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A COMBINED SINGLE RANGE AND SINGLE IMAGE DEVICE FOR LOW-COST MEASUREMENT OF BUILDING FAÇADE FEATURES

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Abstract

The dimensions of building façades and window apertures are usually determined by making direct measurements using tapes and plummets. This approach, however, has a number of drawbacks including the physical risk to which the persons making the measurements are exposed. This paper proposes an indirect approach based on close range photogrammetry that is inexpensive, simple, fast and safe, and which does not require specialist staff or direct ground control measurements. The method is based on taking a picture using a digital camera and measuring the distance to the object using a handheld laser distance meter. Both items of equipment are mounted on a specially designed support that allows the laser distance meter to move independently of the camera.

Keywords: building façade, close range photogrammetry, digital camera, laser distance meter, window aperture measurement

Introduction

An advantage of photogrammetry over other measuring techniques is its capacity to make measurements without having to make contact with the object. In the construction field, objects are typically measured using direct methods involving the use of tapes and plummets. Using an indirect approach based on close range photogrammetry has important advantages, however. These include improved precision, time savings and coarse error elimination, and the fact that a digital record of the object photographed is created. Furthermore, from a safety perspective, the indirect approach reduces the physical risk to operators who have to move around buildings, lean out of windows and go up onto roofs to hang tapes and plummets. Nonetheless, the success of these indirect methods depends on

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them being both inexpensive and accessible to people with little or no knowledge of photogrammetry or surveying.

Low-cost close range photogrammetry has been the subject of studies both by software companies which develop software such as Elcovision, Iwitnessphoto and Photomodeler and by researchers looking to close the gap between photogrammetry and non-specialist uses. It is mainly based on the use of inexpensive digital cameras and on avoiding ground control point measurement methods and topographic survey equipment. Ethrog (1984) described a photogrammetric method for determining interior orientation parameters and angles using objects with parallel and perpendicular lines rather than control points. Mulawa and Mikhail (1988) introduced the concept of linear features and described a formula for combining photogrammetric observations and linear features in an adjustment procedure. Van den Heuvel (1998) studied the use of a single image with geometrical restrictions for rebuilding objects. The restrictions were based on geometric relationships between straight lines, such as coplanarity, parallelism, perpendicularity, symmetry and distance. Haralick (1989) used a similar method in order to obtain the interior orientation parameters of the camera by means of a photographic exposure at an unknown scale introducing a distance into the object. Arias et al. (2006) used a simple close range photogrammetry method to document agro-industrial constructions in Galicia (Spain), based on the use of a conventional calibrated digital camera and vertical plummets that enabled the orientation of the models generated, with scale calculated by means of marks made on the plumb lines at known intervals. Finally, Tommaselli and Lopes Reiss (2005) described a photogrammetric method based on the use of a camera and a handheld laser meter coupled in such a way that their axes were parallel. With the aim of determining the dimensions of flat surfaces using a single picture and measuring the distance to this surface, the method was applied to calculating the dimensions of placards and billboards.

This paper proposes an improvement on the method described by Tommaselli and Lopes Reiss (2005), based on a rigid support which permits relative rotations of the distance meter and the camera and which assumes parallelism between the axes of the devices. The Tommaselli and Lopes Reiss orientation method, furthermore, requires three orientation angles to be calculated, whereas the present method only needs two.

The system developed in this research consists of uniting the camera and the laser meter on a support that allows the laser meter to be set in different positions and in a way that does not require the axes of the two devices to be parallel. This is very useful for measuring door and window apertures in building façades, when the distance from the camera to the façade plane must be measured from the external wall of the aperture.

DESIGN AND CONSTRUCTION OF THE SUPPORT

The support system for the measuring equipment was designed taking into account the different situations that can occur in the daily routines for which the equipment was conceived. The technical characteristics required of the system—and thus determining the design—are as follows:

(a) It must be small, light and easy to handle.
(b) It must be possible to use it with or without a tripod.
(c) It must be valid for all types of cameras and laser meters.
(d) It must provide a rigid link between the camera and the laser meter.
(e) The devices must be easily and quickly mounted and dismounted without needing to be recalibrated.

