DETERMINATION OF CAMERA'S ORIENTATION PARAMETERS BASED ON LINE FEATURES

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Abstract

Determining camera's orientation parameters is one of the most important tasks in photogrammetry and robot vision. The paper presented a new mathematical model to determine the position and attitude of camera. The technique employed the coplanar relationship of the projection center, 3D straight line and its 2D image to construct the basic constrain equations. In the processing, the position and attitude of camera were divided into two steps and computed respectively. Since amount of obvious known geometrical objects such as horizontal and vertical lines exist in man-made environment, they are all be able to be used as controls effectively in our new method. This made it possible to do the space resection with fewer absolute controls. The method was based on stronger theory of mathematics and geometric, so it's robust, accurate and possesses semi or full automation.

The proposed approach was tested with simulated and real data. The result verified the method robust, accurate and reliable automation.

1. INTRODUCTION

Determining the orientation parameters of camera is one of the most fundamental tasks in photogrammetry and machine vision. These parameters include camera's position and orientation (exterior parameters) in world coordinate system, the true image center, scale factor and the lens focal length (interior parameters) and the distortions of lens (radial and decentring). For the past decades, a lot of methods have been developed and served us well in many applications (Fukui, 1981; Lenz and Tsai, 1988; Fischler and Bolles,1981; Tsai, 1986; Maybank and Faugeras, 1992). However, among these methods almost all are point-based. They are more and more not enough for the need of the coming of digital photogrammetric era because of their several weaknesses: time consuming, error-prone, necessity of some sort of structured target or calibration range, and difficulty of automation.

Straight edges are the most popular features in large scale images of man-made environment. From the view point of image processing, they are easier detected and extracted from a digital noisy image at subpixel accuracy than point features. This makes the measurement automatically. In addition, amount of geometric constrains such as parallel, perpendicular, horizontal and vertical can be used as controls. These characters make them used in many applications such as determining the camera's orientation parameters automatically, relative and absolute orientation (Mulawa and Mikhail, 1988; Tommaselli and Lugnani, 1988; Dhome et al, 1989; C.L. Tozzi, 1986; Chen et al, 1989; Salari and Jong 1990; Liu et al 1990; Wang and Tsai, 1990; Lee et al, 1990; Echigo, 1990; Chen and Jiang, 1991; Chen and Tsai, 1991; Tommaselli and Tozzi, 1992).

The paper presented a new mathematical model which is based on the coplanar condition constructed by the perspective center, straight line in object space and its projection on the image plane to determine the camera's exterior parameters. In the method the exterior orientation parameters were divided into two groups (position and attitude) and calculated respectively. This character makes it possible to use some known information provided by GPS and INS and reduce the calculation.

In this method the calibration targets include a set of parallel lines (horizontal and vertical) and one more known control lines. These straight lines are extracted with dynamic programming method firstly and then fitted in the least square from simulated and real images. The sub-pixel measuring accuracy of image can be ensured.

2. MATHEMATICAL MODEL

As other computer vision applications we take the interior parameters of the camera remain as stable in the solution and calibrated in advance. In addition, the lens distortion parameters are known.

2.1. Condition Equations

From figure 1 we see that the project center, straight line in 3D object space and its projection on image plane can form a plane (shaded in figure 1) when the image was taken. The geometrical condition is the foundation of this new mathematical model which is constructed by the two normal vectors the plane, one is in the image space and the other in the object space.

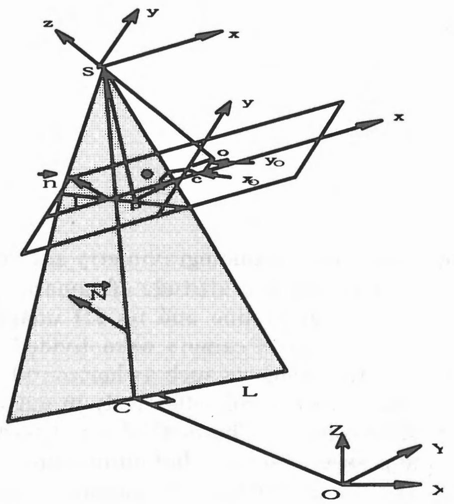


Figure 1. Interpretation plane and normal vectors.

