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Low-cost documentation of traditional agro-industrial buildings by close-range photogrammetry

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Abstract

Traditional agro-industrial buildings are an important part of the heritage of Galicia (northwest of Spain), but these buildings are now in danger of disappearing. In order to preserve it, an exhaustive and rigorous work of documentation should be undertaken, as well as other actions.

This paper is about the graphic and metric documentation put together by the authors in relation to a group of traditional farm buildings in Galicia. We used a method based on close-range photogrammetry techniques. The method is simple, cheap and accessible to the layperson. The tools we used were low-cost conventional cameras, plumb lines and monoscopic digital photogrammetric stations. The accuracy of our method compared to topographic methods proved satisfactory, although it must be borne in mind that the type of building surveyed is not particularly tall.

Keywords: Close-range photogrammetry; Agro-industrial buildings; Documentation

1. Introduction

The concept of heritage is now broader than ever before, its scope growing wider every day. The change from the traditional idea of monument to the current concept of cultural heritage proves that there is a growing concern in society about the need to preserve and upkeep heritage so it can be passed on to future generations. A new approach focuses on the protection of certain instances of human intervention [1]. Humans have modelled the environment to meet their needs when both farming and exploiting natural resources, thus creating what are known as 'cultural landscapes'. Traditional farm buildings are part of our popular heritage and as such they deserve to be preserved to bear witness to the way our ancestors lived [1]. According to De Llano [2], the heritage of Galicia—traditionally a farming region—has been disappearing at an alarming rate since well before the 1960s. This decay was brought about by a number of factors, namely emigration to large cities (for its part due to the crisis in the farming economy), the introduction of modern building techniques and changes in the type of crops.

Photogrammetric techniques are one of the most valuable tools for the documentation of traditional farm buildings [3]. Adequate documentation allows us to obtain information on the state of the building at the time the pictures are taken (techniques and building styles, materials used, geometry and state of conservation). This information, when gathered accurately, can be used to undertake several types of action, such as reconstruction and rehabilitation, reutilisation, and relocation.

Several factors account for the 'universalisation' of photogrammetry as a documentation technique. The use of simple, cheap, and fast methods that are accessible to a great number of people would definitely be among these [4]; some terms, such as 'the democratisation of photogrammetry' [5] or 'photogrammetry for everybody' have been coined with the purpose of defining this phenomenon [6]. This new trend has prompted attempts to document traditional agro-industrial buildings, which have typically

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been disregarded by the governmental institutions in charge of heritage preservation, more intent on architectural monuments.

2. Traditional agro-industrial buildings in Galicia

In Galicia, traditional farm buildings are an extension of the farm house. They were conceived to make life on the farm easier and their primary function has to do with produce storage. Most of these buildings are now in an advanced state of deterioration and neglected and unless their study and documentation are undertaken soon they are doomed to disappear.

Documentation [7] is one of the stages involved in the process of conservation and reutilisation of traditional farm buildings. The documentation stage is itself divided into another two: the cataloguing and classifying stages. There are several criteria used for classification: function, material and location, amongst others [8]. We have organised our classification of traditional farm buildings in Galicia according to their productive sector and function. The classification is summed up in Table 1, where the buildings are classified according to the productive sector and the kind of use assigned to them.

Table 1
Classification proposed for traditional agro-industrial architecture in Galicia

Productive sector	Use of the building	Designation
Production Primary sector	Storage	Alpendres (*sheds*), palleiras (*haystacks*), hórreos (*traditional granaries*)
	Cattle	Cortes (stables), pombais (pigeon houses), albarizas (buildings designed to enclose and protect beehives)
	Hunting and fishing	Foxos (*pits*), pesqueiras (*fishing places*), peiraos (*piers*)
Industrial production	Transformation	Eiras (threshing floors), muiños (mills), adegas (wine cellars) and lagares (press houses), fornos (ovens)
	Handcraft production	Oleiros (ceramic workshops), telleiras (tilemakers' workshops), batáns (fulling mills), ferrerías (blacksmiths' quarters), serradoiros (sawmills)
Public service for the community	Communal buildings	Pozos (wells), fontes (fountains), lavadeiros (washing places), apeadeiros (stopping places)
	Town and country planning	Pontes and pontellas (various types of bridges), presas (dams) and conducciones de agua (pipings)

These buildings are characterised and differentiated by the structure and plant geometry, the type of roof, the characteristic height of the masonry, the maximum length and types of masonry, the length of existing gaps, and the building materials used. Some authors, like Bas [9,10], Caamaño [11] and De Llano [2,12,13], have undertaken a thorough study of these features. Our goal, in turn, is to provide a documentation technique for the generation of plans and scale three-dimensional (3D) models. This low-cost technique can be used by non-qualified people.

3. Methods for building documentation

According to Scherer [14], the four most commonly used methods for the documentation of buildings are traditional manual methods, topographic methods, photogrammetric methods and scanning methods. All of them are geared to providing metric information on the building on which plans and 3D models can be created. The method used for each particular case depends on their specific objectives, the required degree of accuracy and the characteristics of the piece of heritage to be documented.