(f) The devices must be able to adopt different relative positions and must allow exact repeatability. Horizontal and vertical movement must be possible in order to aim the laser at a specific point avoiding possible gaps or obstacles that might interfere with the data gathering process. Movement must be quick and precise and should not require any tools.

(g) The maximum rotation angles of the laser meter must be such that the target spot will be visible in the picture. Thus, assuming that the camera axis is perpendicular to the object (otherwise, the insignificance of the variations can be easily checked), let α be the angular field of the camera, B_x the horizontal distance between the camera centre and the laser source, and D the distance between the camera centre and the object to be measured (that is, the object at which the laser ray is aimed); the maximum angles between the camera axis and the laser ray direction (Fig. 1) are then given by the following equations:

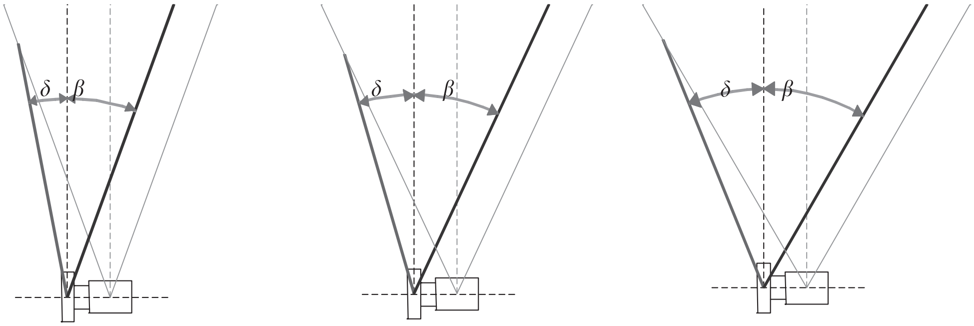
$$\tan\beta = \tan\ \alpha/2 + \frac{B_x}{D} \tag{1}$$

$$\tan\delta = \tan\ \alpha/2 - \frac{B_x}{D}. \tag{2}$$

The expressions for the maximum rotation angles in the vertical plane are the same as those given above, merely that B_x is substituted by B_y (B_z does not affect the calculation of the angles).

Obviously, the maximum values for β and δ increase with the value of α, with β decreasing and δ increasing in line with distance D. For a B_x value equal to 15 cm (the value for the built prototype) and for an angular opening value of 60 gon, the maximum values for β and δ, respectively, are 37 and 30 gon, which are the values used in the designed support.

The support was designed with the aid of CAD SolidWorks (SolidWorks, 2005), which enables an evaluation of component assembly, movement viability, and final weight and appearance. Fig. 2 shows the 3D model created using this program, with an indication of its basic components.



α = 40·0000 gon
β = 20·0000 gon
δ = 11·0242 gon

α = 50·0000 gon
β = 25·0000 gon
δ = 16·4446 gon

α = 60·000 gon
β = 30·0000 gon
δ = 21·9720 gon

FIG. 1. Relationship between the angular aperture of the camera and maximum rotation angles of the laser meter.

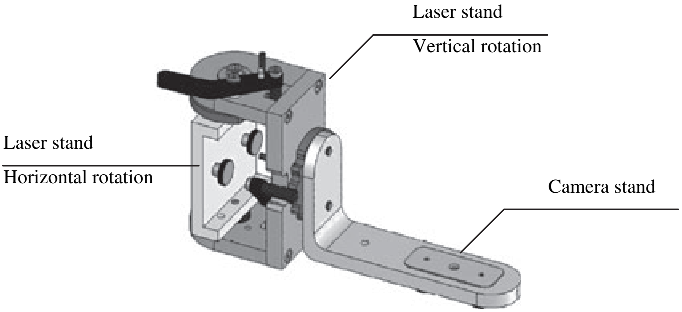


FIG. 2. 3D model of the support.

