

## ORIENTATION AND RECONSTRUCTION OF CLOSE-RANGE IMAGES USING LINES

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### ABSTRACT

The aim of this paper is to present two problems where straight lines were used as the primary source of control.

The first problem is the orientation of images using vertical and horizontal lines for flat surface monoplottting. A mathematical model has been adapted to generate linear equations both for vertical and horizontal lines in the object space. These lines are identified and measured in the image and the rotation matrix is computed. In order to compute image scale and coordinates over the flat surface, a distance between the camera and the surface is measured using a laser device. Using these elements, the geometric elements of the flat surface, mainly areas and lengths can be accurately computed. Some experiments with real data have been performed and the results were obtained with errors within 3%.

The second problem is the camera calibration both of the interior and exterior orientation parameters using straight lines. A mathematical model using straight lines that consider both interior and exterior orientation parameters as unknowns has been derived. This model is being designed to enable camera self calibration on the fly, with no control points. Straight lines that are already in the environment are to be used as control. The inner parameters being considered are the camera focal length, the coordinates of the principal point and the x-scale factor. The radial lens distortion parameters are supposed to be previously known, because they are stable and well determined with batch calibration..

### 1 INTRODUCTION

Image orientation has been a topic of interest both for Photogrammetrists and for Machine Vision Scientists. Interior (or intrinsic) and exterior (or extrinsic) parameters modelling both the camera geometry and the relationship between camera and object reference systems must be accurately computed using features previously matched in both spaces. Conventional photogrammetric approaches rely on control points, using collinearity equations as the mathematical model. Control points, however, do not exist in real environments and they must be signalled, normally with retro reflective targets and measured with field surveying techniques.

Line based orientation of digital images has gained interest, basically due to the potential of automation and the robustness of some methods of line detection which are superior to isolated point detection. Recent and important developments using straight lines have brought these alternative to a status of a practical approach with applications in aerial triangulation and matching (Habib, 1999). Also new problems, such as generation of textures and reconstruction of close-range environments for Virtual Reality, measurement of plane surfaces with integration of sensors, can be benefited by using these methods of image orientation.

The classical calibration or space resection methods solve the problem using control points, which coordinates are known both in image and in object reference systems. The non-linearity of the model and problems in point location in digital images are the main drawbacks of the classical approaches. The proposed solutions to overcome these problems include either the use of linear models (Lenz and Tsai, 1988) or the use of linear features: Tommaselli and Lugnani (1988), Mulawa and Mikhail (1988), Liu et al (1990), Wang and Tsai (1990), Lee et al (1990), Tommaselli and Tozzi (1996), Quan and Kanade (1997). Prescott and McLean (1997) presented some experiments using real data comparing their line based method for calibration of radial lens distortion with the point based linear method of Tsai (Lenz and Tsai, 1988) and reported similar results showing the accuracy potential of line based approaches.

Linear features are easier to locate than points and can be determined with subpixel precision, but the automatic feature extraction and automatic correspondence remain a drawback. One approach to solve the correspondence problem of sets of straight lines has been proposed by Tommaselli and Dal Poz (1999), but the search for matches can still be time consuming.

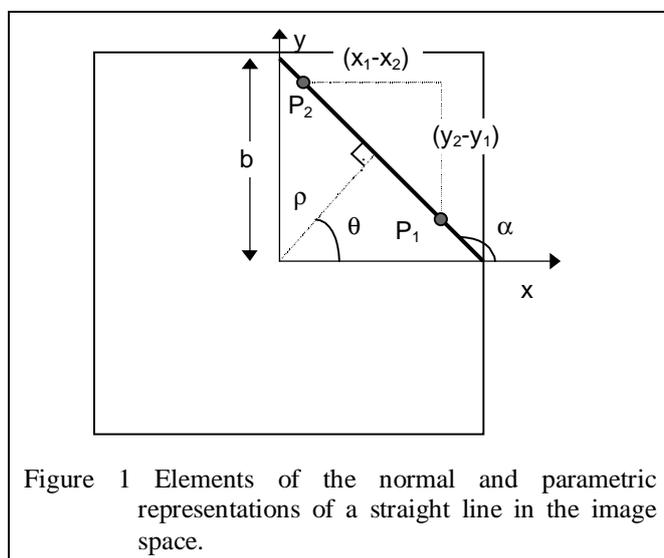
In this paper two problems are being approached using straight lines as the primary source of control. The first problem is the orientation of images from vertical and horizontal lines for flat surface monoplotting. The idea is to avoid any contact with the surface by considering both the vertical and horizontal edges as a source of control. This monoplotting approach is useful for measurement of outdoors advertisement areas and for the rectification of flat surfaces that are to be used as textures in Virtual Reality.

