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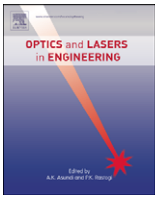

Flat elements on buildings using close-range photogrammetry and laser distance measurement

Jaime Rodríguez [a,*], María T. Martín [a], Pedro Arias [b], Celestino Ordóñez [b], José Herráez [c]

[a] Surveying Engineering School, University of Santiago de Compostela, 27002 Lugo, Spain
[b] Mining School, University of Vigo, Rua Maxwell s/n, 36310 Vigo, Spain
[c] Cartographic Engineering School, Polytechnic University of Valencia, 46022 Valencia, Spain

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ABSTRACT

The dimensions of building facades and window apertures are usually measured by direct methods using tapes and plummets. These methods require several operators, are slow and in many cases imply working in conditions of high risk. This paper proposes to replace these procedures by indirect methods based on close-range photogrammetry and laser distance measurement, resulting in a low cost, quick, simple and safe method. The method is based on taking three photographs with a digital camera and measuring the three distances with a laser meter, with both instruments mounted on a support that is calibrated in multiple turning positions in order to simultaneously measure different elements on a plane that has regular or irregular geometry.

1. Introduction

In the construction industry, objects are usually measured using direct methods and using tapes and plummets. Replacing these methods by techniques based on close-range photogrammetry allows us to eliminate the contact with the object. This eliminates the risk to operators who previously had to move around buildings under construction, lean out of windows and climb roofs to hang tapes and plummets. This approach also gives more precision to the measurements, is more productive, and creates a digital record that can be added to a database of the photographed elements.

In order for these methods to be accepted for use, they must be inexpensive and accessible to people with no knowledge of photogrammetry or surveying. Low-cost close-range photogrammetry has been studied for the last few years by various researchers aiming to bring photogrammetry closer to non-specialized users. The method is mainly based on using inexpensive digital cameras and eliminating topographic methods that require specific equipment for measuring ground control points. Van den Heuvel [1], for example, studied the use of a single image with geometric restrictions to reconstruct objects. Research into using a single image and the geometry of the elements in the image [2] was used to produce 3D models from a single photogrammetric image with geometrical restrictions based on relationships among straight lines (co-planarity, parallelism, perpendicularity, symmetry and distance). The analysis of building structures that present a clear risk of collapse has also been evaluated by simple close-range photogrammetry methods [3]. Close-range photogrammetry—based on the use of a conventional calibrated digital camera and plummets to level out photogrammetric models and mark the plummet thread for model scaling [4]—has also been applied to measuring and studying distortions in bridges [5,6]. In Galicia (Spain) close-range photogrammetry has been used to document agroindustrial constructions, using a conventional calibrated digital camera and plummets to level out photogrammetric models, and marking the plummet thread for model scaling [4]. Tommaselli and Lopes [7] used close-range photogrammetry and laser measurement, and parallel camera and laser meter axes, to determine flat surface dimensions on rectangular publicity panels. More recently, a device for measuring topographic surfaces based on photos and laser measurements was developed by Ohdake and Chikatsu [8] based on the same idea, although they included a system of mirrors to align the axes of the two instruments.

The method proposed in this paper is based on a system that uses a digital camera and an attached laser meter, both mounted on a support, which is calibrated in different rotation positions. This method, which simultaneously measures one or more elements in a plane, is especially designed to measure window

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* Corresponding author at: Polytechnic School, University of Santiago de Compostela, 27002 Lugo, Spain. Tel.: +34 982285900; fax: +34 982285926.
E-mail addresses: jairodpe@lugo.usc.es (J. Rodríguez), mmartin@lugo.usc.es (M.T. Martín), parias@uvigo.es (P. Arias), cgalan@uvigo.es (C. Ordóñez), jherraez@cgf.upv.es (J. Herráez).

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apertures in buildings under construction, avoiding parallel or aligned axes for the two devices. The method used consists of taking three photographic images in the same position and three laser distances at different calibrated positions. Defined thus is the object plane which intersects with the conical beam defined by the marked vertices on the image.