The body of the support was made of steel. Apart from the ease with which steel can be machined, the system will not deform and reliable calibration and measurement is ensured. With a view to reducing the final weight of the equipment, this will be ultimately constructed in a lighter material (such as aluminium) but with a similar construction. Fig. 3 depicts a photographic camera and a laser meter assembled on a support.

CALIBRATING THE MEASURING EQUIPMENT

The system must be calibrated before it can be used to measure objects. This task can be performed in a laboratory or by the user on site, following the procedure described below for determining the different parameters:

(1) The relative position between the laser measuring source point (X_L, Y_L, Z_L) and the camera optical centre (X_0, Y_0, Z_0) is defined by the vector $\mathbf{L}(X_L - X_0, Y_L - Y_0, Z_L - Z_0)$.
(2) The angular component between the camera optical axis and the measuring axis of the laser meter is defined by a unit vector $\mathbf{U}(U_X, U_Y, U_Z)$.

A procedure needs to be designed that allows the position of at least two different points in the laser path trajectory to be calculated. The most precise definition of the laser centre is obtained when one of the points is located as close as possible to the starting point. The most

FIG. 3. Measuring system.

precise definition of the **U** vector is obtained when one of the points is located as far as possible from the starting point.

The procedure used involved taking two pictures (photographic exposures) from two different positions on a calibrated panel (point grid) with the corresponding distance measurements. Each exposure and its associated distance measurement is referred to as a "shot" for brevity in the following account. The calibration sequence and the calculation of the calibration parameters are summarised as follows:

(1) A reference system is defined in a rectangular panel that assigns coordinates to each corner and defines the coordinate origin for any one of the corners (for example, the top left corner). The panel is assumed to be completely flat, and thus all the points will have the same Z coordinate.

(2) The first shot is taken assuming the following to be unknowns: the camera coordinates $(X_0^{(1)}, Y_0^{(1)}, Z_0^{(1)})$, its rotations with respect to the panel $(\omega_0^{(1)}, \phi_0^{(1)}, \kappa_0^{(1)})$ and the spatial coordinates of the laser pointer on the panel $(X_{PL}^{(1)}, Y_{PL}^{(1)}, Z_{PL}^{(1)})$. Since the values for the four corners of the panel are known, the coordinates can be easily obtained for the camera and its rotations with respect to the coordinate system defined in the panel using the collinearity condition developed for the image coordinates (Zhizhuo, 1990). Using the least squares method (Mikhail and Gracie, 1981) to resolve the problem, an estimate of precision as well as the unknown values in a given number of iterations can be obtained.

(3) The previous process is repeated with the second shot, obtaining a second camera position $(X_0^{(2)}, Y_0^{(2)}, Z_0^{(2)})$ and its rotations $(\omega_0^{(2)}, \phi_0^{(2)}, \kappa_0^{(2)})$ regarding the panel, as well as the second spatial position of the laser meter $(X_{PL}^{(2)}, Y_{PL}^{(2)}, Z_{PL}^{(2)})$.

(4) Since the movement of the measuring equipment in regard to the calibrated panel is relative, it can be considered that the panel is moved rather than the camera, in such a way that two real positions of the camera are obtained from the same theoretical position, and the fixed panel position as two different theoretical positions. Applying this transformation, two 3D laser coordinates are obtained aligned from the same theoretical position as the camera, obtaining the position **L** with respect to the camera as the direction vector **U** with regard to the optical axis of the camera (Fig. 4). The distance between the spatial laser pointer and the camera in each shot (D_{c_i}) is calculated. This distance will be independent of the translations or rotations from the origin of the coordinate system, since it is a relative magnitude. Once both relative distances have been obtained, it is sufficient to consider the camera to be in the position (0, 0, 0) and to recalculate the 3D positions of the laser points in the new reference system established through the following photogrammetric equations:

$$X_{PL}^{(i)} = Z_{PL}^{(i)} \frac{x_{PL}^{(i)}}{-c} \tag{3}$$

$$Y_{PL}^{(i)} = Z_{PL}^{(i)} \frac{y_{PL}^{(i)}}{-c} \tag{4}$$

where

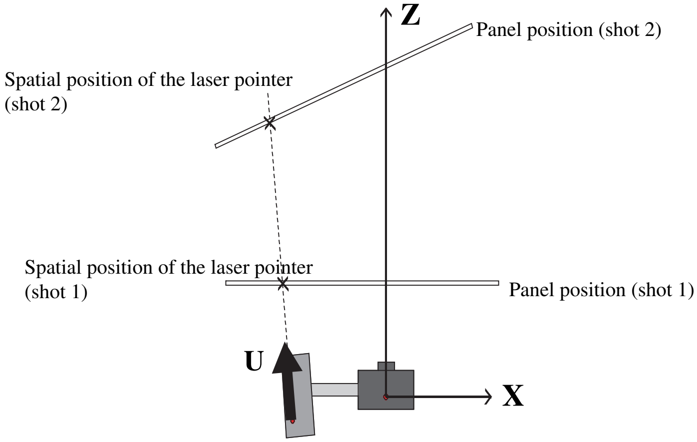


FIG. 4. System calibration process.

$(X_{PL}^{(i)}, Y_{PL}^{(i)}, Z_{PL}^{(i)})$ are the transformed laser coordinates,
$(x_{PL}^{(i)}, y_{PL}^{(i)}, -c)$ are the laser pointer photo-coordinates and where
$Z_{PL}^{(i)}$ is obtained from the distance D_{c_i}:

$$D_{c_i} = \sqrt{\frac{Z_{PL}^{(i)2} x_{PL}^{(i)2}}{c^2} + \frac{Z_{PL}^{(i)2} y_{PL}^{(i)2}}{c^2} + Z_{PL}^{(i)2}}. \tag{5}$$

Replacing the value of $Z_{PL}^{(i)}$ in (3) and (4) the 3D coordinates are obtained from the laser transformed for both positions in the new reference system.

(5) With both the (aligned) pointer spatial positions and the distances measured by laser, the laser origin position **L** and the direction vector **U** are obtained according to the following expression:

$$\begin{pmatrix} X_L \\ Y_L \\ Z_L \end{pmatrix} = \begin{pmatrix} X_{PL}^{(i)} \\ Y_{PL}^{(i)} \\ Z_{PL}^{(i)} \end{pmatrix} - D_{m_L}^{(i)} \begin{pmatrix} U_x \\ U_y \\ U_z \end{pmatrix} \tag{6}$$

where $D_{m_L}^{(i)}$ is the measured distance for the laser in each position.

IMAGE ORIENTATION

The dimensions for the photographed elements are obtained by calculating the distances between the points that define their geometry from the coordinates. The method used to determine these coordinates is based on the external orientation of the image plane through parallel and perpendicular lines visible in the photograph (van den Heuvel, 1997). All that is needed is to take a photograph and measure the distance from the camera to the object plane. In the present case, since the purpose of the system is the measurement of the magnitude of the object element independently from each spatial position, a variant of the van den Heuvel method was used that restricts the rotation calculations to just two by determining the vanishing line in the image space.

The limit line can be determined by means of vanishing points calculated for the object to be measured or for any other object found in the same or parallel planes that meets with the requirements (Criminisi et al., 1999).