In the second problem to be presented a mathematical model using straight lines is expanded to consider both interior and exterior orientation parameters as unknowns. This model is being designed to enable camera self calibration on the fly, with no control points. Instead of, straight lines that are already in the environment are to be used as control. The inner parameters being considered are the camera focal length, the coordinates of the principal point and the x-scale factor. The radial lens distortion parameters are supposed to be previously known, because they are stable and well determined with batch calibration or even using lines, as proposed by Prescott and McLean (1997).

## 2 MEASUREMENT OF STRAIGHT LINES IN THE IMAGE SPACE

### 2.1 Straight line geometry in the image space

Straight line equation in the image space is given by eq. (1). The parametric representation is given by (2).



$$\cos \theta .x + \sin \theta .y - \rho = 0 \quad (1)$$

$$y = a .x + b \quad (2)$$

with:  $a = \tan \alpha$

The following relations between the elements are also well known.

$$\tan \theta = -\cotan \alpha \quad e \quad \tan \alpha = -\cotan \theta \quad (3)$$

and

$$a = -\cotan \theta = \tan \alpha \quad e \quad b = \rho / \sin \theta = -\rho / \cos \alpha \quad (4)$$

For near vertical straight lines a different equation can be defined with

$$x = a^* .y + b^* \quad (5)$$

An interpretation plane can be defined as being the plane which contains the straight line in the object space, the projected straight line in the image space, and the perspective centre of the camera (See fig. 4).

The normal vector to the interpretation plane in the image space can be stated as

$$\vec{N} = \begin{bmatrix} A \\ B \\ C \end{bmatrix} = \begin{bmatrix} f \cdot \cos \theta \\ f \cdot \sin \theta \\ -\rho \end{bmatrix} \quad (6)$$

with  $f$  being the camera focal length.

### 2.2 Feature extraction

The straight lines can be extracted in the image by using image processing methods. A pipeline of methods for feature extraction has been empirically selected and are briefly described in this section.

The first step is the edge preserving smoothing, which is applied over the grey level image. Following an edge detection algorithm can be used to segment lines. One of the approaches is to compute gradients in some predefined directions by convolving the image with a set of templates at equally spaced directions. The largest magnitude is taken as the gradient response and the direction of that template is the edge angle. The Nevatia and Babu technique is based on 12 gain-normalised 5x5 masks, which are utilised to detect edges in 30 degrees increments. Two images can be derived

applying these operators: one is the magnitude of the gradient for each pixel, except for the borders of the image that are set as null; the other is an image containing the edge directions for each pixel.

After edge detection a suitable threshold must be determined in order to maintain only the significant edges. Several approaches can be used either setting an arbitrary value or using some automatic selection method, based on objective criteria. The gradients with magnitude less than the computed threshold are automatically set to zero, and the remaining ones are assumed to be edges and its values are maintained.

