

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/224603807>

# Calibration of Line-Scan Cameras

Article in IEEE Transactions on Instrumentation and Measurement · September 2010

DOI: 10.1109/TIM.2009.2031344 · Source: IEEE Xplore

CITATIONS

69

READS

4,500

4 authors, including:



**C. A. Luna Vazquez**

University of Alcalá

30 PUBLICATIONS 299 CITATIONS

[SEE PROFILE](#)



**Manuel Mazo**

University of Alcalá

222 PUBLICATIONS 3,768 CITATIONS

[SEE PROFILE](#)



**José Luis Lázaro**

University of Alcalá

156 PUBLICATIONS 1,833 CITATIONS

[SEE PROFILE](#)

# Calibration of Line-Scan Cameras

Carlos A. Luna, Manuel Mazo, *Member, IEEE*, José Luis Lázaro, *Member, IEEE*, and Juan F. Vázquez

**Abstract**—This paper presents a novel method for calibrating line-scan cameras using a calibration pattern comprising two parallel planes with lines that can be described using known equations. Using pattern geometry and a line that is captured by a line-scan camera, we calculate the 3-D coordinates of the points corresponding to the straight lines of a pattern that is captured by the line-scan camera. These coordinates are used to obtain the intrinsic and extrinsic parameters of the line scan using a standard calibration procedure that is based on a recursive least squares method. In this paper, the procedure of calibration and the results obtained for a specific line scan will be shown; specifically, the obtained median residual error is 0.28 pixel. Also, the repetitiveness of the calibration process was verified for a sequence of 500 times.

**Index Terms**—Intrinsic and extrinsic camera parameters, line-scan calibration, optical distortion, perspective projection, pine-hole camera model.

## I. INTRODUCTION

THE USE of line-scan cameras for measurement in areas such as the automotive industry, construction and restoration of buildings, and bioengineering, and in systems of monitoring and railroad detection is increasing [1]–[4]. In many applications, line scans are replacing 2-D (matrix) cameras because they increase the efficiency and the accuracy of the measure. The 1-D data that line scans provide are easier and faster to process than 2-D images, and the size of the line-scan cameras (may reach 12 kpixels) takes advantage of the matrix cameras.

However, it seems that only scant information appears to be available on the subject of line-scan camera calibration. In [5], a multiline calibration method has been proposed to calculate the extrinsic parameters and the coordinates of the intersection point of the optical axis with the line image (the center point). The calibration pattern consists of four coplanar straight lines. The first three are mutually parallel, and the fourth makes an angle with the direction of these three. The equations of these lines are known in the global coordinate frame. By using this method, the authors have determined that eight parameters of calibration exist, which represent the geometric position of the line-scan camera with respect to the pattern and from which the rotation-translation matrix can be obtained. In this proposal, it

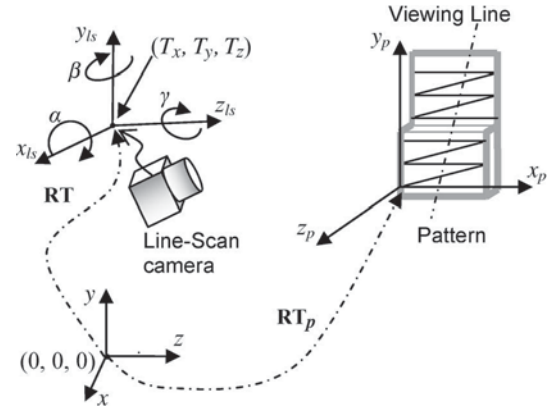


Fig. 1. Reference coordinates and the rotation-translation matrix that are used in our calibration method.

is necessary to move the calibration pattern in the  $Y$  and/or  $Z$  directions with known increments. This means that the results of the calibration depend on the precision of the displacements. In this paper, we propose a calibration method in which it is not necessary to change the position of the calibration pattern.

The rest of this paper has been organized as follows: Section II presents the proposed method. Section III describes the simulation results for an ideal line-scan camera using the proposed method of calibration. Section IV details the obtained results for a line-scan camera of 2048 pixels. Finally, in Section V, conclusions and recommendations of this paper are exposed.