2. Design and construction of the support

The support system for the measuring equipment was designed taking into consideration the different situations that can arise in the routine everyday use for which the device is conceived. The technical characteristics required of the system are the following:

1. It must be capable of being used with or without a tripod.
2. It must be small and light enough for easy handling.
3. It must provide a fixed union between the digital camera and the laser meter.
4. It must be quickly and easily set up and dismantled without needing recalibration.
5. It must be valid for different types of cameras and laser meters.
6. It must permit connections with peripheral equipment (for example, a PDA).
7. It must be possible for the camera and the laser meter to be used in different relative positions and it must permit exact repeatability. Horizontal and vertical movement must be permitted in order to overcome any type of obstacles in the data-gathering process. Movements must be quick and precise, and additional tools should not be necessary.
8. The maximum rotation angles of the laser meter must be such that the laser pointer will be visible in the photographic image.

CAD SolidWorks [9] was used for the support design, allowing element assembly, movement viability. Final weight and appearance have to be evaluated. Fig. 1 shows the 3D model made with this program, and the basic components are indicated.

Steel was used as the basic material to build the support body. Steel is easy to work with; furthermore, the steel support will not deform, which will ensure that calibration and measurement are reliable. With a view of reducing the final weight of the equipment, steel will eventually be replaced by a lighter material (such as aluminum) with similar properties. Fig. 2 shows a camera and a laser meter assembled on a support.

For the method described to work correctly, it is essential that there is no movement in the system while the data is being gathered. To ensure this, the distance must be measured and the photograph taken simultaneously. We did this using a Bluetooth transceptor and a connection between the system and the PDA that stores the measurements of the distances.

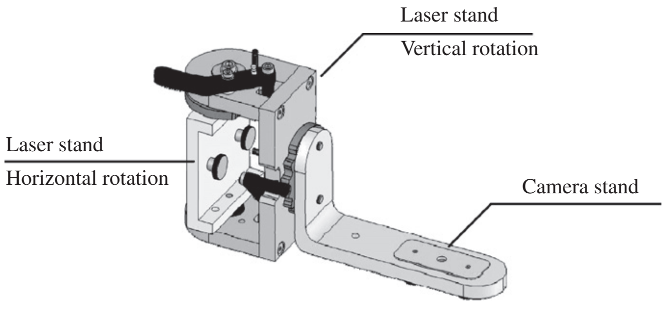

Fig. 1. 3D support design.

Fig. 2. Built prototype.

3. Equipment calibration through moving objects

The system we designed is composed of two information capture devices: a digital photographic camera (calibrated using conventional methods [10]) and a laser meter attached to the camera. The digital camera captures the geometry of the object and the laser meter measures the distance from the system to the object. To measure objects, the system must be calibrated for each rotation position of the laser meter, so that for all possible cases, the system calibration [11] will determine the relative position between the instruments that make up the system (Fig. 3). This requires the following parameters to be determined [12]:

1. The relative position between the laser-measuring source point and the camera optical center, which is defined by the vector $\mathbf{L}(B_X, B_Y, B_Z) = \mathbf{L}(X_L - X_0, Y_L - Y_0, Z_L - Z_0)$, where the sub-index L refers to laser coordinates and the sub-index 0 refers to camera center coordinates.
2. The angular components between the camera optical axis and the measuring axis of the laser meter, which are defined by a unitary vector $\mathbf{U}(U_X, U_Y, U_Z)$.

We needed to design a procedure that allowed us to calculate the position of at least two different points in the laser path trajectory. The most precise definition of the laser center is obtained if one of the points is located as close as possible to the starting point, and the most precise definition of the vector is obtained when one of the points is located as far as possible from the starting point. A relative movement between the measuring system and the photographed object is thus required (the movement of either one is equally valid).

The procedure used consists of taking several photographic images with a fixed camera on a moving object (Fig. 4). The calibration sequence and the calculation of the calibration parameters are described as follows:

1. The reference system is fixed on the camera, assigning coordinates (0, 0, 0) to the principal point and null rotations to the image plane. Thus, the laser pointer coordinates in the object space for each photograph can be calculated by applying the co-linearity condition [13], as follows:

$$X^{(i)}_{\mathrm{PL}} = Z^{(i)}_{\mathrm{PL}} \frac{x^{(i)}_{\mathrm{PL}}}{-c} \tag{1}$$

$$Y^{(i)}_{\mathrm{PL}} = Z^{(i)}_{\mathrm{PL}} \frac{y^{(i)}_{\mathrm{PL}}}{-c} \tag{2}$$

where $(X^{(i)}_{\mathrm{PL}}, Y^{(i)}_{\mathrm{PL}}, Z^{(i)}_{\mathrm{PL}})$ are the object coordinates of the laser pointer photocoordinates.