After thresholding edges are thinned with suppression of the pixels that are not local maxima. Each edge pixel is considered and it is passed if those neighbouring pixels in the normal direction of the edge are less than or equal to its gradient magnitude. Edgels are pixels that are part of an edge but they are still not connected. Edge linking attempts to perform neighbourhood analysis in order to connect these edgels. Linking of edgels is based on the similarity of gradient magnitude and direction. The scan and label approach (Venkateswar and Chellappa, 1992). has been chosen because it is easy to implement and it is computationally efficient. The original approach has been adapted to consider 12 directions instead of the original 8 directions and a new set of masks has been designed as well. The scan-and-label approach scans the image from left to right and from top to bottom assigning a label to the edgels and building a structure that describes each labelled line. This structure is a file that stores the beginning and ending points of the line, the number of pixels labelled, the direction according to the code and the average magnitude of the gradient. The algorithm assigns the same label to edgels that fall along the same straight line. The next step is to connect unit support lines, i.e., line registers to which only one edgel has been assigned. A similar scan-and-label algorithm is applied with a few different masks attempting to connect unit support lines to a neighbour one.

As a consequence of noise, occlusions and other problems, several lines remain disconnected in the label structure. It is necessary to connect these lines and to eliminate those that are less significant. Linking of collinear lines is a further stage, proposed also by Venkateswar and Chellappa (1992) which aims to connect neighbour lines with similar orientation and gradient magnitude. Lines that fall in this window and are compatible in gradient magnitude and direction are identified. A geometric analysis of collinearity is performed to check whether the endpoints of the two lines being analysed are collinear or not. If passed, then the two lines are merged; the endpoints (start and end pixels) are updated in the label register structure and the labels are changed in the label image.

The edge pixel coordinates are stored in the frame buffer reference system, i.e., rows and columns. Reduction to a near photogrammetric reference system, is performed using the image centre and the pixel size. In this step, systematic errors can be corrected, after line fitting. A Least Squares adjustment is then used to fit a straight line to the selected set of image edge points, with subpixel precision. Two sets of equations can be defined and used according to the edge orientation (Tommaselli and Tozzi, 1996). In order to avoid gross errors, the residuals are computed and verified after line fitting, eliminating the pixel with largest residual and performing a new line fitting. This process is repeated while a predefined number of points remains in the set and the residuals are larger than a previously defined threshold. If large residuals still remain, considering a previously defined minimum number of points, than the straight line is eliminated.

### 3 COMPUTING ORIENTATION FROM VERTICAL AND HORIZONTAL LINES

#### 3.1 Liu & Huang mathematical model

Liu et al (1990) proposed a mathematical model in order to estimate rigid body motion using straight lines. This approach is advantageous because it is a two stage approach: in the first step rotations are computed and in the second step translations are estimated.

In the first step the rotations are computed from the following condition equation:

$$n^T \cdot R \cdot N = 0 \quad (7)$$

where  $n$  is direction vector of the straight lines in the object space;  $N$  is the vector normal to the interpretation plane in the image space and  $R$  is the rotation matrix. The rotated normal vector is considered perpendicular to the direction vector. Considering a non-linear solution at least three straight line correspondences are required.

$$[a \ b \ c] \cdot \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}^T \cdot \begin{bmatrix} A \\ B \\ C \end{bmatrix} = 0 \quad (8)$$

As just the direction vector is considered at this stage, this model is suitable to be adapted to compute orientation from vertical and horizontal lines. The translations are normally computed in the second stage. In our approach the translations are directly established. The distance between the camera and the object is measured with a laser device and the X and Y coordinates can be arbitrary.

### 3.2 Liu & Huang model adapted.

The parametric equation of a straight line in the object space is given by:

$$\begin{cases} x = x_1 + t \cdot l \\ y = y_1 + t \cdot m \\ z = z_1 + t \cdot n \end{cases} \quad (9)$$

and the direction vector is:

$$\vec{d} = [l \quad m \quad n] \quad (10)$$

### 3.3 Computing Orientation from vertical and horizontal lines

Direction vectors of horizontal and vertical edges in the object space are:  $\vec{u}_H = [1 \ 0 \ 0]$  e  $\vec{u}_V = [0 \ 1 \ 0]$  respectively. Introducing these constraints into the original model, two equations are easily obtained which one for a horizontal or vertical line.