One of the main features of photogrammetric methods is the short length of time required on-site to carry out measurements. Office work during the evaluation stage is actually longer [15]. Three types of photogrammetric methods can be used in relation to their degree of accuracy [16]:

- Very accurate photogrammetric methods: for works requiring 1 mm or even better rates of accuracy. These are usually applied to decorative elements and statues and provide both a reproduction of elements and a detailed analysis of surfaces (degradation, pathology of materials, etc.). The most commonly used scales are 1:10, 1:5 and 1:2.
- Accurate photogrammetric methods: used when accuracy rates of about 1 or 2 mm are required. Clearly identifiable control points on the pictures must be used. Such points are normally determined by means of topographic procedures. Their main applications are monument analysis, restoration and conservation performances and archaeological and decorative element surveys. These methods are the most widely used. Representation scales are usually 1:10, 1:50 and 1:20.
- Fast and simple photogrammetric methods: these methods stand out for their simplicity and the low cost

of the equipment required. We found them appropriate for the documentation of traditional agro-industrial buildings. Maximum errors below 5 cm are usually considered acceptable. In this case, 1:100 and 1:200 are the most commonly used scales and front and section views are typical. Control points can be established by measuring the distances in relation to horizontal or vertical references.

Specific techniques and equipment are required for each one of the above-mentioned methods. The method discussed in this paper can be included in the fast and simple methods category. According to the criteria established by CIPA's group 3 [4], it is a simple method insofar as it is simple to use (even for people with no extensive knowledge of photogrammetry) and easy to acquire (the equipment used is standard, available in the market, easy to acquire and inexpensive, its price under 10,000 dollars).

4. Methodology

Traditional farm buildings in Galicia have certain features in common and these specific features have defined the guidelines we used when choosing a documentation methodology. These are the features the buildings have in common:

- Rather simple architectonic structures with no decorative adornments or elements, and with very simple structural solutions.
- Almost identical construction patterns for every type of building.
- The same kind of building materials is used.
- They are all of small size and low height.
- There is a large number of buildings spread all over Galicia.
- There is a large number of buildings at a great risk of disappearing.

The documentation technique used can be included in the group of fast and relatively simple photogrammetric methods. The main features of these methods are:

- Simplicity.
- Low-cost equipment.
- Maximum error of about 5 cm.
- Restitution in monoscopic or stereoscopic, analogical or digital systems.
- Use of calibrated and uncalibrated photographic cameras, of small or medium format, equipped with CCD sensors or conventional film.

The study is divided into two stages. The first of these is field work. During this stage, the scaling and the orientation methods and elements are analysed, and the photographs are taken. The second stage is laboratory work. During this stage, the information is processed in order to deliver plans and 3D models reproducing the original structure on a certain scale.

4.1. Work equipment

With regard to the equipment used, a distinction must be made between the equipment employed to obtain 3D models—which we will call work equipment—and the equipment used to assess the accuracy of such models (called control equipment). Cameras, plumb lines and photogrammetric digital stations made up the work equipment.

4.1.1. Cameras

Two different low-cost standard digital cameras were used: the RICOH 6000 and the KODAK Dx 3500. Both cameras are fitted with fixed-focus optics granting stability in the inner orientation, although some authors have reported some instability in the principal point [17,18]. Both of them are fitted with CCD, the first of them affording a 2.140.000 pixel resolution and the second a 2.300.000 pixel resolution. The image resolution of the first is 1600×2000 pixels, and that of the latter 1800×1200. Both of them store files in JPEG format.

4.1.2. Plumb lines

Plumb lines are regular plumbs suspended by a line where predetermined marks have been made. The colour of the adhesive tape the marks have to be made with should be different from that of the wall so that the marks will stand out from the background. The distance between the marks can be measured with a tape measure.

4.1.3. Digital photogrammetric station

The Photomodeler Pro.4.0. monoscopic station was used to perform the (inner and outer) orientation of the photographs and the restitution and construction of the 3D models.

4.2. Control equipment

4.2.1. Targets

They are placed on the walls of the building in order to make it easier to identify the common points in all of the different photographs that will be used for the outer orientation. The minimum size of the targets T is worked out taking into account the distance between the camera and the object (D), the focal length (f), and the pixel size (p), according to the following expression:

$$T = \frac{D \cdot p}{f}. \tag{1}$$

Increasing T the accuracy of point location will also be increased using methods for target location with subpixel precision, e.g., centroid determination or least squares matching [19].

4.2.2. Topography equipment

A Leica X-range 102 laser total station was used to determine the coordinates of the points previously signalled on the walls. These points enable model accuracy to be monitored. The station includes a laser telemeter for the purpose of carrying out measurements of up to 200 m without prism.