In order to have a good understanding of this, we take the following symbols:

- **L**: straight line in the object space;
- **l**: projection of **L** on the images plane;
- **S**: perspective center of image;
- **c**: the center of the image;
- **c-xy**: image plane coordinate system;
- **o**: the principle point of the image;
- x_0, y_0: coordinate of the principle point's in **c-xy**;
- **cp**: the line perpendicular to **l**;
- ρ: the length of **cp**;
- θ: the angle measured counterclockwise from positive **x**-axis to **cp**;
- **n**: the normal vector of plane defined by **S** and **l**;
- N: the normal vector of plane defined by **S** and **L**;
- **S-xyz**: image space coordinate system;
- **O-XYZ**: the world coordinate system.

Suppose the system errors of image have been corrected, thus the equation of **l** in coordinate system **o-xy** as:

$$x\cos\theta + y\sin\theta = \rho - x_0\cos\theta - y_0\sin\theta \qquad (1)$$

The direction vector of **l** in image space coordinate system **S-xyz** as:

$$\vec{l} = \begin{bmatrix} \sin\theta \\ -\cos\theta \\ 0 \end{bmatrix} \qquad (2)$$

The direction vector of **Sp** as:

$$\vec{S}p = \begin{bmatrix} \rho\cos\theta - x_0 \\ \rho\sin\theta - y_0 \\ -f \end{bmatrix} \qquad (3)$$

Take **n** as the cross-product of **l** and **Sp** we obtain the normal vector of plane **Sl** in **S-xyz** as:

$$\vec{n} = \begin{bmatrix} f\cos\theta \\ f\sin\theta \\ \rho - x_0\cos\theta - y_0\sin\theta \end{bmatrix} \qquad (4)$$

Now transform vector **n** from **S-xyz** to **O-XYZ** with the rotation matrix **R** and scale factor λ we get **N** as:

$$\begin{bmatrix} Nx \\ Ny \\ Nz \end{bmatrix} = \lambda\, R \begin{bmatrix} f\cos\theta \\ f\sin\theta \\ \rho - x_0\cos\theta - y_0\sin\theta \end{bmatrix} \qquad (5)$$

Where, **Nx**, **Ny** and **Nz** are three components of **N** on the X-, Y-, and Z-axes respectively.
$\mathbf{R} = \mathbf{R}(\varphi)\mathbf{R}(\omega)\mathbf{R}(\kappa)$, and

$$R = \begin{bmatrix} a1 & a2 & a3 \\ b1 & b2 & b3 \\ c1 & c2 & c3 \end{bmatrix} \qquad (6)$$

where, a_i, b_i, c_i (i=1,2,3) are the direction cosines or the elements of the rotation matrix **R**.

For straight line **L**, we usually use six parameters (one point and one direction vector) to describe it. Take **C** (**Xc, Yc, Zc**,) as the point and (α, β, γ) as the direction vector of **L**, the line equation can be written as:

$$\begin{cases} X = Xc + t\alpha \\ Y = Yc + t\beta \\ Z = Zc + t\gamma \end{cases} \qquad (7)$$

Where, (**X, Y, Z**) is the coordinate of any one point on **L**, **t** is the corresponding scale factor of (**X, Y, Z**).

In order to simplify the problem, **C** is often chosen the nearest point to **O**, and (α, β, γ) one unit vector. Because **N** is the normal vector of plane **S-l-L**, we have the following geometric relationship:

$$\begin{cases} Xc\,\alpha + Yc\,\beta + Zc\,\gamma = 0 \\ Nx\,\alpha + Ny\,\beta + Nz\,\gamma = 0 \\ Nx\,(Xs-Xc) + Ny\,(Ys-Yc) + Nz\,(Zs-Zc) = 0 \end{cases} \qquad (8)$$

2.2. Geometric Constrains

Suppose **L'** is any one straight line in the object space and parallel to straight line **L**. From last section we know the projection center **S**, the straight line **L'** and its projection on the image plane are in one plane. **N'** is the normal vector of the plane. **C'** is the nearest point on **L'** to the original point of the world coordinate system **O-XYZ**. **L"** is the intersected line by the both planes **S-L** and **S-L'**. **N"** is the direction vector of **L"**. From the theory of perspective geometry we know that **L"** passes through the vanishing point on the image plane, which is defined by all parallel lines of **L**. As mentioned above, **N** and **N'** are both perpendicular to **L** and **L'**. So the vector **N''** can be obtained by the cross-product of **N** and **N'** (i.e. $N'' = N \times N'$ see figure 2).

