{(\sigma_{j2}^X, \sigma_{j2}^Y, \sigma_{j2}^Z)\}_{j=1}^m$ (standard deviations of the estimated coordinates for each point $i$ and $j$, respectively) depends on many factors, especially the geometry of the individual shots and the redundancy level of the measurements. As the sizes of the samples of $i$ and $j$ points are increased, the more precise will be the estimates of the crack size.

A further advantage of the multi-station bundle adjustment is that it permits the evaluation of interior orientation parameters without significant loss of accuracy when cameras have not been previously calibrated.

*Measurement of the Growth of Cracks: Surface Area Comparison*

As has been previously indicated, in order to measure the crack it is necessary to transform the outline cloud of points to a representation at the same scale in each measurement. A way of doing it consists in first defining the enclosed surface by the points that define the border of the crack in the damaged wall, and then calculating the area. The simplest basic planar form is the triangle. Delaunay triangulation, commonly used in surveying and mapping, computer vision, finite element analysis and so forth, can be used to approximate the $S_1$ and $S_2$ surfaces starting from the clouds of points $i$ and $j$, respectively.

The area of each component triangle of the surface $S_1$ can be computed as

$$A = \sqrt{s(s - d_1)(s - d_2)(s - d_3)}$$

where $d_1$, $d_2$, $d_3$ are the lengths of the sides of the triangle, computed as a function of the coordinates of the vertices, and $s$ denotes the semiperimeter. Similarly, the area of component triangles of $S_2$ is computed. The total areas $\hat{A}_1$ and $\hat{A}_2$ of the surfaces $S_1$ and $S_2$ are obtained as arithmetical sums of the areas of each of the triangles. The estimated crack growth in the time interval between the successive measurements can be obtained through the calculation of the arithmetical difference between the estimated areas: $\widehat{Dif} = \hat{A}_2 - \hat{A}_1$.

*Crack Growth Accuracy Assessment: Bootstrap-Based Confidence Intervals*

In order to detect whether the true difference $Dif = A_2 - A_1$ is significant, it is necessary to build an interval where the hypothetical value $Dif$ is placed with a determined probability. That is to say, that the lower limit ($LL$) and the upper limit ($UL$) are calculated in a way that the following probability is complied with:

$$p(LL \leq Dif \leq UL) = 1 - \alpha$$

where $[LL, UL]$ is a confidence interval (CI) for $Dif$ with a confidence level of $1 - \alpha$. However, in order to build such an interval, it is necessary to know the distribution of the estimation $\widehat{Dif}$. In this section the bootstrap method is proposed that was introduced by Efron in 1979 (see Efron and Tibshirani, 1993; Härdle and Mammen, 1993; Kauermann and Opsomer, 2003; Roca-Pardiñas et al., 2004, 2005), in order to close up the distribution of $\widehat{Dif}$, which will allow the corresponding approximated CI to be obtained. The bootstrap methods are statistical resampling methods to analyse the variability of an estimator $T$ obtained from a sample $\mathbf{X} = X_1, \ldots, X_n$ of the distribution $F$. The procedure to approximate the distribution of $T = T(\mathbf{X}, F)$ is as follows:

 

(a) Computation of the empirical distribution $\hat{F}_n(x) = n^{-1} \sum_{i=1}^{n} I_{\{X_i \le x\}}$ for $b = 1, \ldots, B$, $B$ being a large number.
(b) Simulation of a random sample $\mathbf{X}^{*,b} = X_1^{*,b}, \ldots, X_n^{*,b}$ from the empirical distribution $\hat{F}_n$ (that is, $X_i = X_j^*$, probability $n^{-1}$).
(c) Evaluation of $T$ for the bootstrap sample; the bootstrap version of the statistic $T^{*,b} = T(\mathbf{X}^{*,b}, F_n)$ is obtained.

Finally, the distribution of $T$ is approximated through the histogram corresponding to the values $T^{*,1}, \ldots, T^{*,B}$.

The variations of the standard method, as the non-parametric bootstrap, parametric bootstrap, smoothed bootstrap or wild bootstrap, differ in the distribution function $\hat{F}$ that is considered in the resampling (Cao-Abad and González-Manteiga, 1993; Härdle and Mammen, 1993). The original bootstrap procedure may often be modified in order to match the theoretical model. The selection of the resampling plan is essential in achieving a distribution of $T^*$ that properly approximates the distribution of $T$.