The laser station has the following technical features: laser plumb line; magnification $30\times$; typical deviation in angle measurement 2 in (according to DIN 18723/ISO 12857); electronic level sensitivity: 20 in/2 mm; twofold axis compensator; measurement accuracy of distances with prism: 2 mm + 2 ppm; measurement accuracy of distances without prism: 3 mm + 2 ppm.

4.3. Field work

Field work can be summed up in the following stages:

(a) Establishment of objectives: before initiating any documentation work, objectives must be defined in a clear and accurate way. Assessments as to which buildings and elements deserve in-depth analysis should be made at this stage. Poorly defined objectives will clearly affect the quality of the results adversely.

(b) Register of field data: filing cards were devised to store the information gathered during the field work stage. The design of these filing cards is instrumental in the improvement of the method's effectiveness. The filing card we used was based on the ideas set forth by authors Galáz [20], Kuipers [21] and Valentová and Dolansky [22]. The filing cards include the following information: author and basic data (date, hour, name of the building, initial study or updating of previously registered data); location and access (province, municipality, parish, street, square, village, approximate UTM coordinates); description of the building (number, function and structure of the buildings; features of the building concerning shape and size; gaps; number of floors; structural configuration; especially relevant elements and plan sketch of the building and all of its sides indicating doors, windows and relevant elements); topographic works, when considered necessary (specifying type of equipment, topographic method and location of the control points); photographic works (specifying the camera and the film used plus a sketch of how the cameras were placed when the photographs were taken).

(c) Placing the plumb lines and measuring distances on them in order to undertake the alignment and scaling required for the geometry of the models. The plumb lines must drop in a perfect vertical line and should be suspended from any projecting element on the walls of the building. To achieve this, some auxiliary element might be required in the joint with the wall in order to ensure that no contact between them takes place. The direction of the plumb line defines the direction of the Z-axis in the photogrammetric coordinate system. The length of the plumb lines will vary depending on the height of the building. A minimum of two plumb lines are used. When buildings were of a considerable size, positive experimental results were achieved by using one plumb line for each side of the building. Some visible marks are placed on the plumb lines so as to avoid confusion. As the model scale will be based on the distances between them, these marks must be measured accurately beforehand.

(d) Image acquisition: photographs are taken with conventional, low-cost digital cameras, using CCD as the sensor element, according to the basic principles of photography. The following aspects should be taken into account: using the right lighting conditions, averting shadows, reflections, backlights or burned photographs; calculating the depth of field, which must be large enough to prevent poor exposure and objects being out of focus; the speed of the camera, which in the case of automatic cameras depends on lighting conditions; the way the camera is held, although it is usually better just to place the camera on a tripod; and framing, which has to be adjusted to the contours of the building so that the sky does not take up too much space in the photograph.

The position of the camera is determined for each photograph taking into account that restitution is carried out using digital monoscopic equipment. The following guidelines must be observed:

- Every element must be included in a minimum of three photographs. It is also possible to use only two photographs, but in that case only one verification of the three coordinates obtained (x, y, z) can be carried out, and the results of such a verification make a weak starting point if the convergence of the photos is not great. However, if each detail observed can be found in three photos, the first two have a weak validation and the third provides complete validation that the point has been successfully identified, since the three photos together produce three validations. Furthermore, the third photo, which is taken near perpendicular to the object, allows us to obtain photorealistic textures of the object that can later be applied to the 3D models.
- The convergence of photographs taken from different places must have an optimal value of 90° and a good value of 60° so that bundle adjustment can be carried out in good conditions.
- If possible, two photographs will be taken at a 90° angle and one perpendicular to the face of the object or building to be photographed.
- There will be at least a 50% overlapping between photographs.
- The photographs will be taken in such a way that the element being photographed covers most of the picture.

- A large number of both general and close-up photographs must be taken. The redundancy of images facilitates the detection and elimination of gross error.

4.4. Laboratory work

Laboratory work is a subsequent stage to field work. Laboratory work serves the purpose of processing previously gathered information. It is carried out in two stages: one involving the storage of data contained on the index cards and the other involving data processing. In the first stage a database must be created in order to speed up the management of information. In the second stage, 3D models reproducing the original structure on a fixed scale are obtained by means of a digital photogrammetric station. This data processing stage is divided into the following stages:

(a) Inner orientation. This operation entails the reconstruction of perspective rays in conditions similar to their formation within the photographic camera, using the values obtained in the calibration process (radial and decentring lens distortion, focal length and position of the principal point). By means of inner orientation we can get rid of errors arising from the use of non-metric cameras. The camera calibration has been done using the Camera Calibrator 4.0 software included in the Photomodeler Pro 4.0 digital photogrammetric station. The method used by this software is the self-calibrating bundle adjustment, which requires taking some previous shots of a calibration grid [23] in order to obtain the inner orientation parameters of the camera. This calibration process is clearly described by Arias [24], Atkinson [25], Chen and Schenk [26] or Herráez and Navarro [27].