## II. PROPOSED CALIBRATION METHOD

In the calibration process of the matrix cameras, an important problem is to determine the coordinates of the projection in the image plane for the significant points of the pattern. These significant points are usually the center of circles or the intersections between lines [6]–[8]. In the case of line-scan cameras, it is very hard to match the viewing line with the specific points of the pattern. In this paper, we propose a calibrating pattern and a method to obtain these points from the pattern geometry and the captured line.

The reference coordinates and the rotation-translation matrix used in our method are shown in Fig. 1, where  $(T_x, T_y, T_z)$  and  $(\alpha, \beta, \gamma)$  are the components of the translation vector and rotation angles between the calibration reference and the camera system.

The pattern that is used in our method is formed by two parallel planes ( $\Pi_{\text{sup}}$  and  $\Pi_{\text{inf}}$ ), where each one of the seven straight lines has been drawn (Fig. 2). The equations of these lines ( $L_i$ , where  $i = 1, 2, \dots, 14$ ) are known in the calibration coordinate frame ( $RT_p$  is known). Lines  $L_1, L_3, L_5, L_7, L_8$ ,

Manuscript received February 26, 2008; revised June 15, 2009; accepted June 16, 2009. Date of publication October 13, 2009; date of current version July 14, 2010. This work was supported by the Ministry of Public Works of Spain under Project T5/2006.

C. A. Luna, M. Mazo, and J. L. Lázaro are with the Department of Electronics, University of Alcalá, 28871 Alcalá de Henares, Spain (e-mail: caluna@depeca.uah.es; carl\_luna@yahoo.es).

J. F. Vázquez is with the Research and Development Department, LogyTel SL, 28805 Alcalá de Henares, Spain (e-mail: jfvglez@yahoo.es).

Color versions of one or more of the figures in this paper are available online at <http://ieeexplore.ieee.org>.

Digital Object Identifier 10.1109/TIM.2009.2031344

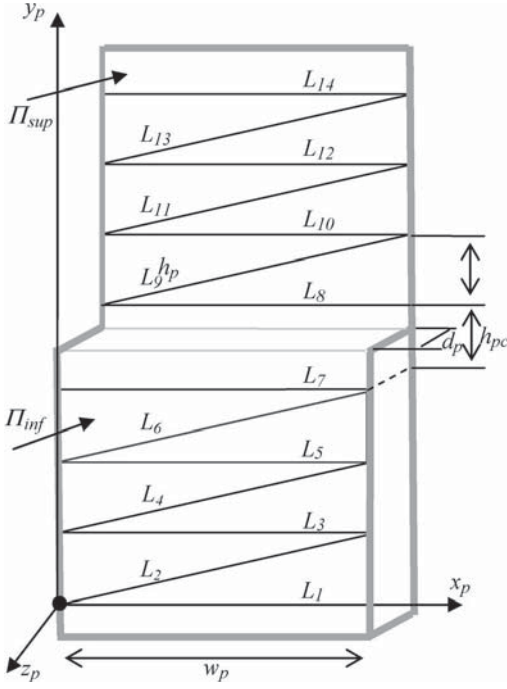


Fig. 2. Pattern that is used in our method for the calibration of line scan.

$L_{10}$ ,  $L_{12}$ , and  $L_{14}$  and the  $x_p$  axis are mutually parallel, and lines  $L_2$ ,  $L_4$ ,  $L_6$ ,  $L_9$ ,  $L_{11}$ , and  $L_{13}$  make an angle with the direction of the  $x_p$  axis. The  $z_p$  axis is perpendicular to the  $x_p$ - $y_p$  plane.

The proposed calibration method consists of two steps.

- 1) From the line captured by a line scan and the geometry of the pattern, one can obtain the coordinates  $(X_i, Y_i, Z_i)$  of the points  $(\mathbf{P}_i)$  corresponding to the straight lines of the pattern.
- 2) With the  $\mathbf{P}_i$  points and their corresponding values in the captured line, by means of a traditional method of calibration, the intrinsic (the focal length  $f$  and the main point  $v_0$ ) and extrinsic line-scan parameters are obtained.