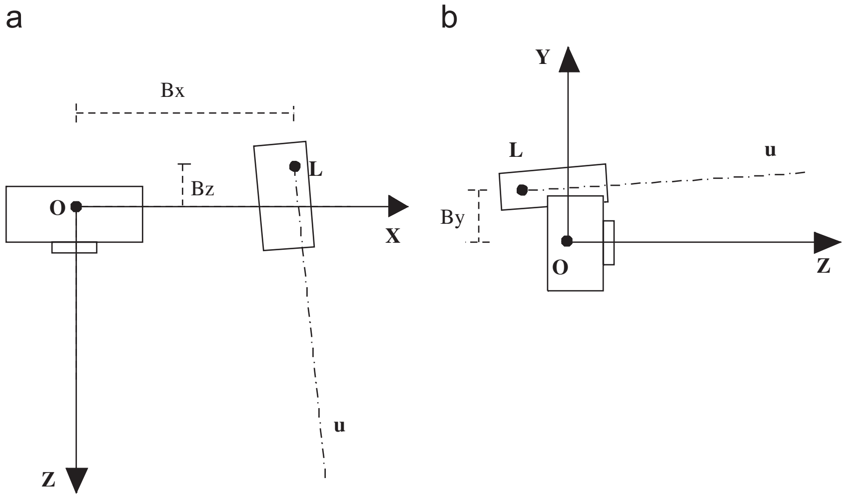

Fig. 3. Calibration parameters.

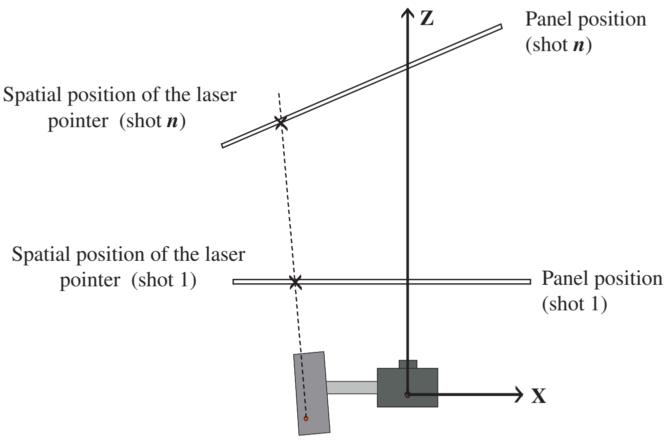

Fig. 4. System calibration process.

2. The following expression determines the origin of the laser measurement and the direction vector:

$$\begin{pmatrix} X_{\mathrm{L}} \\ Y_{\mathrm{L}} \\ Z_{\mathrm{L}} \end{pmatrix} = \begin{pmatrix} X_{\mathrm{PL}}^{(i)} \\ Y_{\mathrm{PL}}^{(i)} \\ Z_{\mathrm{PL}}^{(i)} \end{pmatrix} - \mathrm{Dm}_{\mathrm{L}}^{(i)} \begin{pmatrix} U_X \\ U_Y \\ U_Z \end{pmatrix} \tag{3}$$

   where $\mathrm{Dm}_{\mathrm{L}}^{(i)}$ is the distance measured by laser for each position. C the focal distance of the camera.
   The resulting unknowns in each photograph are the laser measurement origin $(X_{\mathrm{L}}, Y_{\mathrm{L}}, Z_{\mathrm{L}})$ coordinates, their direction vector $\mathbf{U}(U_X, U_Y, U_Z)$, and the coordinate $Z_{\mathrm{PL}}^{(i)}$.
3. Substituting (1) and (2) in (3), and developing the equation system for three or more laser pointer spatial positions, an estimation of the unknown values is obtained and their precision is obtained using the least-squares method [14].