(b) Exterior orientation. In this stage the rays generated in the inner orientation process are positioned in relation to the ground in the very same position adopted at the moment of exposure of the photographs. The photogrammetric coordinates for a minimum of five points shared by another photograph already orientated or to be orientated in the same process must be measured. As ground control points are not available, the system will carry out a free network adjustment. This includes two operations arranged in sequences known as relative and absolute orientation.

(b.1) Relative orientation. The evaluation of the exterior orientation elements of one camera with regard to the photo coordinate system of another is known as relative orientation. The simultaneous intersection of at least five pairs of homologue rays distributed through the model is enough for the remaining points to intersect as well, according to perspective geometry. The rays' equations are calculated analytically and the relative orientation parameters can be calculated applying the co-planarity conditions to the homologue rays (vectors defining the projection of every ground point on the photographs) for each pair of photos.

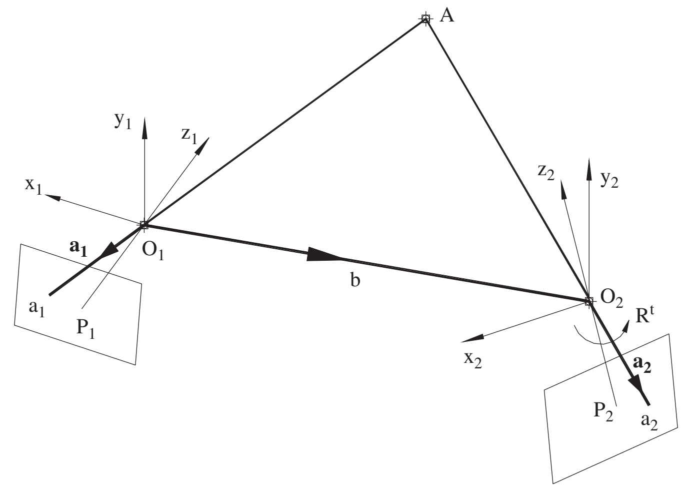

Fig. 1. Reference systems of two photograms in order to carry out relative orientation.

Adopting the coordinate system based on the first picture (origin in the centre of projection, X- and Y-axes on a plane parallel to the plate, and the Z-axis in the direction of the principal axis), the relative orientation solves the problem of calculating the relation between the photogrammetric coordinate system and the model coordinate system by means of the co-planarity condition (Fig. 1):

$$\begin{vmatrix} 1 & \dfrac{b_y}{b_x} & \dfrac{b_z}{b_x} \\ x_1 & y_1 & -f \\ x_2 & y_2 & z_2 \end{vmatrix} = 0, \tag{2}$$

where b_x, b_y and b_z are the distances between the centre of projection of two photographs according to axes X, Y and Z, respectively; $(x_1, y_1, -f)$ image coordinates of a point in the first picture referred to the principal point (f being the camera focal length); and (x_2, y_2, z_2) the coordinates of the point in the second picture, referred to the coordinate system of the first. The latter are obtained starting from the coordinates of the point in the coordinate system of the second picture $(x'_2, y'_2, -f)$ by means of a rotation and a translation:

$$\begin{bmatrix} x_2 \\ y_2 \\ z_2 \end{bmatrix} = R \cdot \begin{bmatrix} x'_2 \\ y'_2 \\ -f \end{bmatrix} + \begin{bmatrix} b_x \\ b_y \\ b_z \end{bmatrix}, \tag{3}$$

R being the rotation matrix:

$$R = \begin{bmatrix} \cos\varphi\cos\kappa & \sin\omega\sin\varphi\cos\kappa + \cos\omega\sin\kappa & -\cos\omega\sin\varphi\cos\kappa + \sin\omega\sin\kappa \\ -\cos\varphi\sin\kappa & -\sin\omega\sin\varphi\sin\kappa + \cos\omega\cos\kappa & \cos\omega\sin\varphi\cos\kappa + \sin\omega\cos\kappa \\ \sin\varphi & -\sin\omega\cos\varphi & \cos\omega\cos\varphi \end{bmatrix} \tag{4}$$

and (ω, φ, κ) rotation angles around axis X, Y and Z, respectively.

The collinearity condition will solve the same problem, plus it will allow calculating the ground coordinates for a point in n photographs starting from the image coordinates (and inversely). The principle of collinearity states that an image point a $(x_a, y_a, -f)$, the perspective centre O (X_O, Y_O, Z_O), and object point A (X_A, Y_A, Z_A) are all on the same straight line (Fig. 1). The collinearity equations can be expressed as follows:

$$
\begin{aligned}
x_a &= -d\frac{r_{11}(X_A - X_O) + r_{12}(Y_A - Y_O) + r_{13}(Z_A - Z_O)}{r_{31}(X_A - X_O) + r_{32}(Y_A - Y_O) + r_{33}(Z_A - Z_O)},\\
y_a &= -d\frac{r_{21}(X_A - X_O) + r_{22}(Y_A - Y_O) + r_{23}(Z_A - Z_O)}{r_{31}(X_A - X_O) + r_{32}(Y_A - Y_O) + r_{33}(Z_A - Z_O)},
\end{aligned}
\tag{5}
$$

where r_{ij} are the elements of the matrix of rotation R in which the rotation angles to be determined appear. The coordinates of the perspective centre O and of object points A will be model coordinates if relative orientation is being carried out, and ground coordinates when absolute orientation is being performed.