#### A. Obtaining the 3-D Coordinates of the $\mathbf{P}_i$ Points of the Pattern

The frontal side of the used pattern and the line that is captured (line image) by line scan are represented in Fig. 3. Fourteen points  $\mathbf{V}_i$  are captured on the line image, which represent the projections of  $\mathbf{P}_i$  intersection points of the viewing plane with  $L_i$  straight lines of the pattern.

The pattern dimensions ( $w_p$ ,  $h_p$ ,  $h_{pc}$ , and  $d_p$ ) are known, and, therefore, the equations of the  $L_i$  straight lines are also known (Figs. 2 and 3). The  $Y$  and  $Z$  coordinates of  $\mathbf{P}_1$ ,  $\mathbf{P}_3$ ,  $\mathbf{P}_5$ ,  $\mathbf{P}_7$ ,  $\mathbf{P}_8$ ,  $\mathbf{P}_{10}$ ,  $\mathbf{P}_{12}$ , and  $\mathbf{P}_{14}$  are known with respect to the pattern reference, independent of the position and the orientation of the line scan. The  $X$  and  $Y$  coordinates  $\mathbf{P}_2$ ,  $\mathbf{P}_4$ ,  $\mathbf{P}_6$ ,  $\mathbf{P}_9$ ,  $\mathbf{P}_{11}$ , and  $\mathbf{P}_{13}$  are unknown.

To find all  $\mathbf{P}_i$  coordinates, we consider that the ratio between the segments  $\Delta L_{bj}$  and  $\Delta L_{aj}$ ,  $j = \{1, 2, \dots, 6\}$ , on the pattern is equal to the ratio of its projections in the captured line, i.e.,

$$\Delta L_{bj} \sim \Delta v_{bj} \quad (1)$$

This relation is fulfilled when the pattern planes and the line image of the camera are parallel.

In Section III, we demonstrate that, although (1) is not fulfilled accurately, the error in obtaining calibration parameters is insignificant.

The equations that are used to calculate  $\mathbf{P}_i$  coordinates are shown in Table I.

Once the  $\mathbf{P}_i$  coordinates are obtained, the following step is made to obtain the parameters for the calibration of the line-scan camera.

#### B. Obtaining the Calibration Parameters

The calibration parameters can be obtained by classic methods that are based on the pinhole camera model [6]–[9]. For the case of the matrix cameras, this model may be represented by

$$\begin{cases} u + e_u = u_0 + \frac{do_x}{du} + f_x \frac{r_{11}X + r_{12}Y + r_{13}Z + T_x}{r_{31}X + r_{32}Y + r_{33}Z + T_z} \\ v + e_v = v_0 + \frac{do_y}{dv} + f_y \frac{r_{21}X + r_{22}Y + r_{23}Z + T_y}{r_{31}X + r_{32}Y + r_{33}Z + T_z} \end{cases} \quad (2)$$

$f_x$	$= f/du$ ;
$f_y$	$= f/dv$ ;
$f$	camera focal distance;
$(u_0, v_0)$	main point that represents the coordinates (in pixels) of the intersection point of the optical axis of the camera with the image plane;
$(u, v)$	coordinates onto the image plane of the projection of a 3-D point $(X, Y, Z)$ ;
$d_u$ and $d_v$	pixel dimensions in $u$ and $v$ axes, respectively;
$e_u$ and $e_v$	errors detected in $u$ and $v$ , respectively;
$r_{xx}$	parameters of the rotation matrix;
$do_x$ and $do_y$	components of optical distortion for the lens, which can be divided into two parts—radial and tangential distortion [7], [9], [10].

If the line scan is considered as the central line ( $u = 0$ ) of a matrix camera with a long focal length (we use  $f$  at approximately 100 mm), it is possible to assume that the optical distortion is small and negligible. Then, rewriting (2), we have

$$v + e_v = v_0 + f_y \frac{r_{21}X + r_{22}Y + r_{23}Z + T_y}{r_{31}X + r_{32}Y + r_{33}Z + T_z} = Q(\Phi) \quad (3)$$

where  $\Phi = [v_0, f_y, T_x, T_y, T_z, \alpha, \beta, \gamma]^T$  is a vector that contains two intrinsic parameters ( $v_0$  and  $f$ ) and six extrinsic parameters ( $T_x, T_y, T_z, \alpha, \beta$ , and  $\gamma$ ).