The first step in the external orientation consists of determining the rotation angle ψ (Fig. 5) around an axis perpendicular to the image plane that places the Y axis (from the reference system in the image plane) parallel to the vanishing line. If A and B are the two vanishing points, with image coordinates (x_a, y_a) and (x_b, y_b), respectively, obtained by the intersection of the parallel straight lines in the object space in the image, the angle is given by

$$\psi = \arctan\frac{x_a - x_b}{y_a - y_b}. \qquad (7)$$

Given the ψ rotation, a new rotation of the camera axis system is implemented, this time for an angle μ and taking the Y axis as reference (Fig. 5), so as to locate the image plane parallel to the object plane:

$$\mu = \arctan\frac{c}{d} \qquad (8)$$

where c is the focal length of the camera and d is the distance between the main point and the vanishing line in the image space (Fig. 5), given as a function of the coordinates of a and b by the following expression:

$$d = \frac{|y_a x_b - y_b x_a|}{\sqrt{(x_b - x_a)^2 + (y_b - y_a)^2}}. \qquad (9)$$

Knowing the spatial position of the image, a system of coordinates adapted to the present purposes can be defined in order to apply the collinearity condition and obtain the coordinates for any point in the object space. The coordinate system is placed at the optical centre of the camera, in such a way that the Z axis is vertical and the X and Y axes are placed parallel to the plane that contains the object.

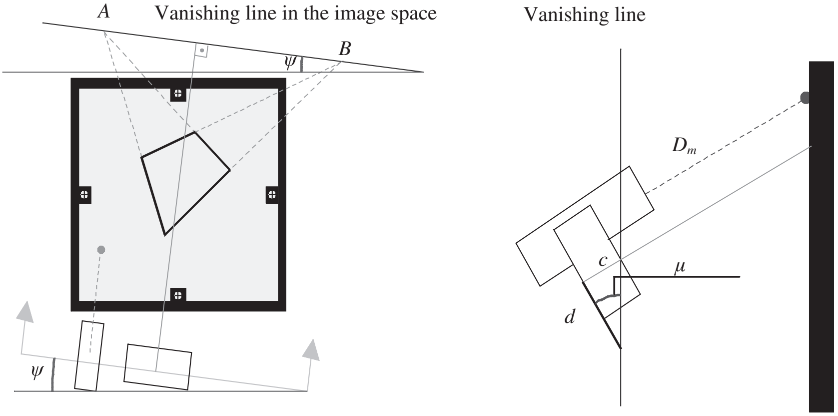


FIG. 5. Image orientation: ψ and μ rotations.

The collinearity equation is as follows:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = k\mathbf{R}_{\psi}\mathbf{R}_{\mu} \begin{pmatrix} x \\ y \\ -c \end{pmatrix} \tag{10}$$

where
(X, Y, Z) are the coordinates of any given point in the object space
$(x, y, -c)$ are the photo-coordinates of the point in the image space
k is the scale coefficient
$\mathbf{R}_{\psi}$ is the ψ angle rotation matrix and
$\mathbf{R}_{\mu}$ is the μ angle rotation matrix.

In order to determine k, it is necessary, in the first place, to apply the same ψ and μ rotation angles as used for the camera to the laser meter, in such a way that both devices will move in unison. Thus, the coordinates of the laser pointer over the object are obtained from the following expression:

$$\begin{pmatrix} X_{PL} \\ Y_{PL} \\ Z_{PL} \end{pmatrix} = \mathbf{R} \left[\begin{pmatrix} X_L \\ Y_L \\ Z_L \end{pmatrix} + D_{m_L} \begin{pmatrix} U_X \\ U_Y \\ U_Z \end{pmatrix} \right] \tag{11}$$

where
(X_{PL}, Y_{PL}, Z_{PL}) are laser pointer coordinates,
$\mathbf{R} = \mathbf{R}_{\psi}\mathbf{R}_{\mu}$ is the combined angular rotation matrix,
(X_L, Y_L, Z_L) are the laser meter centre coordinates,
D_m is the distance measured by the laser meter and
(U_X, U_Y, U_Z) is the laser direction vector.