In this case, the bootstrap methodology can be adapted to obtain the CI for $A_1$, $A_2$, and $Dif = A_2 - A_1$. The steps are as follows:

*Step 1*: Starting from the original data $\{(\hat{X}_{i1}, \hat{Y}_{i1}, \hat{Z}_{i1})\}_{i=1}^{n}$ and $\{(\hat{X}_{j2}, \hat{Y}_{j2}, \hat{Z}_{j2})\}_{j=1}^{m}$, the estimated areas $\hat{A}_1$ and $\hat{A}_2$ are obtained, and the difference $\widehat{Dif} = \hat{A}_2 - \hat{A}_1$, as explained in previous sections.

*Step 2:* The bootstrap samples $\{(\hat{X}_{i1}^{*b}, \hat{Y}_{i1}^{*b}, \hat{Z}_{i1}^{*b})\}_{i=1}^{n}$ and $\{(\hat{X}_{j2}^{*b}, \hat{Y}_{j2}^{*b}, \hat{Z}_{j2}^{*b})\}_{j=1}^{m}$ are generated for a large number of repetitions, $b = 1, \ldots, B$. The corresponding values of area $\hat{A}_1^{*b}$ and $\hat{A}_2^{*b}$, and the difference $\widehat{Dif}^{*b} = \hat{A}_2^{*b} - \hat{A}_1^{*b}$ are obtained. The bootstrap replicas have been generated according to $\hat{X}_{i1}^{*b} \sim N(\hat{X}_{i1}, \sigma_{i1}^{X})$, $\hat{Y}_{i1}^{*b} \sim N(\hat{Y}_{i1}, \sigma_{i1}^{Y})$, $\hat{Z}_{i1}^{*b} \sim N(\hat{Z}_{i1}, \sigma_{i1}^{Z})$, $\hat{X}_{i2}^{*b} \sim N(\hat{X}_{i2}, \sigma_{i2}^{X})$, $\hat{Y}_{2i}^{*b} \sim N(\hat{Y}_{i2}, \sigma_{i2}^{Y})$ and $\hat{Z}_{i2}^{*b} \sim N(\hat{Z}_{i2}, \sigma_{i2}^{Z})$.

*Step 3:* Finally the $100\% \times (1 - \alpha)$ limits for the bilateral CI of $A_1$ and $A_2$ are computed by

$$\mathrm{CI}(A_1) = (2\hat{A}_1 - \hat{A}_1^{1-\alpha/2}, 2\hat{A}_1 - \hat{A}_1^{\alpha/2})$$

$$\mathrm{CI}(A_2) = (2\hat{A}_2 - \hat{A}_2^{1-\alpha/2}, 2\hat{A}_2 - \hat{A}_2^{\alpha/2})$$

where $\hat{A}_1^p$ and $\hat{A}_2^p$ represent the percentiles $p$ of the bootstrapped estimates $\hat{A}_1^{*1}, \ldots, \hat{A}_1^{*B}$ and $\hat{A}_2^{*1}, \ldots, \hat{A}_2^{*B}$.

Moreover, to verify whether the hypothesis $A_2 > A_1$ is significant, the unilateral CI for $Dif$ is built:

$$\mathrm{CI}(Dif) = (a, +\infty)$$

where $a = 2\widehat{Dif} - Dif^{1-\alpha}$, being $Dif^p$ the percentile $p$ of $\widehat{Dif}^{*1}, \ldots, \widehat{Dif}^{*B}$, and $a > 0$ is checked.

## A Case Study

The *Basílica da Ascensión* in Allariz, north-west Spain (Fig. 1), is important in the national architectural heritage. The basilica forms part of an important site known as Santa Mariña de Augas Santas, which includes an abundance of archaeological remains revealing ancient settlement in the area. The construction of the *Basílica da Ascensión* began in the 14th

 