Once the external coordinate system for the first image has been defined, it will be the one used for each image added whose relation will be obtained with the co-planarity condition (relative orientation).

(b.2) Absolute orientation. Once the model has been established, we must adjust it to the ground coordinate system by means of absolute orientation. The z-axis is established from the direction defined by the plumb lines and this is how the model is levelled. The scale factor is attained via the distances measured on the plumb lines by means of a simultaneous bundle adjustment. Then we proceed to a new adjustment which ensures correct levelling, orientation and scaling of the 3D model. The homothetic relation (scale factor) between the model obtained in the relative orientation and the ground truth is calculated by measuring the real distances between the points marked in the plumb line and comparing them with the distances in the model.

Levelling is achieved applying rotations around X- and Z-axes (that means that $\varphi = 0$ in the rotation matrix), which is the result of testing the model coordinates for the points marked in the plumb lines (the fact that these are vertical enable to establish that after the transformation they have the same X and Z coordinates). The transformation equations for the photogrammetric systems (x, y, z) to the ground coordinate system (X, Y, Z) are similar to the ones used in relative orientation:

$$
\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = k \cdot R \cdot \begin{bmatrix} x \\ y \\ z \end{bmatrix} + \begin{bmatrix} X_O \\ Y_O \\ Z_O \end{bmatrix}, \tag{6}
$$

where (X_O, Y_O, Z_O) are the camera principal point ground coordinates, k the scale factor previously calculated and R a rotation matrix with Ω and K rotation angles obtained in the model levelling stage.

Table 2
Comparison between monoscopic and stereoscopic restitution systems

	Monoscopic systems	Stereoscopic systems
Advant.	The photogrammetric station is the only cost	More comfort when identifying points
	Easy to use	Initially, greater precision in the results obtained
	Can be used anywhere on computer, be it a laptop or a desktop	
	Presence of epipolar lines	
Disadvant.	Identifying the points is harder	The cost of the stereoscopic vision system must be added
	It is necessary to recognise the same point in two or more photos	A certain experience is needed when setting down
	There must be good convergence among photograms	Depending on the vision system requirements may be more demanding, and not every computer may be adequate

(c) Restitution of the models (after scaling and orientation). The information contained in the photographs will be materialised in a document, irrespective of whether such photographs are plans and digital files (3D and/or 2D), coordinates lists with information on the mistakes observed, etc. Several modalities of restitution are available: points, lines, polylines (or other graphic entities of interest, like cylinders, circumferences, etc.).

As mentioned earlier, a monoscopic station is used in the restitution process, and this kind of station is not as accurate as a stereoscopic station when locating points although it does have some advantages, as can be seen in Table 2.

The resulting models containing metric information and the 3D models are ready to be exported in conventional formats (dxf, dxb, vrml, etc.) into other programs in order to be visualised, edited or processed. Another feature of the system is its capability to generate 3D models of surfaces and the subsequent projection of real textures, captured from the object's photographs, onto these models.

4.5. Accuracy control

The accuracy of the method has been assessed comparing the coordinates provided by the digital photogrammetric workstation with the coordinates obtained by means of more accurate topographic methods with regards to a series of points homogeneously distributed on the object. Since both systems of coordinates—topographic and photogrammetric—are different, the photogrammetric system must be altered in order to adjust it to the topographic system so that the differences between them can be accurately accounted for. With that purpose, the extended orthogonal procrustes analysis (EOP) has been used.

Procrustes analysis is a well known technique to provide least square matching of two or more factor loading matrices or for the multidimensional rotation and scaling of different matrix configurations. Applied at first as a useful tool in factor analysis, it has become a popular method of shape analysis [28], and recently some authors have proposed the application of the method (with some variations, as generalised orthogonal procrustes analysis or weighted procrustes analysis) in geodesy, to transform 3D coordinates related to WGS 84 reference ellipsoid into 3D coordinates of a local reference system [29], and also in photogrammetry, to adjust blocks of photograms by independent models [30]. The analysis consists of a least squares method for fitting a given matrix A to another given matrix B under choice of an unknown rotation R, an unknown translation t, and an unknown scale factor c in such a way as to minimise the sum of squares of the residual matrix $E = cAR + jt^{\mathrm{T}} - B$, that is, $\mathrm{tr}(E^{\mathrm{T}}E) = \min$, under the orthogonal condition for matrix R that is $R^{\mathrm{T}}R = I$, where $j^{\mathrm{T}} = [1, \ldots, 1]$ is a $(1 \times N)$ unit vector, matrices A and B are $(N \times k)$ dimensional which contain N corresponding points in the k-dimensional space, R is $(k \times k)$ orthogonal rotation matrix, t is $(k \times 1)$ translation vector and c is a scale factor.