4. Determining the dimensions of the object

The dimensions of the elements in the photographic image are determined from the coordinates in the object space of the points that define the contours. Points are manually marked on the photograph.

The designed support must ensure that there are no camera movements when the laser meter positions are changed—to ensure that the three images are exactly the same. It should be sufficient to take just one photograph, but it is important to rectify the trio of images [15] in order to obtain a unique image plane and ensure the absence of movement due to agents external to the support. This procedure consists of correcting two of the photographic images to the position of the photograph taken as fixed and with null rotations through the photocoordinates of the points common to the three images, and not taking into account the differential movements that the support could transmit to the laser meter in data gathering. This transformation in the photographic image is given by the expression

$$\begin{bmatrix} x_i' \\ y_i' \\ c \end{bmatrix} = K[R] \begin{bmatrix} x_i'' \\ y_i'' \\ c \end{bmatrix} + \begin{bmatrix} \mathrm{d}x \\ \mathrm{d}y \\ \mathrm{d}z \end{bmatrix} \tag{4}$$

where (x'_i, y'_i, c) denote photocoordinates of point i in photograph 1. (x'_i, y'_i, c) denote photocoordinates of point i in photograph 2. $[R]$ the rotation matrix between both images. $K = 1$ and $(\mathrm{d}x, \mathrm{d}y, \mathrm{d}z)$ denote the CDP differential translations considered null.

Once the image to rotation matrix $[R]$ for image 1 has been determined, the object coordinates for laser pointer 2 applied to these rotations as if they really were in image 1, will be recalculated.

$$\begin{bmatrix} X_{\mathrm{PL}}^{(2)'} \\ Y_{\mathrm{PL}}^{(2)'} \\ Z_{\mathrm{PL}}^{(2)'} \end{bmatrix} = [R] \begin{bmatrix} X_{\mathrm{PL}}^{(2)} \\ Y_{\mathrm{PL}}^{(2)} \\ Z_{\mathrm{PL}}^{(2)} \end{bmatrix} = [R] \left(\begin{bmatrix} X_{\mathrm{L}} \\ Y_{\mathrm{L}} \\ Z_{\mathrm{L}} \end{bmatrix} + Dm_{\mathrm{L}}^{(2)} \begin{bmatrix} U_x \\ U_y \\ U_z \end{bmatrix} \right) \tag{5}$$

where $(X_{\mathrm{PL}}^{(2)}, Y_{\mathrm{PL}}^{(2)}, Z_{\mathrm{PL}}^{(2)})$ is the laser pointer object coordinates (shot 2) $(X_{\mathrm{PL}}^{(2)\prime}, Y_{\mathrm{PL}}^{(2)\prime}, Z_{\mathrm{PL}}^{(2)\prime})$ is the laser pointer 2 object coordinates turned to photograph 1 and $\mathrm{Dm}_{\mathrm{L}}^{(2)}$ is the distance measured by the laser in photograph 2.

Applying the same procedure to image 3 in relation to image 1, the rectified laser pointer 3 object coordinates $(X_{\mathrm{PL}}^{(3)\prime}, Y_{\mathrm{PL}}^{(3)\prime}, Z_{\mathrm{PL}}^{(3)\prime})$ are obtained.

The three repositioned laser pointers define the plane where the object to be measured is situated, and whose vertices, which are contained in the plane, must be validated with the expression

$$\begin{vmatrix} X_i - X_{\mathrm{PL}}^{(1)} & V_x & W_x \\ Y_i - Y_{\mathrm{PL}}^{(1)} & V_y & W_y \\ Z_i - Z_{\mathrm{PL}}^{(1)} & V_z & W_z \end{vmatrix} = 0 \tag{6}$$

where (V_x, V_y, V_z) is the vector formed by $(X^{(1)}_{\mathrm{PL}}, Y^{(1)}_{\mathrm{PL}}, Z^{(1)}_{\mathrm{PL}})$ and $(X^{(2)\prime}_{\mathrm{PL}}, Y^{(2)\prime}_{\mathrm{PL}}, Z^{(2)\prime}_{\mathrm{PL}})$ (W_x, W_y, W_z) is the vector formed by $(X^{(1)}_{\mathrm{PL}}, Y^{(1)}_{\mathrm{PL}}, Z^{(1)}_{\mathrm{PL}})$ and $(X^{(3)\prime}_{\mathrm{PL}}, Y^{(3)\prime}_{\mathrm{PL}}, Z^{(3)\prime}_{\mathrm{PL}})$ (X_i, Y_i, Z_i) are denoted the vertex coordinates in the object plane.