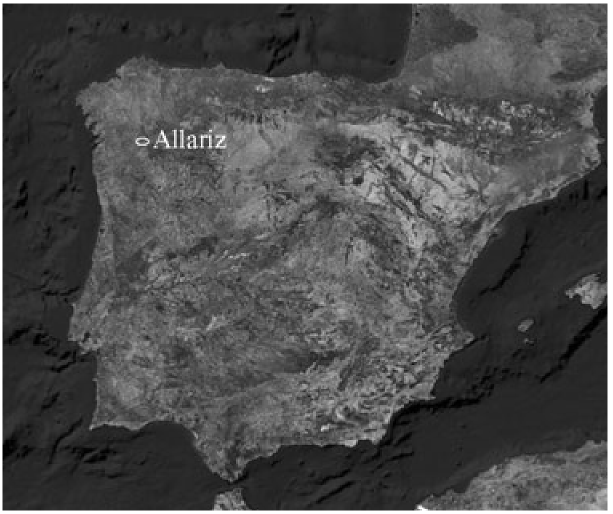


FIG. 1. Location of the *Basílica da Ascensión*, Allariz (Orense), Galicia, Spain.

FIG. 2. Image of the *Basílica da Ascensión*.

century, but the building was never completed (Fig. 2). There is a height of six layers of granite ashlars in some parts of the nave. The basilica has a nave 10 m wide, whose intended length cannot be specified because the building is unfinished. However, the length of the surviving structure is about 16 m. It is believed that the building was designed to receive a wooden roof in the nave and a masonry vault in the apse. Unfortunately this monument is an example of Spain's unsuccessful policies for the protection of ancient monuments: the eastern wall shows a large crack from the bottom to the top, about 3 m high. This defect is present as spacing between blocks and the cracking of one of the blocks (see Fig. 3).

The eastern wall containing this crack was documented by photogrammetric survey on two dates at an interval of 3 years, in order to apply the proposed procedures to real data, and to evaluate the size and stability of the damage to this important structure. Multi-station convergent systems were employed for both measurements, but without permanent reference marks, and with different instruments and different operators.

 

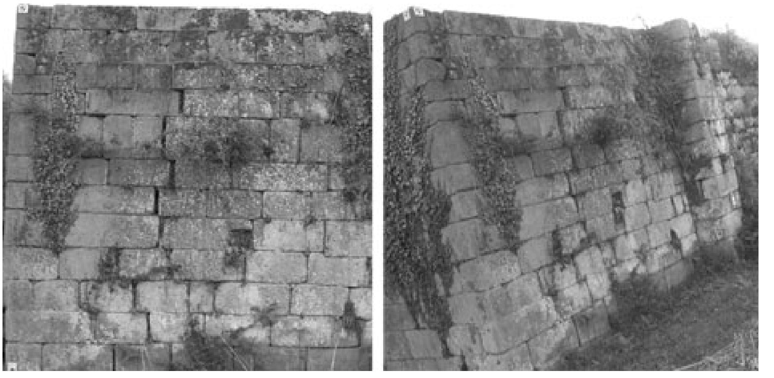

FIG. 3. Images of the crack in the eastern wall of the *Basílica da Ascensión*: frontal view (left) and oblique view (right).

TABLE I. Calibration parameters of the Rolleiflex 6006 and Canon EOS 10D cameras.

| | *Focal length (mm)* | *Film/CCD size (mm)* | *Principal point coordinates* | | *Radial distortion* | | |
|---|---|---|---|---|---|---|---|
| | | | $X_P$ | $Y_P$ | $A_1$ | $A_2$ | $R_0$ |
| Rolleiflex 6006 | −51·10 | 60 × 60 | −0·01 | 0·19 | −0·0212 | 0·00001055 | 20·00 |
| Canon EOS D10 | 20·331 | 22·65 × 15·11 | 11·181 | 7·407 | 0·000226 | −0·0000004906 | |

$A_1$, $A_2$ = radial distortion; $R_0$ = distance where radial distortion is zero. Units in mm.

In the first survey a Rolleimetric 6006 analogue semi-metric camera was used. The film, Kodak Professional Ektachrome E100SW (6 cm × 6 cm format), was digitised using a standard HP SCANJET 7400 C scanner, with 2400 × 2400 dpi optical resolution. The interior orientation values of the camera were obtained from the calibration certificate; parameters are shown in Table I. The coordinates of paper targets placed on the wall surface were measured by topographic methods using a local coordinate system and arbitrary origin. They were used as control points in the scaling and levelling processes. Details of the data collection can be found in Arias et al. (2005).