Developing equation (11) for coordinate Z, the following equation is obtained:

$$Z_{PL} = m_{31}(X_L + D_{m_L} U_X) + m_{32}(Y_L + D_{m_L} U_Y) + m_{33}(Z_L + D_{m_L} U_Z) \tag{12}$$

where

$$\begin{aligned} m_{31} &= \sin\psi \\ m_{32} &= -\sin\mu\cos\psi \\ m_{33} &= \cos\mu\cos\psi. \end{aligned}$$

Knowing Z_{PL}, the scale factor k is calculated using the third row of equation (10):

$$k = \frac{Z_{PL}}{m_{31}x_{PL} + m_{32}y_{PL} - m_{33}c}. \tag{13}$$

RESULTS

To prove the suitability of the system, a series of tests was conducted using the following devices:

(1) Canon EOS 10D calibrated camera:
Focal distance: 20·2157 mm

Format: 22·5203 mm × 15·0132 mm
3072 × 2048 pixels
Principal point: (11·1601, 7·5245).

(2) Zinder Leica Disto Plus laser meter:
Precision: ±1·5 mm (between 0·2 and 200 m).

(3) Calibrated panel:
Dimensions: 100 cm × 80 cm
Targets every 10 cm forming a mesh of 11 × 9 (99 marks in total).

Calibration

The results obtained for the calibration are shown in Table I. As can be observed, the highest precision was obtained for the horizontally convergent position of the laser meter. This level of precision was reduced slightly in the parallel axis position, and to a greater degree in the laser divergent position. This is entirely logical, as the inverse intersection is supposed to be made with the smallest angles at the different positions.

Distance to the object was a determining factor for the angular field of the system. At short distances, the angular field for the divergent laser meter position was greatly reduced. Exactly the opposite happened for the convergent case. The convergent position covered a greater angular field than that for the camera, while the divergent position reached this value, in the best of the cases, at an infinite object distance.

So, taking both factors into consideration, the results show a better adjustment and a greater range of options in the laser meter convergent position.

It is important to point out that the theoretical methodology described above, which calculates two positions for the camera (keeping the focus setting fixed) for each calibrated rotation position, can be reinforced in reality by taking more shots. In this way, a least squares adjustment is carried out so as to improve accuracy and reduce the error deriving from an excessively small image of the panel at greater distances.

As for the system calibration tests performed, noteworthy is the mechanical and dimensional stability shown by the system, resulting in insignificant variations in the results for the repeatability studies conducted in several sessions for the different positions studied. This result would reinforce the initial hypothesis in regard to the suitability of using heavy but sturdy materials such as steel to construct the support. Likewise, the

Table I. Calibration results of the camera–laser meter system (metres).

Value	*Vertically downwards and parallel to the camera axis*	*Vertically upwards and parallel to the camera axis*	*Horizontally divergent*	*Horizontally parallel*	*Horizontally convergent*
$X_L - X_0$	−0·21416 ± 0·004794	−0·20595 ± 0·008601	−0·16400 ± 0·006943	−0·21110 ± 0·000589	−0·23519 ± 0·000172
$Y_L - Y_0$	0·02208 ± 0·005053	−0·02295 ± 0·009764	0·00032 ± 0·000343	−0·00009 ± 0·000167	−0·00118 ± 0·000104
$Z_L - Z_0$	0·13444 ± 0·009015	0·14511 ± 0·01281	0·17330 ± 0·013195	0·11689 ± 0·001397	0·14742 ± 0·001240
U_x	−0·02073 ± 0·001659	−0·04175 ± 0·002057	−0·39211 ± 0·000086	−0·03354 ± 0·000115	0·36112 ± 0·000054
U_y	−0·40838 ± 0·000822	0·39173 ± 0·001000	0·01090 ± 0·000044	0·01927 ± 0·000079	0·00230 ± 0·000042

mechanical solutions for adjusting the different components can be judged satisfactory. This conclusion was reached on the basis of repeating the process after repeatedly dismounting and reassembling the camera and the laser meter, thereby proving that the solutions adopted mean there is no need to recalibrate the system and also guarantee the exact position.