Applying the co-linearity conditions (1) and (2) to each vertex that determines the object in photograph 1 and forcing them to comply with the laser-defined plane (6), we obtain

$$\begin{vmatrix} Z_i \frac{x'_i}{-c} - X^{(1)}_{\mathrm{PL}} & V_x & W_x \\ Z_i \frac{y'_i}{-c} - Y^{(1)}_{\mathrm{PL}} & V_y & W_y \\ Z_i - Z^{(1)}_{\mathrm{PL}} & V_z & W_z \end{vmatrix} = 0 \tag{7}$$

where (x'_i, y'_i, c) are photocoordinates of the vertex i.

The expression from Z_i is obtained by determining (X_i, Y_i) through expressions (1) and (2). The same procedure is repeated for each vertex i of the object to be measured.

5. Results

To prove the suitability of the system, a series of tests were carried out using the following instruments:

1. Calibrated camera Canon EOS 10D:
   Focal distance: 20.2157 mm
   Format: (22.5203 × 15.0132) mm (3,072 × 2,048) pixels
   Principal point: (11.1601, 7.5245) mm
   Radial distortion parameters:
   Decentering distortion parameters:

$$P_1 = 4.034e - 5\ \mathrm{mm}^{-1} \pm 2.2e - 6$$
$$P_2 = -1.726e - 5\ \mathrm{mm}^{-1} \pm 2.9e - 6$$

2. Laser meter Zinder Leica Disto Plus:
   Precision: ±1.5 mm (between 0.2 and 200 m).

5.1. Calibration

The results obtained from the calibration are shown in Table 1. As can be observed, the precisions obtained are quite satisfactory for all the calibrated rotation positions, with typical deviations of less than 1 cm.

From the system calibration test performed, we can point to the mechanical and dimensional stability of the system. This proves that the variations in the results obtained in the repeatability studies conducted during several sessions and in the different positions are insignificant. The results support the initial hypothesis of using materials that are both heavy and robust, and they also confirm that the mechanisms used for setting the different rotation positions are reliable. We can also confirm that the mechanical adjustment solutions for the different elements are satisfactory. We reached this conclusion after having repeated the previous process and after having set up and dismantled the camera and the laser meter on repeated occasions. The solution adopted for the support means that there is no need for recalibrating the system and so an exact position is assured.

The results obtained using the measuring methodology have also revealed that the camera and laser meter readings are independent of each other. This is due to the support, which isolates both elements from relative movements when one of them varies.

5.2. Measurements

In order to determine the precision of the system in measuring plane elements, different tests, which measured calibrated panels in the laboratory, were performed. Panels with different dimensions and geometry were placed on walls and floors, and then photographed from different distances and with different viewpoints. Different windows were measured from different distances, from different angles (two shown in this paper as an example) and in different lighting and weather conditions, and the laser beam was shone on surfaces made of different materials. In this way we sought to take into account the different situations that the equipment's end users might encounter. More than 50 interior and exterior measurements were calculated.

The dimensions of the photographed objects are determined from the coordinates in the object space of the points that define the border, with the vertices marked manually on the image. This manual procedure allows us to select the points that define the shape of the object to be measured, even when the photographs are not very clear. This is not possible if automatic recognition algorithms are used. This manual measurement will depend on the skill of the person who marks the defining points, introducing errors of one pixel if carried out carefully.

Shadows also affect the manual procedure and limit precision. So it is advisable to try taking the photographic images with suitable lighting. However, for extremely shadowy situations, it is possible to use algorithms for calculating vertices using the edges of the window. It is also advisable to avoid taking exterior measurements when it is raining because raindrops on the lens will deform the photographic image.

Best results are obtained when the photographs are taken perpendicularly closer to the object, with small differences obtained in cases where the photographs are oblique and/or at a greater distance, due to the uncertainty in marking element vertices caused by the camera perspective and resolution. The relative error was less than 1.2% in 90% of the objects measured.