For the second survey a calibrated Canon EOS 10D digital camera with a CCD array of 6·3 megapixel resolution was used. The corresponding calibration parameters are also shown in Table I. A set of nine paper targets were fixed to the wall and the 3D coordinates of the mid-cross point were determined with a Leica X-Range 1102 laser total station. These were used in the levelling and scaling stages. The relative orientation was performed by matching natural features, mainly crystals in the ashlars.

Sets of 78 and 80 points were captured on the surface of the ashlars along the crack boundary in the first and second surveys, respectively (see Fig. 4). Table II shows the errors, at 95% confidence level, in the estimates of 3D coordinates of the points on the crack at the two epochs.

Starting from points bounding the area of the crack in both models, $S_1$ and $S_2$ surfaces were generated by Delaunay triangulation for models 1 and 2, respectively (Fig. 5). Based on estimated spatial coordinates of the vertices of each triangle, total estimated area values were obtained for the crack in each model: $A_1 = 0{\cdot}366\,\text{m}^2$ and $A_2 = 0{\cdot}412\,\text{m}^2$, respectively. The difference of $0{\cdot}046\,\text{m}^2$ implies an annual increase of 4·2%. This result may seem alarming;

 

FIG. 4. Cloud of points corresponding to the crack outline.

however, it should be noted that while the error in the estimation of the coordinates of each point can itself be estimated, its effect on the area of the crack in each measurement is not known, and thus neither is the statistical significance of these values. In order to assess this, the bilateral CI for the estimated areas and for the differences between areas were then calculated by means of the bootstrap procedure for $B = 1000$.

In Fig. 6, the CI of the areas of the crack in each measurement are presented. As can be seen, the error in the points is uneven, with the CI being greater for the second measurement than for the first. These results are non-symmetric and partially overlap and it is necessary to obtain the CI of *Dif* to check the statistical significance of the value obtained. Table III contains the estimated values and the corresponding CI for the areas and for the difference value. As can be observed, for a 95% probability, the interval for *Dif* takes positive values, demonstrating that an increase in the crack size has occurred. A confirmation of this conclusion is provided by the computation of unilateral CI for different confidence levels, which are shown in Fig. 7. According to this figure, it cannot be deduced that the difference is statistically significant at 98% confidence or higher values. But, accepting the 95% confidence level, as is common in

 

TABLE II. Accuracy results in modelling the crack in 3D at two epochs.

| *Control surveys* | *Object accuracy 95% confidence level (mm)* | | | *Image rms error (pixels)* |
|---|---|---|---|---|
| | *X* | *Y* | *Z* | |
| Model 1 | 0·2 | 3·6 | 6·5 | 0·76 |
| Model 2 | 4·4 | 4·2 | 4·9 | 0·17 |

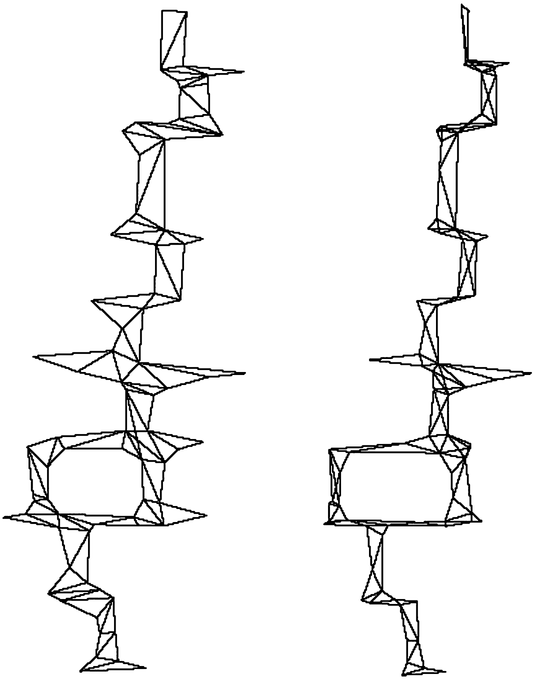

FIG. 5. 3D Delaunay triangulation: model 1 (left) and model 2 (right). Note that the visible differences in the shape cannot be attributed to displacement of the points, since they refer to different coordinate systems.

checking statistical significance of results (Cadarso-Suárez et al., 2006), it can be deduced that the crack is not stable but has increased in the 3 years between the two surveys.