Measurement

In order to determine the precision of the system when measuring plane objects, several tests were run by making measurements over a rectangular panel of known dimensions placed on a wall. The best results were obtained when the camera axis was not perpendicular to the wall plane but located so as to precisely define the vanishing lines.

Once the image was set, the four corners of the panel were marked on the image and their coordinates were calculated. The height and width dimensions of the panel were then calculated.

For a specific relative position and distance between the camera and the panel, the measurements varied slightly depending on the two pairs of parallel lines used to determine the vanishing points. Fig. 6 shows the cumulative frequency distribution of the absolute error, obtained by comparing the panel measurements with the measurements obtained using the proposed system for a single photograph taken at a distance of 3 m from the panel. A total of

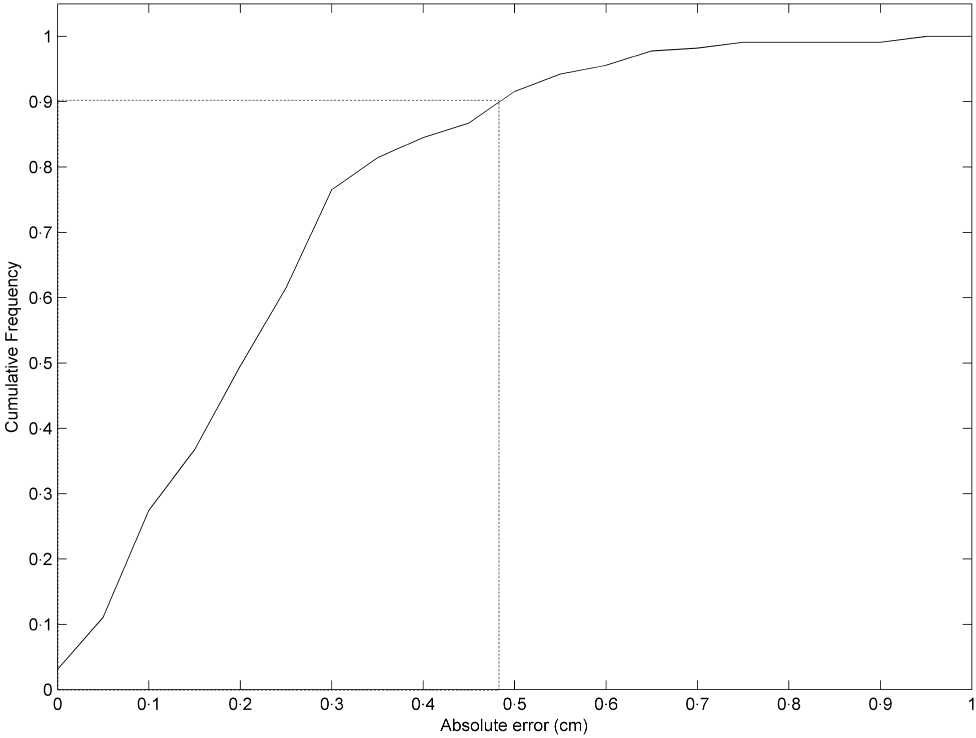


FIG. 6. Cumulative frequency of absolute error in panel measurement.

TABLE II. Window measurements made using a measuring tape and the proposed method for different definitions of the vanishing line (metres).

Tape	*Photo.*	*Diff.*	*Tape*	*Photo.*	*Diff.*
1·407	1·400	0·007	0·798	0·789	0·009
1·407	1·399	0·008	0·798	0·791	0·007
1·407	1·402	0·005	0·798	0·792	0·006
1·407	1·398	0·009	0·798	0·789	0·009
1·407	1·397	0·010	0·798	0·793	0·005
1·407	1·402	0·005	0·798	0·790	0·008
1·407	1·401	0·006	0·798	0·791	0·007
1·407	1·399	0·008	0·798	0·789	0·009

50 panel measurements were calculated (hence, 50 error values were obtained), each corresponding to a vanishing line obtained from two pairs of parallel lines. As can be seen, 90% of the errors were less than 5 mm, giving a maximum relative error of 0·6% (the panel measures 100 cm × 80 cm).