For each  $\mathbf{P}_i$  point corresponding to the straight lines of the pattern, we have an equation. This set forms an overconstrained system of 14 nonlinear equations and 8 unknowns.

Since  $Q(\Phi)$  are nonlinear functions of  $\Phi$ , it is necessary to use nonlinear methods of optimization [6], [9] to compute a solution. The approximation least squares method of solution allows the determination of  $\Phi$ , diminishing the error in the measurement of the coordinates  $v_i$  in the captured line.

Rewriting (3) in a matrix form, we obtain

$$e_v = Q(\Phi) - v_i = \mathbf{V}(\Phi). \quad (4)$$

The remaining error vector  $\mathbf{V}(\Phi)$  has coordinates in pixels,

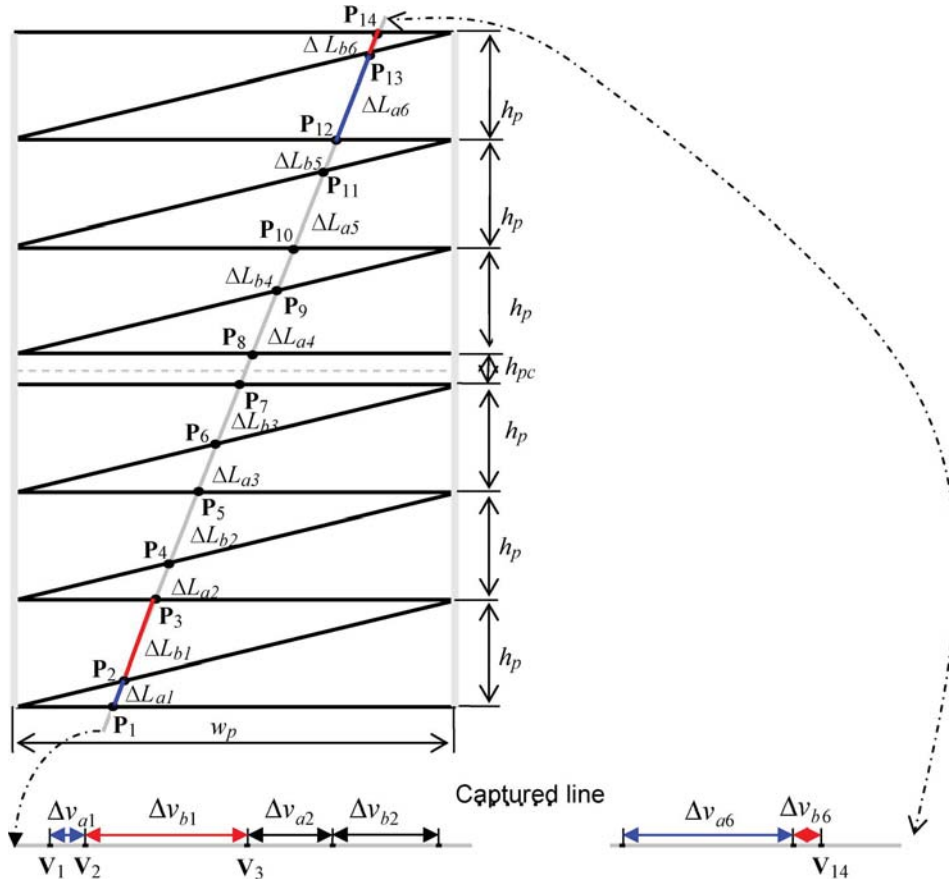


Fig. 3. Frontal side of the pattern and the captured line.