It is perhaps important to suggest that a comparison of CI of the estimated areas from the bootstrap replicas alone, does not provide an entirely satisfactory indicator of the stability of the damaged wall. No overlap could be interpreted as a significant growth of the area. However, if the CI of crack areas in different epochs overlap, as in this case, neither the growth nor the stability of the crack can be certain. In contrast, the computation of the CI of the difference of areas allows the detection of an increase in the crack size with a significance of 95%.

In relation to the quantification of damage, a large variation of the values for the difference between areas has been obtained, ranging from 0·27 to 8·65% per year. Minimum values might correspond to the expected natural evolution of a damaged structure, while the highest values of growth can only be due to a triggering external effect. A succession of measurements and additional environmental data would be needed to infer the cause of the increase in the crack size.

 

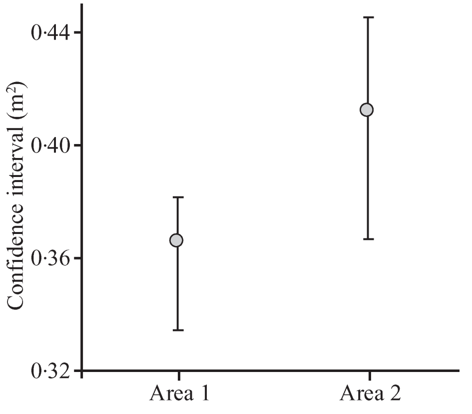


FIG. 6. Bootstrap test: bilateral confidence intervals for crack area in model 1 (area 1) and model 2 (area 2). Units: $m^2$.

TABLE III. Results of the bootstrap method: initial estimated values and corresponding confidence intervals.

| *Variable* | *Bilateral confidence intervals* | |
|---|---|---|
| | *Estimated value ($m^2$)* | *Confidence interval 95% confidence ($m^2$)* |
| $A_1$ | 0·366 | (0·334; 0·382) |
| $A_2$ | 0·412 | (0·367; 0·446) |
| *Dif* | 0·046 | (0·003; 0·095) |

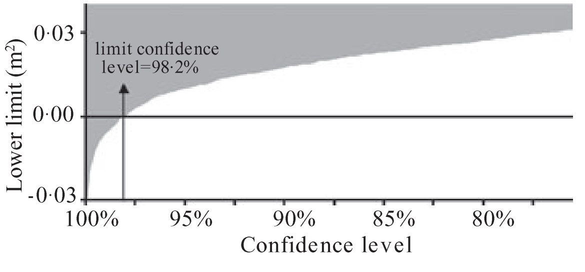


FIG. 7. Bootstrap test: unilateral confidence intervals for the difference between surface areas. The limit between the shadowed and light areas represents the lower limit of the intervals for each confidence value.

## CONCLUDING REMARKS

In this paper, a systematic procedure to evaluate the stability of structural damage is proposed, which uses digital photogrammetry as a measuring technique, shape parameters for damage quantification, and a bootstrap test to obtain measures of reliability of the results.

The measurement of a crack at a given moment is done by the restitution of points over the edges of the ashlars that constitute the surroundings of the crack, the definition of the surface enclosed by the cloud of points and the calculation of the area of that surface. The use of the arithmetic differences between successive areas as a dimensional parameter allows successive photogrammetric models to be compared without the necessity to refer the models to a common coordinate system. Consequently, it is not necessary to provide permanent reference marks or targets on the building nor to apply alignment systems. An essential advantage of this technique as a temporal–dimensional control system for cracks is that it does not require direct contact with the structure and allows measurement of cracks which would otherwise be difficult to access using traditional methods.

The main obstacle to the application of close range digital photogrammetry in measuring damaged walls in buildings and its monitoring without a common system of coordinates lies in establishing the statistical consistency of the quantitative comparison among the 3D models so obtained. This problem is solved by applying a bootstrap test that allows the evaluation of the statistical significance of estimated changes in the size of the crack as measured in successive years, starting from the errors derived from the calculation of the spatial position of the border points of the crack. A limitation of this methodology is that it does not permit the determination of small rotations in any cracks within a damaged area.