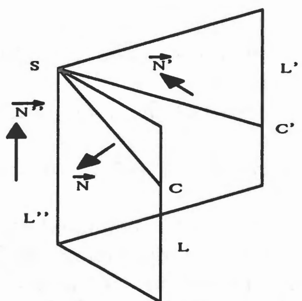


Figure 2. Geometric Constrains Between Two Lines

Now take the normalization forms of these direction vectors we get three unit vectors of **L**, **L'** and **L''** as:

$$\begin{cases} Ix = I'x = I''x \\ Iy = I'y = I''y \\ Iz = I'z = I''z \end{cases} \qquad (9)$$

Where **I**, **I'** and **I''** are the unit direction vectors of **L**, **L'** and **L''** respectively.

In (9) there are three unkonwns φ, ω, κ and four observed values θ, ρ, θ', ρ'. Now we get the basic mathematical equations to calculate the focal length and the attitude of camera as following:

$$I'' = F_{I''}(\theta, \rho, \theta', \rho', \varphi, \omega, \kappa) \qquad (10)$$

Or

$$N'' = F_{N''}(\theta, \rho, \theta', \rho', \varphi, \omega, \kappa) \qquad (11)$$

Where, **F** = function of θ, ρ, θ', ρ', φ, ω and κ.

Horizontal Situation

When **L** and **L'** are horizontal lines, their components projected on the **Z**-axis of the world coordinate system equal zero. This case is true because these horizontal lines abound in the man-made scene. Thus (11) can be written as:

$$N''z(\theta, \rho, \theta', \rho', \varphi, \omega, \kappa) = 0 \qquad (12)$$

Vertical Situation

Similar to (12), when **L** and **L'** are vertical lines, we will get two equations as:

$$\begin{cases} N''x(\theta, \rho, \theta', \rho', \varphi, \omega, \kappa) = 0 \\ N''y(\theta, \rho, \theta', \rho', \varphi, \omega, \kappa) = 0 \end{cases} \qquad (13)$$

2.3. Calculation of the Focal Length and the Attitude of Camera

To keep the mathematical model as general as possible, it is assumed that the unknown parameters have a priori measured values and approximated values. This will contribute to the following:

$$\begin{cases} L^0 + V = L \\ X^0 + \Delta X = X \end{cases} \qquad (14)$$

where, L^0, **V**, and **L** = observations, residuals, and adjustments matrices for the observations (θ, ρ, θ', ρ');
X^0, ΔX, and **X** = approximates, corrections, and adjustments matrices for the unknown parameters (φ, ω, κ, and **f**).

After linearizing (12) and (13) by Newton's first-order approximation, and assuming that more than three pair of parallel lines, which can be horizontal or vertical, are available in the object space, the mathematical model can be written in the following matrix form by combining (12), (13), and (14):

$$AV + B\Delta X + W = 0 \qquad (15)$$

where, **A** = residual coefficient matrix of **V**;
B = correction coefficient matrix of ΔX;
W = the constant column matrix.
The least-square solution to this model results in the following normal equation:

$$\Delta X = -(B^T(AP^{-1}A^T)^{-1}B)^{-1}B^T(AP^{-1}A^T)^{-1}W \qquad (16)$$

Where **P** = weight matrix corresponding to the observations **L**.
The calculation must be done iteratedly until to the allowance error.

2.4.. Calculation of the Position of Camera

After the attitude of camera have been obtained the normal vectors of all planes are known. From equation (8) we see, only the camera position parameters are unknown. To calculate the three unknown parameters we only need three control lines, which are all not in the same plane. The solution equations are:

$$\begin{cases} Nx_1(Xs-Xc_1) + Ny_1(Ys-Yc_1) + Nz_1(Zs-Zc_1) = 0 \\ Nx_2(Xs-Xc_2) + Ny_2(Ys-Yc_2) + Nz_2(Zs-Zc_2) = 0 \\ Nx_3(Xs-Xc_3) + Ny_3(Ys-Yc_3) + Nz_3(Zs-Zc_3) = 0 \end{cases} \qquad (17)$$

3. RELATED IMAGE PROCESSING STRATEGY

As previously mentioned, the systemic errors such as lens distortions and scale difference of two directions of one pixel must be corrected before the determining task. The calibration method requires completion of following major tasks:

- Image smoothing filter.

- Detection of linear features in images.
- Systematic errors correction.
- Optimization of the linear features

3.1. Image Smoothing Filter

Smoothing filter is a general notion of transforming a digitized image in some way in order to improve picture quality. It mainly consists of removing noise, debluring object edges, and highlighting some specified features.

The paper use edge-preserving smoothing, which searches the most homogeneous neighborhood of each pixel and assigns to it the average gray value of that neighborhood. The homogeneity is expressed in terms of variance. When the pixel under consideration lies on an edge there will be, when moving away, directions where the variance is low, i.e., the pixel belongs to that region, and directions with high variance. The principal notion is to rotate with an interval (e.g. 450), an elongated mask around the pixel and to compute the variance of the gray values in the bar. The average of the gray values of the bar with the smallest variance is assigned to the pixel.