$$\begin{aligned} F_H : f \cdot \cos \theta \cdot r_{11} + f \cdot \sin \theta \cdot r_{21} - \rho \cdot r_{31} &= 0 \\ F_V : f \cdot \cos \theta \cdot r_{12} + f \cdot \sin \theta \cdot r_{22} - \rho \cdot r_{32} &= 0 \end{aligned} \quad (11)$$

At least three non parallel straight lines are required to compute the  $\kappa$ ,  $\varphi$  e  $\omega$  orientation parameters. Ideally more than three correspondences are available and an estimation method must be used to get an optimum value for the parameters. The least squares method of adjustment with conditions (Mikhail and Ackerman, 1976) is used to estimate parameters from the functional model presented in eq. (11) and from the observations obtained using feature extraction methods.

### 3.4 Monoplotting

Once the rotation matrix is computed by using vertical and horizontal straight lines, ground coordinates of point lying on the flat surface can be determined. Inverse collinearity equation is the most suitable model to perform this task.

$$\begin{aligned} X &= X_0 + (Z - Z_0) \cdot \frac{r_{11}x + r_{21}y + r_{31}z}{D} \\ Y &= Y_0 + (Z - Z_0) \cdot \frac{r_{12}x + r_{22}y + r_{32}z}{D} \\ D &= r_{12}x + r_{23}y + r_{33}z \end{aligned} \quad (12)$$

where  $x$  and  $y$  are the coordinates of a point in photogrammetric reference system;

$Z$  can be considered the same for all point lying on the flat surface, which means  $Z_i = 0$ ;

$r_{ij}$  are the elements of the rotation matrix;

$X_0$  e  $Y_0$  are the translations of the Perspective Centre related to the surface reference system and can be considered  $X_0 = Y_0 = 0$ ;

$Z_0$  is the length between the flat surface and the perspective centre;

Recovery of the ground coordinates can be thus obtained with no control points, enabling computation of areas and lengths for several applications.



Figure 2 Measurement unit, integrating a laser device and a digital camera.

### 3.5 Results

The algorithms were implemented using C++ and were firstly tested with simulated data. Straight line equations in the image space were generated using the collinearity equation and random errors with standard deviation of 0.05mm were introduced to the image data. The camera focal length was set to 47mm and the camera were considered to be 2m apart from the flat surface. Considering this arrangement the angles were recovered with true errors within 2' and the resulting errors in the areas, computed from ground coordinates using inverse collinearity, were within 0.12%, which is a very good result.

A prototype integrating a Kodak DC40 digital camera and a laser measurement device was then used (Figure 2). The digital camera was firstly calibrated using self calibrating bundle adjustment of images taken on a steel plate with precisely marked control points (figure 3).

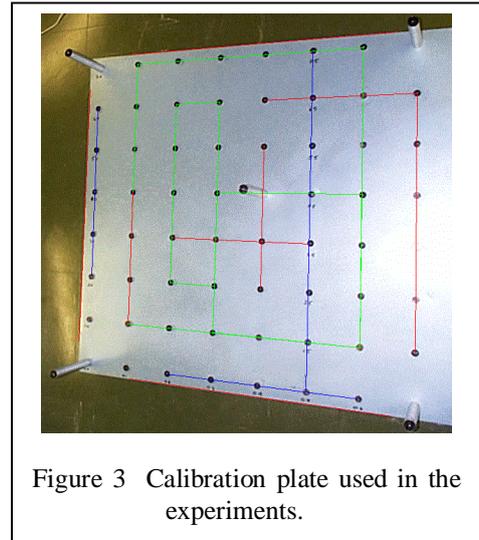


Figure 3 Calibration plate used in the experiments.

Some experiments were conducted in order verify the accuracy of the proposed approach. The same image as depicted in fig. 3 was used and vertical and horizontal straight lines linking aligned points were measured. The measured lines are depicted in fig. 3, as well. Table 1 presents the results obtained using the proposed approach. In the second column it is presented the error in the rotational parameters when compared to those obtained using bundle calibration. Ground coordinates of the signalised points were computed using eq. (12) and, then, areas and lengths on the surface were derived. The fifth and the sixth columns present the errors in three squared areas; the ninth and the tenth columns present the errors in three lengths. The real values were known because the target coordinates were accurately established. Results obtained in these experiments data show that areas can be measured with error within 3% and distance within 0.3% of error.