TABLE I  
EQUATIONS THAT ARE USED TO CALCULATE  $\mathbf{P}_i$  COORDINATES

$i$	$j$	$\mathbf{P}_i$		
		$X_i$	$Y_i$	$Z_i$
2, 4, 6	$\frac{i}{2}$	$\frac{w_p}{\frac{L_{bj}}{L_{aj}} + 1}$	$h_p \cdot (j-1) + \frac{h_p}{\frac{L_{bj}}{L_{aj}} + 1}$	0
1, 3, 5, 7	$\frac{i}{2}$	$x_2 + \frac{x_4 - x_2}{y_4 - y_2} (y_i - y_2)$	$h_p \cdot \frac{(i-1)}{2}$	0
9, 11, 13	$\frac{i-1}{2}$	$\frac{w_p}{\frac{L_{bj}}{L_{aj}} + 1}$	$h_{pc} + h_p \cdot (\frac{i-3}{2}) + \frac{h_p}{\frac{L_{bj}}{L_{aj}} + 1}$	$d_p$
8, 10, 12 14	$\frac{i-1}{2}$	$x_7 + \frac{x_9 - x_7}{y_9 - y_7} (y_i - y_7)$	$h_{pc} + h_p \cdot (\frac{i}{2} - 1)$	$d_p$

pixel detected and the reprojection of the 3-D point of the reconstructed pattern for each line.

Linearizing (4) by the Newton–Raphson method, the following is obtained:

$$\mathbf{V}(\Phi) = \mathbf{V}(\Phi_0) - \frac{\partial \mathbf{V}(\Phi)}{\partial \Phi} \cdot \Delta \Phi. \quad (5)$$

Furthermore, the final solution is

Making  $\mathbf{V}_0 = \mathbf{V}(\Phi_0)$  and  $\mathbf{J} = \partial \mathbf{V}(\Phi) / \partial \Phi$ , then

$$\Delta \Phi = (\mathbf{J}^T \cdot \mathbf{J})^{-1} (\mathbf{J}^T \cdot \mathbf{V}_0). \quad (7)$$

For the calculation of the initial values of  $\Phi_0$ , we use the parameters of the manufacturer ( $\mathbf{f}$ ,  $d\mathbf{v}$ ) and the approximate values of geometric parameters ( $T_x, T_y, T_z, \alpha, \beta, \gamma$ ) that were measured manually.

We have implemented an algorithm to determine the  $v_i$  coor-

with subpixel accuracy. This algorithm reduces the effects of the illumination changes. Whenever an abrupt negative change of intensity is detected in the line image, the pixel with smaller intensity  $v_{i,\min}$  is selected, and an increase that depends on the intensity of adjacent pixels ( $I(v_{i,\min-1}), I(v_{i,\min+1})$ ) is added to  $v_{i,\min}$ . This increase is calculated using the following criteria:

- If

$$I(v_{i,\min-1}) = I(v_{i,\min+1}) \rightarrow v_i = v_{i,\min}. \quad (8)$$

- If

$$I(v_{i,\min-1}) < I(v_{i,\min+1}) \rightarrow v_i = v_{i,\min} + \frac{I(v_{i,\min-1}) - I(v_{i,\min+1})}{2 \cdot [I(v_{i,\min+1}) - I(v_{i,\min})]}. \quad (9)$$

- If

$$I(v_{i,\min-1}) > I(v_{i,\min+1}) \rightarrow v_i = v_{i,\min} + \frac{I(v_{i,\min-1}) - I(v_{i,\min+1})}{2 \cdot [I(v_{i,\min-1}) - I(v_{i,\min})]}. \quad (10)$$

We have considered that a pixel belongs to a negative change of intensity whenever the following expression is fulfilled:

$$I(v_i) \leq \frac{I(v_{i-w-1}) + I(v_{i+w+1})}{2} \cdot H \quad (11)$$

such that the expression  $2w + 1$  represents a maximum number of pixels that correspond to pattern lines, and  $H$  is a constant that is obtained in an empirical form. The  $H$  value is determined by the difference between the intensity of pixels that belong to the straight lines and pixels that correspond to the pattern background. In this paper, we selected  $H = 0.8$ , which assumes that pixels along a straight line have a 20% less intensity than the background pixels. With this empirical value of  $H$ , we were able to obtain the best results.

### III. EFFECTS OF NONPARALLELISM BETWEEN THE LINE IMAGE AND THE PATTERNS PLANE

The error produced due to nonparallelism between the pattern planes and the line image was determined by means of simulations. The simulations involve the following steps.