In order to satisfy the minimum condition, a Lagrangean function, defined as

$$F = \mathrm{tr}(E^{\mathrm{T}}E) + \mathrm{tr}[L(R^{\mathrm{T}}R - I)], \tag{7}$$

must be minimised, where

$$\begin{aligned}\mathrm{tr}[E^{\mathrm{T}}E] = {} & \mathrm{tr}[B^{\mathrm{T}}B] + c^2\,\mathrm{tr}[R^{\mathrm{T}}A^{\mathrm{T}}AR] + Nt^{\mathrm{T}}t - 2c\,\mathrm{tr}[B^{\mathrm{T}}AR] \\ & - 2\,\mathrm{tr}[B^{\mathrm{T}}jt^{\mathrm{T}}] + 2c\,\mathrm{tr}[R^{\mathrm{T}}A^{\mathrm{T}}jt^{\mathrm{T}}],\end{aligned} \tag{8}$$

$N = j^{\mathrm{T}}j$ is a scalar, and L is a matrix of Lagrangean multipliers.

The minimum condition is obtained by setting the partial derivative of F with respect to the unknowns be set to zero, that is,

$$\begin{aligned}&\frac{\partial F}{\partial T} = 2c^2A^{\mathrm{T}}AR - 2cA^{\mathrm{T}}B + 2cA^{\mathrm{T}}jt^{\mathrm{T}} + R(L + L^{\mathrm{T}}) = 0,\\ &\frac{\partial F}{\partial t} = 2Nt - 2B^{\mathrm{T}}j + 2cR^{\mathrm{T}}A^{\mathrm{T}}j = 0,\\ &\frac{\partial F}{\partial c} = 2c\,\mathrm{tr}[R^{\mathrm{T}}A^{\mathrm{T}}AR] - 2\,\mathrm{tr}[B^{\mathrm{T}}AR] + 2\,\mathrm{tr}[R^{\mathrm{T}}A^{\mathrm{T}}jt^{\mathrm{T}}] = 0.\end{aligned} \tag{9}$$

Solving this system we obtain the expression of the unknowns T, c and t:

$$\begin{aligned}&R = VW^{\mathrm{T}},\\ &c = \frac{\mathrm{tr}[R^{\mathrm{T}}A^{\mathrm{T}}(I - (jj^{\mathrm{T}}/N))B]}{\mathrm{tr}[A^{\mathrm{T}}(I - (jj^{\mathrm{T}}/N))A]},\\ &t = (B - cAR)^{\mathrm{T}}j/N,\end{aligned} \tag{10}$$

where V and W are orthonormal eigenvector matrices obtained using Eckart–Young decomposition of matrix SS^{T},

$$S = A^{\mathrm{T}}\left(I - \frac{jj^{\mathrm{T}}}{p}\right)B \tag{11}$$

being a $(k \times k)$ dimensional matrix.

The degree of adjustment between the matrices A and B is assessed by means of the root mean square error (RMSE)

$$\mathrm{RMSE} = \sqrt{\mathrm{tr}(E^{\mathrm{T}}E)/(N-1)}, \tag{12}$$

and the closer to zero RMSE is, the better the adjustment obtained.

Besides RMSE, which will give us a measure of the global adjustment between photogrammetric and topographic coordinates, we are interested in assessing the value of the rotation angles with regard to the x- and y-axes of the topographic system (ω and φ, respectively)—which are the ones affecting the verticality of the z-axis—and the scale factor. Rotation angles close to zero indicate that the model is well levelled, whereas a scale factor close to 1 suggests that the distance between points is similar according to both systems.

In addition to the EOP analysis, the accuracy of the method has been assessed by means of a factor showing the differences in the distances existing between all points, taking into account the two methods used for measuring (topographic and photogrammetric), and according to the following expression:

$$DF = \sqrt{\sum_{i=1}^{N}\sum_{j=2}^{N}[(D_i^j)_T - (D_i^j)_F]^2/N}, \quad i<j, \tag{13}$$

$(D_i^j)_T$ being the distance between points i and j measured by means of topographic methods, and $(D_i^j)_F$ the distance between points i and j measured by means of the photogrammetric method proposed here. DF values close to zero suggest that the relative location of the points according to both systems is very similar.

5. Study case: documentation of a hórreo

The above explained methodology was applied to a group of eight traditional agro-industrial buildings in Galicia. Several criteria were taken into account when choosing the buildings. On the one hand, we tried to select buildings of varied typologies with regard to shape, material, types of roof, etc. On the other hand, we took into account the importance of the buildings and the risk of disappearance. We considered more urgent to repair the more dilapidated buildings. Here we will show the works undertaken to document one of those buildings, namely *hórreo*, a very common type of traditional building in Galicia.