Camera Rotations		Areas on the surface			Lengths on the surface				
	Error		True value (mm <sup>2</sup> )	Error (mm <sup>2</sup> )	Error (%)		True value (mm)	Error (mm)	Error (%)
k	0°02'43,419''	A <sub>1</sub>	300000	10198.888	3.40	D <sub>1</sub>	400	-1.064	-0.27
φ	-0°17'07,141''	A <sub>2</sub>	90000	4143.666	4.60	D <sub>2</sub>	400	0.014	0.00
ω	-0°06'19,774''	A <sub>3</sub>	40000	299.338	0.75	D <sub>3</sub>	700	-1.639	-0.23

Table 1 Results of the experiment using vertical and horizontal lines.

A key issue to improve the accuracy of the proposed system is the calibration of the transformation from the laser reference system to the camera reference system. This transformation must be applied to the measured distance, in order to use the proposed methodology.

## 4 CALIBRATION USING STRAIGHT LINES

Computation of the inner orientation parameters of the camera is usually done by self calibrating methods using signalised control points. In several applications, however, is difficult to provide those points and using natural lines can be an alternative. Several approaches have been proposed to compute exterior orientation from straight lines; a few of them included inner orientation parameters. In this paper a mathematical model using straight lines that consider both interior and exterior orientation parameters as unknowns is derived.

This model is being designed to enable camera self calibration on the fly, with no control points. Straight lines that are already in the environment are to be used as control. The inner parameters being considered are the camera focal length, the coordinates of the principal point and the x-scale factor. The radial lens distortion parameters are supposed to be previously known, because they are stable and well determined with batch calibration or using lines as well (Prescott and Mclean, 1997).

### 4.1 Mathematical model using straight lines

The mathematical model proposed by Tommaselli and Tozzi (1996) is based on the equivalence between the vector normal to the interpretation plane in the image space and the vector normal to the rotated interpretation plane in the object space. The interpretation plane contains the straight line in the object space (**L**), the projected straight line in the image space (**I**), and the perspective centre of the camera (**PC**) (Fig. 6).

The vector  $\mathbf{N}$ , normal to the interpretation plane in the image space, is given by eq. (6). The vector  $\mathbf{n}$ , normal to the interpretation plane in the object space, is defined by the vector product of the direction vector of the straight line ( $\mathbf{d}$ ) and the vector difference ( $\mathbf{PC}-\mathbf{C}$ ) (See Fig. 6).

$$\mathbf{n} = \begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix} = \begin{bmatrix} -n \cdot (Y_c - Y_1) + m \cdot (Z_c - Z_1) \\ n \cdot (X_c - X_1) + l \cdot (Z_c - Z_1) \\ -m \cdot (X_c - X_1) + l \cdot (Y_c - Y_1) \end{bmatrix} \quad (13)$$

Where:

$X_c, Y_c, Z_c$  are the coordinates of the Perspective Centre ( $\mathbf{PC}$ ) of the camera related to the object reference system;  $X_1, Y_1, Z_1$  are the 3D coordinates of a known point ( $\mathbf{C}$ ) of a straight line in the object model;  $l, m, n$  are the components of the direction vector  $\mathbf{d}$  of the straight line; all defined in the object space reference system.

Multiplying vector  $\mathbf{n}$  by the rotation matrix  $\mathbf{R}$  eliminates angular differences between the object and the image reference systems and results in a vector normal to the interpretation plane in object space that has the same orientation as vector  $\mathbf{N}$ , normal to the interpretation plane in the image space, but different in magnitude.

$$\mathbf{N} = \lambda \mathbf{R} \mathbf{n} \quad (14)$$

where  $\lambda$  is a scale factor and  $\mathbf{R}$  is the rotation matrix defined by the sequence  $R_z(\kappa) \cdot R_y(\varphi) \cdot R_z(\omega)$  of rotations.