One of the factors that has the greatest bearing on the precision of the measurements is the area in the photo of the object to be measured in relation to the total area of the photograph. If this ratio is small, errors increase considerably (in quite a few cases, to a level that is unacceptable for the intended use).

Table 1
Calibration results for the camera-laser meter set

Value	Vertically downwards and parallel to the camera axis	Vertically upwards and parallel to the camera axis	Horizontally divergent	Horizontally parallel	Horizontally convergent
B_X	−0.21408 ± 0.00249	−0.20602 ± 0.00506	−0.16407 ± 0.00413	−0.21109 ± 0.00004	−0.23517 ± 0.00016
B_Y	+0.02201 ± 0.00031	−0.02299 ± 0.00613	+0.00030 ± 0.00032	−0.00009 ± 0.00010	−0.00119 ± 0.00008
B_Z	+0.13451 ± 0.00015	+0.14512 ± 0.00217	+0.17334 ± 0.01305	+0.11690 ± 0.00012	+0.14738 ± 0.00095
U_x	−0.02077 ± 0.00154	−0.04169 ± 0.00211	−0.39213 ± 0.00010	−0.03356 ± 0.00009	+0.36110 ± 0.00004
U_y	−0.40843 ± 0.000387	+0.39180 ± 0.00098	+0.01089 ± 0.00001	+0.01925 ± 0.00006	+0.00229 ± 0.00003

Units are in meters.

Table 2
Window measuring results in meters at mean distances of less than 10 m

Real	Obs	Diff	Real	Obs	Diff	Real	Obs	Diff	Real	Obs	Diff
Distances between 1 and 5 m (window dimensions of 1.270 × 0.663 m^2)											
1.270	1.267	0.003	0.663	0.657	0.006	1.270	1.265	0.005	0.663	0.659	0.004
1.270	1.267	0.003	0.663	0.662	0.001	1.270	1.263	0.007	0.663	0.657	0.006
1.270	1.265	0.005	0.663	0.662	0.001	1.270	1.268	0.002	0.663	0.658	0.005
1.270	1.267	0.003	0.663	0.658	0.005	1.270	1.265	0.005	0.663	0.659	0.004
1.270	1.267	0.003	0.663	0.659	0.004	1.270	1.264	0.006	0.663	0.658	0.005
Distances between 5 and 0 m (window dimensions of 1.407 × 0.798 m^2)											
1.407	1.399	0.008	0.798	0.791	0.007	1.407	1.399	0.008	0.798	0.793	0.005
1.407	1.402	0.005	0.798	0.792	0.006	1.407	1.399	0.008	0.798	0.790	0.008
1.407	1.398	0.009	0.798	0.789	0.009	1.407	1.400	0.007	0.798	0.794	0.004
1.407	1.402	0.005	0.798	0.790	0.008	1.407	1.402	0.005	0.798	0.789	0.009
1.407	1.401	0.006	0.798	0.791	0.007	1.407	1.401	0.006	0.798	0.792	0.006

Differences obtained compared to the conventional method.

Table 2 shows the dimensions of two different windows, obtained from different distances using the proposed method, and also measured with a tape. The differences were less than 0.9 mm on distances of less than 10 m. To measure each of them, different combinations of laser-calibrated positions forming the object plane were used, verifying that precision increases minimally according to the spatial distribution of the points.

6. Conclusions

This research describes a simple close-range photogrammetry system to measure flat objects, designed for measuring holes in building facades (although other applications are also possible). It is an inexpensive and easy system to use and does not require ground control points as used in topographic methods.

The system and the measuring method described in this article proved to be useful and easy to apply, mathematically, in the data-gathering process in the field, and in coordinate measurements made in the laboratory. Using this method, measurements can be made at any distance from the plane of the facade provided the laser has a sufficient measuring range, and independent of whether or not the target points are visible in the photographic image (due to the fact that the calculation is based on vectors which will have been previously calibrated).

The method shown here allows object space determination to be achieved through iterative procedures, correcting all identifiable points in the three photographs, and/or taking additional photographs. The precision in determining the object plane will be improved in line with better image point distribution quality.

With this method it is possible to simultaneously measure different objects, whatever their geometry, as long as they are within the defined or even parallel planes and visible in the image.

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