- 1) The calibration parameters ( $v_0, f_y, T_x, T_y, T_z, \alpha, \beta, \gamma$ ) are assumed to be well known, and the intersection points ( $\mathbf{P}_i$ ) of the viewing plane of the line scan with the straight lines of the pattern are calculated.
- 2) The  $v_i$  values are calculated by means of perspective transformation of  $\mathbf{P}_i$  points in the line image.
- 3) Using (1), calculate the points ( $\hat{\mathbf{P}}_i$ ) in the space.
- 4) With the values obtained in step 3, calibration parameters  $\hat{v}_0, \hat{f}_y, \hat{T}_x, \hat{T}_y, \hat{T}_z, \hat{\alpha}, \hat{\beta},$  and  $\hat{\gamma}$  are estimated.
- 5) The error  $\varepsilon_{\text{par}}$  between the original and estimated parameters is calculated.

The simulation has been implemented in LabWindows CVI

TABLE II  
CALIBRATION ERRORS CAUSED BY THE ASSUMPTION THAT THE PATTERN AND THE IMAGE LINE ARE PARALLEL (FOR THREE DIFFERENT POSITIONS)

Parameter error	Position 1	Position 2	Position 3
	$\alpha = 0$	$\alpha = 1.9 \text{ deg.}$	$\alpha = 9.9 \text{ deg.}$
	$\beta = 0$	$\beta = 2.0 \text{ deg.}$	$\beta = 0$
	$T_x = 10 \text{ cm}$ $T_y = 6 \text{ cm}$	$T_x = 20 \text{ cm}$ $T_y = 16 \text{ cm}$	$T_x = 10 \text{ cm}$ $T_y = 56 \text{ cm}$
$\varepsilon_{\alpha}, \text{deg}$	$3.2 \cdot 10^{-18}$	$1.65 \cdot 10^{-5}$	$8.63 \cdot 10^{-5}$
$\varepsilon_{\beta}, \text{deg}$	$2.1 \cdot 10^{-16}$	$5.41 \cdot 10^{-5}$	$2.37 \cdot 10^{-4}$
$\varepsilon_{\gamma}, \text{deg}$	$6.0 \cdot 10^{-15}$	$9.77 \cdot 10^{-3}$	$3.41 \cdot 10^{-2}$
$\varepsilon_{T_x}, \text{m}$	$2.1 \cdot 10^{-16}$	$1.210^{-5}$	$8.49 \cdot 10^{-5}$
$\varepsilon_{T_y}, \text{m}$	$1.1 \cdot 10^{-16}$	$3.32 \cdot 10^{-5}$	$7.75 \cdot 10^{-5}$
$\varepsilon_{T_z}, \text{m}$	$9.1 \cdot 10^{-17}$	$4.45 \cdot 10^{-5}$	$9.18 \cdot 10^{-5}$
$\varepsilon_{f_y}$	$3.4 \cdot 10^{-14}$	$1.95 \cdot 10^{-3}$	$4.12 \cdot 10^{-2}$
$\varepsilon_{v_0}, \text{pixel}$	$5.3 \cdot 10^{-17}$	$2.45 \cdot 10^{-7}$	$7.48 \cdot 10^{-7}$

Table II shows the results of the simulation for three different positions of the line scan. In all cases,  $v_0 = 1024$  pixels,  $f_y = 10^4$ ,  $T_z = 3 \text{ m}$ ,  $\gamma = 0$ ,  $w_p = 20 \text{ cm}$ ,  $h_p = 4 \text{ cm}$ ,  $h_{pc} = 1 \text{ cm}$ , and  $d_p = 10 \text{ cm}$ . In position 1, the pattern planes and the line image of the camera are parallel, and the error  $\varepsilon_{\text{par}}$  in parameter-obtaining is negligible. In positions 2 and 3, the planes and the line are not parallel, and, nevertheless, the errors are insignificant as well.

### IV. PRACTICAL RESULTS

With the objective of diminishing quantization errors in the selection of the  $v_i$  points corresponding to the straight lines of the pattern, the average values for a sequence of 500 lines were chosen. In Fig. 4, a real sequence of lines in an image form is shown. The used line-scan camera is an AVIIVA SM2 of 2048 pixels, with a pixel size of  $10 \mu\text{m}$  and a focal length of  $100 \text{ mm}$ . The used frame grabber is a CL C64× Camera link. In the calibration of this line scan, a pattern has been used, whose dimensions are  $w_p = 20 \text{ cm}$ ,  $h_p = 4 \text{ cm}$ ,  $h_{pc} = 1 \text{ cm}$ , and  $d_p = 10.8 \text{ cm}$ .