Table II compares the lengths for two sides of a window measured with a measuring tape and using the proposed method. Maximum differences were 1 cm or less, corresponding to a relative difference of less than 1·2%. The distance from the camera to the window was around 5 m. Each of the values corresponds to a different definition of the vanishing line.

CONCLUSIONS

The research describes a simple close range photogrammetry system for measuring apertures in building façades (among other possible applications). It is an inexpensive and easy-to-use system that does not require the ground control point measurements that are necessary for topographical survey methods.

Uniting the capture devices in a single system has added to the precision of each of the devices, with the camera playing a key role in orienting the image and in the precision of the laser measurement vector, and with the laser playing a key role in the scaling process for the object space by its measurement of the distances.

The proposed measuring method is valid for irregularly shaped planar objects provided there are parallel lines in the image that will allow the vanishing line of the plane to be determined. This represents a key advantage over existing commercial software, as data capture is fully externalised and requires no contact with the object.

The tests show that the best relationship between the camera and the laser meter is the convergent position. The best results are obtained, furthermore, with shots oblique to the object, as they enable a better determination of the vanishing points. In this situation, the maximum error levels obtained in the research were less than 0·3% for 90% of panel measurement cases. Measurement of a real window gave a relative error of less than 1·2%.

Although satisfactory results were obtained, work is continuing on improving the design and the weight of the equipment as well as on new measurement methods that require less intervention from the user.

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Résumé

On détermine généralement les dimensions des façades des bâtiments et des embrasures des fenêtres par des mesures directes à l'aide de rubans et de fils a plomb. Cette solution comporte néanmoins un certain nombre d'inconvénients tels que les risques auxquels sont physiquement exposées les personnes chargées des mesures. On propose dans cet article une solution indirecte, simple, rapide et sûre, qui ne nécessite pas un personnel spécialisé, basée sur la photogrammétrie à courte distance, sans recourir à des déterminations directes du canevas de points d'appui, et reste bon marché. Dans cette méthode on saisit l'image avec une caméra numérique dont on mesure la distance à l'objet avec un distance-mètre à laser tenu à la main. On a conçu un support spécialement adapté à ces deux équipements et qui permet au laser de se mouvoir indépendamment de la caméra.

Zusammenfassung

Die Dimensionen von Gebäudefassaden und Fensteröffnungen werden üblicherweise durch direkte Messungen mit Maßband und Lot durchgeführt. Diese Methode hat jedoch einige Nachteile wie z.B. das Unfallrisiko für das Messpersonal. In diesem Beitrag wird eine berührungslose Methode der Nahbereichsphotogrammetrie vorgestellt, die preiswert, einfach, schnell und sicher ist. Sie erfordert keine spezielle Ausbildung und auch keine Passpunktmessungen. Es wird mit einer Digitalkamera eine digitale Aufnahme erstellt und die Distanz zum Objekt mit einem tragbaren Laserdistanzmesser ermittelt. Beide Gerätekomponenten sind auf einem speziell entwickelten Träger montiert, wobei der Laserdistanzmesser unabhängig von der Kamera bewegt werden kann.

Resumen

La determinación de las dimensiones de las fachadas de los edificios y de los huecos de las ventanas se realiza habitualmente mediante métodos de medida *directos empleando cintas métricas y plomadas. Estos métodos adolecen de una serie de inconvenientes, entre los que está el riesgo al que están sometidos los operarios que realizan las mediciones. Este trabajo plantea sustituir los métodos directos por un método, basado en la fotogrametría de objeto cercano, indirecto, barato, sencillo, rápido y seguro, y que no requiere personal especializado o apoyo terrestre directo. El método se basa en la toma de una imagen con una cámara digital y en la medida de la distancia al objeto con un distanciómetro láser, montados sobre un soporte especialmente diseñado que permite mover el distanciómetro independientemente de la cámara.*