After some algebraic manipulations the element  $\lambda$  is eliminated. Equation (14) is split into two sets of equations, according to the value of parameter  $\theta$  (orientation of the straight line in the image) in order to avoid divisions by zero.

for  $45^\circ < \theta \leq 135^\circ$  or  $225^\circ < \theta \leq 315^\circ$

$$a = - \frac{r_{11} \cdot n_x + r_{12} \cdot n_y + r_{13} \cdot n_z}{r_{21} \cdot n_x + r_{22} \cdot n_y + r_{23} \cdot n_z} \quad (15)$$

$$b = - f \cdot \frac{r_{31} \cdot n_x + r_{32} \cdot n_y + r_{33} \cdot n_z}{r_{21} \cdot n_x + r_{22} \cdot n_y + r_{23} \cdot n_z}$$

for  $0^\circ < \theta \leq 45^\circ$  or  $135^\circ < \theta \leq 225^\circ$  or  $315^\circ < \theta \leq 360^\circ$ :

$$a^* = - \frac{r_{21} \cdot n_x + r_{22} \cdot n_y + r_{23} \cdot n_z}{r_{11} \cdot n_x + r_{12} \cdot n_y + r_{13} \cdot n_z} \quad (16)$$

$$b^* = - f \cdot \frac{r_{31} \cdot n_x + r_{32} \cdot n_y + r_{33} \cdot n_z}{r_{11} \cdot n_x + r_{12} \cdot n_y + r_{13} \cdot n_z}$$

where:

$$a^* = -\tan \theta \quad \text{and} \quad b^* = \rho / \cos \theta \quad (17)$$

#### 4.2 Extending the mathematical model to consider inner parameters

The model presented in section 4.1 can be extended to encompass inner parameters such as focal length ( $f$ ), principal point coordinates ( $c_x$  and  $c_y$ ) and the x-scale factor ( $d_s$ ). The optical distortion must be previously eliminated, because it cannot be well parameterised in such an approach. The raw coordinates measured in the digital image can be transformed to photogrammetric coordinates using equation (18).

$$x_i = x_f - c_x + (x_f - c_x)(k_1 \cdot r^2) + (x_f - c_x) \cdot d_s$$

$$y_i = y_f - c_y + (y_f - c_y)(k_1 \cdot r^2) \quad (18)$$

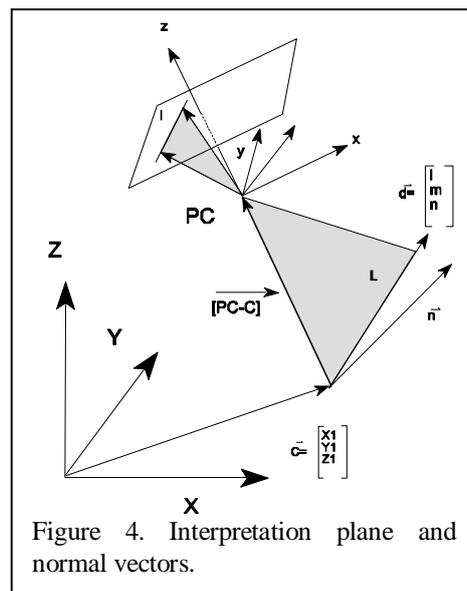


Figure 4. Interpretation plane and normal vectors.

where  $x_f$  e  $y_f$  are the pixel coordinate in the frame buffer reference system;  $x_i$  e  $y_i$  are the photogrammetric coordinates of the same pixel;  $k_1$  is the first order coefficient of the radial lens distortion. From this equation and considering the  $a$  and  $b$  parameters as a function of two endpoints coordinates, the following relations can be derived:

$$a' = \frac{(y_2 - c_y - (y_1 - c_y))}{(x_2 - c_x + (x_2 - c_x)d_s - x_1 + c_x - (x_1 - c_x)d_s)} = \frac{a}{(1 + d_s)} \quad b' = b + a \cdot c_x - c_y \quad (19)$$

$$a^{*'} = a^* \cdot (1 + d_s) \quad b^{*'} = (b^* - c_x + a^* \cdot c_y)(1 + d_s) \quad (20)$$