In our application, the calibrated line scan is used to measure the vibratory movement of a matrix camera and reduce the effect of this movement in the captured images.

In Table III, the average values and the standard deviation obtained for each parameter are shown. The maximum value of the remaining error was 0.71 pixel, and the median value obtained was 0.28 pixel.

### V. CONCLUSION

Within the broad scope of line-scan camera technology, currently, very few applications are using calibrated line scan. Although patents in this area exist, few scientists are making available aspects relating to the calibration of line scan. How-



Fig. 4. Image of 500 lines used in the calibration process.

TABLE III  
AVERAGE AND STANDARD DEVIATION OBTAINED IN THE ESTIMATION OF  
THE CALIBRATION PARAMETERS FOR A SEQUENCE OF 500 LINES

Parameter	Average Value	Standard deviation
$\alpha_s$ (grad.)	-4.76012	$2.21 \times 10^{-3}$
$\beta_s$ (grad.)	-1.54934	$2.84 \times 10^{-2}$
$\gamma_s$ (grad.)	37.80779	$1.59 \times 10^{-1}$
$T_x$ (m)	0.02913	$1.24 \times 10^{-3}$
$T_y$ (m)	0.49167	$1.32 \times 10^{-4}$
$T_z$ (m)	0.06167	$6.54 \times 10^{-4}$
$f_y$	1003.8	$6.27 \times 10^{-2}$
$v_o$ (pixels)	1031.12	0.23

require high-precision calibrated line scan. Examples include systems that measure 3-D position, vibration measurement, inspection, and quality control.

The use of an easily reproducible calibration pattern, which does not require submillimetric precision in its construction, simplifies the method of calibration of this type of cameras, as has been demonstrated. The design of the pattern with sloping lines removes the importance of the relative positioning between the pattern and the line scan, so that the calibration parameters can be estimated from any position between these, as long as the quasi-coplanarity between the sensor and the pattern exists. The fact that the pattern has two planes at different depths allows the system of equations to have a mathematical solution. Furthermore, a single catch calibration can be performed with good accuracy. One of the conclusions that should be mentioned is that, with the existing calibration methods, they do not obtain the rotation matrix translation of the relative position between the camera and the calibration pattern, which gives an added value to this method.

In Section III, the effects of noncoplanarity between the pattern and a camera have been noted and discussed. It has been shown that this coplanarity is not necessary, having conducted

portant because it allows relative positioning of the two components of the system, which does not require great precision; furthermore, bearing in mind that this is a calibration with a single image makes this method very attractive for use.

When determining the position of the captured points of the pattern lines, the solution that has been proposed in this paper gives a subpixel approximation of the centroid of these lines. The proposed algorithm for detecting the centroid of the pattern lines shows that once the less-intensity pixel is located, analyzing the intensity of the neighboring pixels allows us to determine, with subpixel accuracy, the centroid. This allows us to obtain a more accurate calibration of parameters without being able to bring the issue of light adjustment (by working with the centroids).

The obtained practical results demonstrate that the same one is valid for the used optics (100 mm); the maximum value of the remaining error was 0.71 pixels, and the median value was 0.28. The repetitiveness of the calibration process was checked for a sequence of 500 times. Also, to improve the results, it is recommended to make a calibration using a greater number of straight lines in the pattern. However, it is necessary to conduct experiments with a great angle of aperture for the optical components (i.e., of the type fisheye).

#### ACKNOWLEDGMENT

This paper has been carried out thanks to the Logistic and Telecommunications Company (LogyTel S.L.).