The *hórreo* is a historic building normally used in Galicia for the storage of farm produce (Fig. 2). The one we have documented stands out because of its size, being larger than most of the *hórreos* existing in Galicia. The two materials used to make the building were granite and wood. The former was used to make up the structure of the building and the latter to build a hollow filler. The structure is raised and is not in direct contact with the ground. The building rests on two pairs of carefully crafted granite pillars running parallel to each other. The pillars stand on a foundation of irregular blocks of coarsely worked stone, jutting a few centimetres out of the ground surface in order to level the hórreo's floor. The roof is made of Galician tiles. A most remarkable feature of the building's roof can be seen over one of the main façades of the building, namely two simple structures similar to dormer-windows, with their corresponding valleys in the intersection of the slope of the roof and the ridge line. The carpentry of the doors is of chestnut wood and it is in good condition.

In this case, the following work equipment was employed: Ricoh 6000 digital camera working at its highest resolution (camera calibration parameters [31] of this camera are presented in Table 3); two plumb lines made of plastic rope 5 mm thick; and the Photomodeler pro 4.0 digital photogrammetric station. The lines for the plumbs were of bright colours in order to stand out from the building. They were placed as close to the edges of the building as possible. The lines were tied around the edges jutting out of the binding rafters holding the roof structure. The plumbs were suspended from a height of 3 m and enough distance was left in order to ensure they dropped vertically. On every string two marks were made with adhesive tape and the ensuing distances were determined with a tape measure.

Fig. 3 shows a sketch of the positions of the camera when the photographs were taken. This sketch is one of the elements contained in the documentation index card.

Fig. 4 shows a front and a side view restituted on a scale of 1:50.

Fig. 5 is a scaled 3D photorealistic texture model obtained matching photogram textures with a surface model of the *hórreo*.

In order to determine the degree of accuracy of the model, the coordinates obtained by means of the method we used were compared with the coordinates obtained by a topographic method in 27 points distributed throughout all the building. The points were identified by means of signalling targets adhered to the walls of the *hórreo*. The measurements were made from two stations, one on each side of the hórreo and established so they would be intervisible. These were connected by means of reciprocal sights and the measurements were repeated four times. FL (face left) and FR (face right) readings and forced centring were used in order to reduce the error. In a more general case it will be necessary to carry out the measurement from different stations joined together by means of a closed traverse. The maximum standard error among all the points can be easily calculated since we know the features of the total station used and have taken into account the values of the angles and the distances between the stations and from each station to the control points. With this in view, we employ the classic formulae used in topography for error propagation [32]. Thus, the maximum standard

Fig. 2. Photograph of the *hórreo*. Two stones suspended by ropes and acting as plumb lines can be noticed.

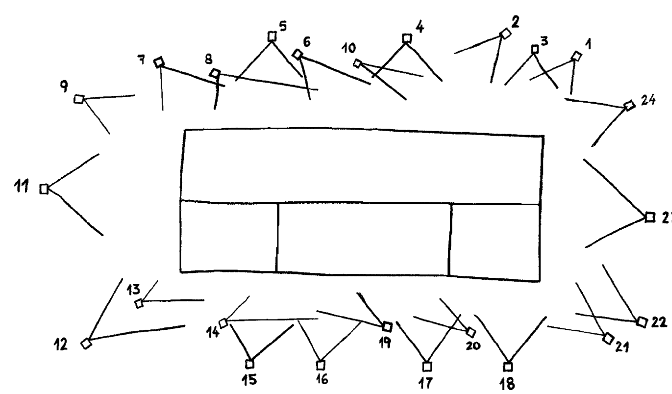

Fig. 3. Sketch showing the positions of the camera when the photographs were taken.

Table 3
Ricoh 6000 camera calibration parameters

Camera	Focal	Height	Width	X_P	Y_P	K_1	K_2	P_1	P_2
Ricoh 6000	7.9920	6.1707	4.6241	3.1921	2.4062	1.718e-3	−1.448e−4	−4.592e−4	−1.366e−4

The parameters used are focal length (mm), size of the digital sensor (mm), principal point position in mm (X_P, Y_P), radial distortion (K_1 and K_2) and tangential distortion (P_1 and P_2).

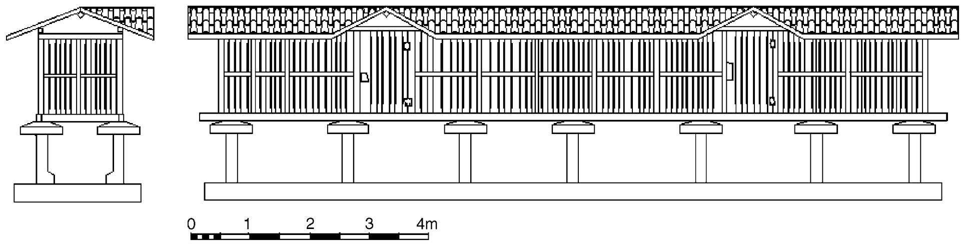

Fig. 4. Restitution of the hórreo. Front (right) and side (left) view.

Fig. 5. Three-dimensional model of the hórreo.

error calculated was in the order of 1 cm for the X and Y coordinates and 2 cm for the Z coordinate.