Equations (19) and (20) establish a relationship between straight line parameters and some of the inner orientation parameters. Using these relations, equations (15) and (16) can be written to consider the inner parameters as

$$a' = - \frac{1}{(1 + d_s)} \frac{r_{11} \cdot n_x + r_{12} \cdot n_y + r_{13} \cdot n_z}{r_{21} \cdot n_x + r_{22} \cdot n_y + r_{23} \cdot n_z} \quad (21) \quad a^{*'} = - (1 + d_s) \frac{r_{21} \cdot n_x + r_{22} \cdot n_y + r_{23} \cdot n_z}{r_{11} \cdot n_x + r_{12} \cdot n_y + r_{13} \cdot n_z} \quad (22)$$

$$b' = (a \cdot c_x - c_y) - f \cdot \frac{r_{31} \cdot n_x + r_{32} \cdot n_y + r_{33} \cdot n_z}{r_{21} \cdot n_x + r_{22} \cdot n_y + r_{23} \cdot n_z} \quad b^{*'} = - f \cdot \frac{r_{31} \cdot n_x + r_{32} \cdot n_y + r_{33} \cdot n_z}{r_{11} \cdot n_x + r_{12} \cdot n_y + r_{13} \cdot n_z} (1 + d_s) + (a^* \cdot c_y)(1 + d_s)$$

It is worth of note some characteristics of this model: in the first equation the  $a$  parameter does not depend on neither the focal length nor the principal point coordinates. If the scale factor is considered negligible then the first equation can be considered independent on the inner orientation parameters. The second equation, on the other hand, holds all the considered inner parameters, mainly focal length and the principal point coordinates.

The application of this proposed model to camera calibration is straightforward. Straight line parameters  $a'$  and  $b'$  are measured in several digital images and the exterior ( $\kappa, \phi, \omega, X_0, Y_0, Z_0$  for each image) and interior ( $c_x, c_y, f, d_s$ ) orientation parameters are estimated using least squares. The estimation process is similar to the calibration with control points, except by the observation equations.

### 4.3 Results

Some experiments were accomplished to evaluate the feasibility of the approach in real tasks. The method has been conceived to enable on the fly calibration, that means to work in real environments with real features. An example of such an environment is presented in figure 5.a, a typical corridor. Figure 5.b depicts the same image after feature extraction showing the segmented edges from which parameters were computed.



Figure 5 Example of images used in the experiments (a) original image (b) extracted features

The results are still preliminary and were obtained with just one and with two images. The resulting inner parameters were compatible with the conventional bundle calibration procedure, although the covariance matrix is worse. One aspect to consider is the quality of the control in the object space; the straight lines in image are sometimes poor in contrast and difficult to connect automatically. Measurement of these lines in the object space were performed with a tape measure, with may lead to systematic errors. It is expected that a multi-image arrangement can improve the results.

## 5 CONCLUSION

The problem of orientation and calibration using straight lines was addressed in this paper by means of two approaches: the first is the camera orientation and recovery of areas of flat surfaces with no control points; the second is the inner camera calibration using straight lines.

In the first problem a mathematical model was adapted to consider exclusively vertical and horizontal lines in the object space. Using a laser device to measure the distance from camera perspective centre and the surface no other source of external information is required to compute orientation and reconstruct coordinates and areas over the flat surface. Experiments showed that areas could be computed with errors within 3% and lengths with 0.3% of error.

In the second problem a mathematical model was extended to encompass both exterior and inner orientation parameters. Some preliminary experiments with real data presented results suitable to the proposed applications, for instance, modelling of virtual environments.

From analysis of the second model important issues that arises are the independence of the first equation with respect to the inner orientation parameters and the calibration of the optical distortions, which was supposed to be done in a previous step. These problems are left as a suggestions for future work.

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