#### REFERENCES

- [1] K. Hirahara and K. Ikeuchi, "Detection of street-parking vehicles using line scan camera and scanning laser range sensor," in *Proc. IEEE Intell. Veh. Symp.*, Jun. 2003, pp. 656–661.
- [2] K. Kataoka, T. Osawa, S. Ozawa, K. Wakabayashi, and K. Arakawa, "3D building façade model reconstruction using parallel images acquired by line scan cameras," in *Proc. IEEE ICIP*, Sep. 2005, vol. 1, pp. 1009–1012.
- [3] K. Hirahara and K. Ikeuchi, "Extraction of vehicle image from panoramic street-image," in *Proc. IEEE Intell. Veh. Symp.*, Jun. 2004, pp. 656–661.
- [4] C. A. Luna, M. Mazo, J. L. Lázaro, J. F. Vázquez, J. Ureña, S. E. Palazuelos, J. J. García, F. Espinosa, and E. Santiso, "Method to measure the rotation angles in vibrating systems," *IEEE Trans. Instrum. Meas.*, vol. 55, no. 2, pp. 232–239, Feb. 2006.
- [5] B. Horvath, B. Mohr, and B. L. J. J. "On single scanning camera calibra-



- [6] J. M. Lavest, G. Rives, and J. T. Rousseau, "Do we really need an accurate calibration pattern to achieve a reliable camera calibration?" in *Proc. ECCV*, Freiburg, Germany, vol. 1, pp. 158–174.
- [7] J. Heikkilä, "Geometric camera calibration using circular control points," *IEEE Trans. Pattern Anal. Mach. Intell.*, vol. 22, no. 10, pp. 1066–1077, Oct. 2000.
- [8] A. Gardel, J. L. Lázaro, and J. M. Lavest, "Camera auto-calibration with virtual patterns," in *Proc. ETFA*, Lisbon, Portugal, Sep. 2003, pp. 566–572.
- [9] J. Heikkilä and O. Silvén, "A four-step camera calibration procedure with implicit image correction," in *Proc. IEEE Comput. Soc. Conf. Comput. Vis. Pattern Recog.*, 1997, pp. 1106–1112.
- [10] Z. Zhang, *Flexible Camera Calibration by Viewing a Plane From Unknown Orientations*. Redmond, WA: Microsoft Res., One Microsoft Way, 1999.



**Carlos A. Luna** received the B.S. degree in electronics engineering and the M.Sc. degree in telecommunication systems engineering from the University of Oriente, Santiago de Cuba, Cuba, in 1994 and 1999, respectively, and the Ph.D. degree in electronics from the University of Alcalá, Alcalá de Henares, Spain, in 2006.

From 1994 to 2004, he was a Professor with the Department of Electronics, University of Oriente. He is currently a Professor with the Department of Electronics, University of Alcalá. His current research

areas include computer vision and instrumentation systems.



**Manuel Mazo** (M'91) received the M.Sc. degree in telecommunications engineering and the Ph.D. degree in telecommunications from the Polytechnic University of Madrid, Madrid, Spain, in 1982 and 1988, respectively.

He is currently a Professor with the Department of Electronics, University of Alcalá, Alcalá de Henares, Spain. During his career, he has collaborated in several research projects and has published more than 100 technical papers. His research interests include electronics control, intelligent sensors (ultrasonic,

infrared, and artificial vision), robot sensing and perception, intelligent spaces, electronics systems for railway safety, and wheelchairs for physically disabled people.



**José Luis Lázaro** (M'95) received the B.S. degree in electronic engineering and the M.Sc. degree in telecommunication engineering from the Polytechnic University of Madrid, Madrid, Spain, in 1985 and 1992, respectively, and the Ph.D. degree in telecommunication from the University of Alcalá, Alcalá de Henares, Spain, in 1998.

Since 1986, he has been a lecturer with the Department of Electronics, University of Alcalá, where he is currently a Professor. His areas of research include robotics sensorial systems by laser, optical

fibers, infrared and artificial vision, motion planning, monocular metrology, and electronics systems with advanced microprocessors.



**Juan F. Vázquez** received the B.S. degree in telecommunications engineering and the M.Sc. degree from the University of Oriente, Santiago de Cuba, Cuba, in 1983 and 1998, respectively, and the Ph.D. degree in electronics from the University of Alcalá, Alcalá de Henares, Spain, in 2005.

From 1984 to 2004, he was a Professor with the Department of Telecommunications, University of Oriente. He has worked in the fields of images processing and computer vision. He is currently with the Research and Development Department, LogyTel

SL, Alcalá de Henares.