Using the values of the photogrammetric coordinates and the topographic values in the control points, a procrustes analysis was carried out in order to measure the precision of the first considering the second a reference. The maximum standard error, as we have just pointed out, was 1 cm in X and Y and 2 cm in Z (in order to get a comprehensive comparison, prior to procrustes analysis the photogrammetric Y- and Z-axes were renamed to Z and Y, respectively, since Y photogrammetric axis corresponds to Z topographic direction). Table 4 displays the values of the parameters of transformation from the photogrammetric coordinate system to the topographic system using EOP, and the root mean square error calculated according to Eq. (11). It can be noticed that the scale factor almost equals the unity, suggesting that the relative location of the points is similar for both systems. On the other hand, the ω and φ angles being very small, we can infer that the Z-axis of the photogrammetric coordinate system is not very much deflected with regard to the topographic Z-axis and, therefore, the 3D model is well levelled. Moreover, a high value for kappa has been obtained (over 200°) as it could be expected, since the method aims to achieve the levelling of the model and not to real ground coordinate assignation. The RMSE, which measures the goodness-of-fit between both systems, is only of 9 mm.

On the other hand, the value of the parameter DF, given by Eq. (12), is 4 mm, which is another argument in favour of the accuracy of the photogrammetric coordinates.

Transferring the origin of the photogrammetric Z-axis to the topographic, using displacement t_z, obtained in the EOP analysis, and calculating the quadratic differences between the photogrammetric Z coordinates (Z_{pht}) and their respective topographic z coordinates (Z_{top}), divided by the number of control points minus 1, the root mean square error in Z is obtained, which is an indicator of the goodness of levelling in the 3D model built:

$$\text{RMSE}_z = \sqrt{\frac{(z_{\text{pht}} - z_{\text{top}})^2}{N-1}} = 0.004\ \text{m}; \quad N = 27. \tag{14}$$

If we consider that each coordinate X, Y and Z has the same contribution to the RMSE obtained in the EOP analysis, the expected error for the Z coordinate should be $9/\sqrt{3} = 5.2$ mm, slightly greater than RMSE_z. Since this was calculated without taking into account any rotation and scale factor, we could conclude that these produce small changes in the Z coordinate.

Fig. 6 is a representation of the error in the Z coordinate throughout the whole model (with an exaggeration factor of 30 on the Z axis in order to improve the interpretation). The residues observed in the model levelling are represented in the Z-axis, that is to say, the difference in absolute value between the photogrammetric Z-axis and the topographic Z-axis. The points have been joined by means of triangles in order to build a continuous surface which will facilitate interpretation. The homogeneity of error in Z can be noticed, with no marked differences being observed in the model.

6. Conclusions

The main advantages of the methodology proposed for the documentation of agro-industrial buildings are its simplicity and low cost. Another beneficial factor is that the user does not require specialised knowledge of photogrammetry, and that no large-scale investments in equipment are needed. Taking into account that we are dealing with isolated buildings, it is unnecessary to adopt a fixed system of coordinates. A levelled model is sufficient and we can do without signalling targets or calculating coordinates by means of topographic methods. Money and time are thus saved.

The degree of accuracy obtained in the three-dimensional models is in accordance with the work objectives and

Table 4
Parameters for the Procrustes transformation between the photogrammetric and topographic coordinate systems

Scale factor	Rotation (Grad)			Translation (m)			RMSE (m)
c	ω	φ	κ	t_x	t_y	t_z	RMSE
1.0029	0.0228	0.0305	201.9340	107.889	111.985	10.108	0.009

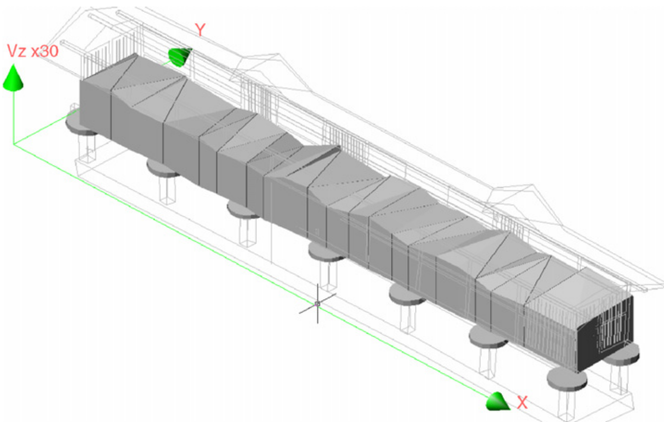

Fig. 6. Error in the Z coordinate along the structure.

it fulfils the recommendations forwarded by CIPA's work group 3.

The method has, however, some limitations when applied to tall constructions (not very common in this type of farm buildings) because a plumb line of great length has to be used in order to prevent unbalance. The unsteadiness brought about by such an approach could entail a lack of verticality in the Z-axis. The wind may also be another disadvantage, because it could make the plumb line move, and a lack of verticality in the model may come about as a consequence.

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