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*Résumé*

*Dans le domaine du patrimoine culturel, on peut tirer un grand bénéfice de l'emploi des techniques de numérisation 3D pour le suivi de l'intégrité des structures. La surveillance des structures et l'analyse des déformations constituent l'étape initiale de la détection des dommages, de façon à pouvoir intervenir en temps voulu et de façon appropriée. Les dispositifs que l'on a utilisés de façon classique pour mesurer les fissures, les lézardes et les cassures sont des outils qui viennent au contact et sont tributaires de l'accessibilité ; de plus ils ne peuvent fournir que des déterminations en des points isolés, sans enregistrer de façon très complète le dommage dans toute sa dimension, comme peuvent le faire les techniques modernes de modélisation 3D. Parmi ces techniques, la photogrammétrie à courte distance reste la solution la plus complète, la plus économique, souple, portable et la plus répandue dans les applications architecturales. On a centré cet article sur l'emploi de la photogrammétrie a courte distance pour la détection et le suivi des dommages des structures. On propose de procéder comme suit : saisie à dfférentes époques de nuages de points 3D au voisinage des cassures ; comparaison de ces nuages successifs de points au moyen de paramètres liés aux formes ; et utilisation d'un programme pour la détection de résultats statistiquement significatifs. On a appliqué cette procédure à l'analyse des dommages détectés sur une structure en maçonnerie particulièrement intéressante du patrimoine culturel : la Basilique de l'Ascension, située dans le Nord-Ouest de l'Espagne.*

*Zusammenfassung*

*Moderne Techniken zur 3D Digitalisierung können die Überwachung von Denkmälern unterstützen. Das Ziel einer Deformationsanalyse oder der Überwachung der Struktur von Objekten ist die frühe Erkennung von Schäden, um rechtzeitig geeignete Gegenmaßnahmen einleiten zu können. Traditionell wurden Geräte zur Vermessung von Klüften, Rissen und Brüchen verwendet, die nicht berührungslos waren, und somit einen Zugang zu diesen Objektstellen bedurften. Diese Methoden liefern allerdings immer nur punktuelle Informationen im Messgebiet, anstelle von kontinuierlichen Aufzeichnungen des gesamten Schadensgebietes, wie es von modernen 3D Modellierungstechniken ermöglicht wird. Unter diesen Techniken ist die Nahbereichsphotogrammetrie immer noch das umfassendste Verfahren, tragbar, flexibel und weit verbreitet in allen Architekturanwendungen und Gegenstand auch dieses Beitrags. Folgendes Verfahren wird vorgeschlagen, um strukturelle Schäden zu erkennen und zu überwachen: (a) die Erfassung von 3D Punktwolken in der Nahbarschaft von Rissen, (b) der Vergleich aufeinander folgender Punktwolken durch Formparameter und (c) die Anwendung eines Bootstrap-Systems für die Erkennung signifikanter statistischer Ergebnisse. Diese Prozedur wird am Beispiel der Analyse strukturellen Schäden in Mauerwerk der Basílica da Ascensión, im Nordwesten Spaniens, vorgestellt.*

*Resumen*

*En el campo del patrimonio cultural, el seguimiento de la integridad de estructuras puede beneficiarse considerablemente de las técnicas de digitalización tridimensional. El objetivo del análisis de deformaciones y medición de estructuras* *es la detección precoz de daños con el fin de reaccionar adecuadamente y a tiempo. Los sistemas empleados tradicionalmente en la medición de fisuras, grietas y fracturas requieren un contacto directo con la estructura y su aplicación está supeditada a la accesibilidad. Además, este tipo de herramientas proporcionan únicamente un número discreto de mediciones puntuales, en lugar de proporcionar un registro continuo de la dimensión del daño en toda el área afectada, información que se puede obtener con las modernas técnicas de modelado tridimensional. Entre éstas, la fotogrametría de objeto cercano es todavía la más completa, barata, flexible y ampliamente empleada en aplicaciones arquitectónicas. Este artículo se ocupa de la aplicación de la fotogrametría de objeto cercano a la detección y seguimiento de daños estructurales. Se propone el siguiente procedimiento de actuación: restitución de nubes de puntos en el contorno de una grieta en diferentes fechas, a continuación comparación entre las sucesivas nubes mediante parámetros de forma, y finalmente aplicación de una prueba de replicación muestral para medir la significancia estadística de los resultados. Este procedimiento se aplica al análisis de los daños estructurales detectados en una construcción de mampostería de un elemento del patrimonio cultural español: la Basílica da Ascensión, en el Noroeste de la Península Ibérica.*

 