3.2. Extracting Edges

Edges of objects (e.g. buildings) in an image are defined as local discontinuities in the gray value appearance. This may result from a depth discontinuity, a surface normal discontinuity, a reflectance discontinuity, or an illumination discontinuity in the scene.

Edge detection has been an important part of many computer vision systems and is widely described in textbooks and presented in scientific works. There are two main types of edge detection techniques which have been widely described in literature: the differential and the template matching techniques. The former performs discrete differentiation of digital image array to produce a gradient field, in which, at each pixel, gradients are combined by a non-linear point operation to create an edge enhancement array prior to a threshold operation. The template matching technique is based on a set of masks representing discrete approximation to ideal edges of various orientations, which are applied simultaneously to produce the gradient field. In that case, the enhancement is formed by choosing the maximum of the gradient array corresponding to each mask. For each type of edge detection technique, a large number of operators have been proposed by different authors.

In our method, we employed the Sobel operator to strength the edges and then used the dynamic programming line following method to extract these lines.

3.3. Systematic Errors Correction

The edge pixel coordinates are defined in the frame reference system. These coordinates must be transformed to the beast positions in the image by correction systematic errors such as radial distortion, decentring distortion, scaling difference in horizontal and vertical directions, translations of the principal point. The systematic errors are corrected using the following equations:

$$\begin{cases} \mathbf{x}_i = \mathbf{x}_f - \mathbf{x}_0 + (\mathbf{x}_f - \mathbf{x}_0)\bullet\mathbf{k}_1\bullet\mathbf{r}^2 + (\mathbf{x}_f - \mathbf{x}_0)\bullet\mathbf{d}_s \\ \mathbf{y}_i = \mathbf{y}_f - \mathbf{y}_0 + (\mathbf{y}_f - \mathbf{y}_0)\bullet\mathbf{k}_1\bullet\mathbf{r}^2 \end{cases} \qquad (18)$$

where:

$\mathbf{x}_i$ and $\mathbf{y}_i$ are the image coordinates of a pixel related to the principal point;

$\mathbf{x}_f$ and $\mathbf{y}_f$ are the coordinates of the same pixel in the frame;

$\mathbf{x}_0$ and $\mathbf{y}_0$ are the image coordinates of the principal point;

$\mathbf{r}$ is the distance of one pixel to the principal point;

$\mathbf{k}_1$ is the coefficient of radial distortion (higher order coefficients and decentring distortion are neglected);

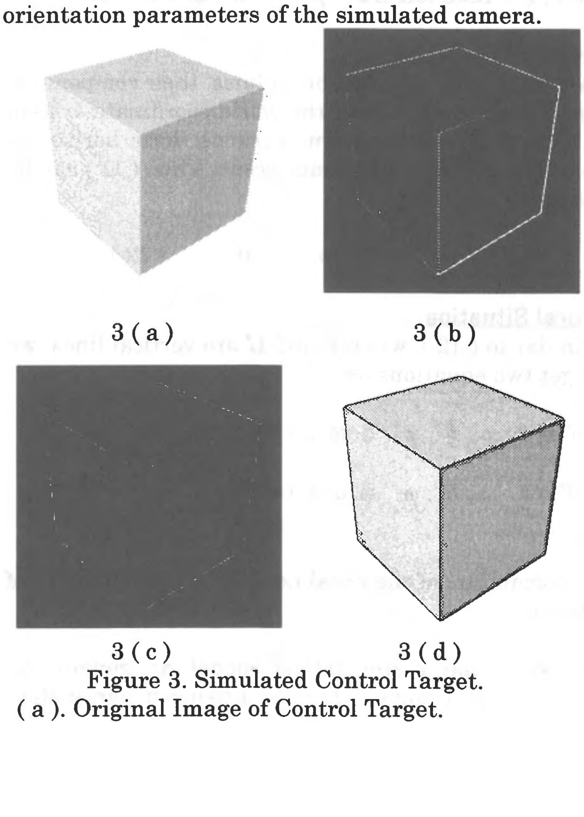
$\mathbf{d}_s$ is the scale factor in $\mathbf{x}$.

3.4. Optimization of the linear features

Once the system errors of image have been corrected, the straight lines in the image plane can be expressed as the form of equation (1) with the least square adjustment at sub-pixel precision.

4. EXPERIMENTAL RESULT

One simulated test and one real have been conducted in order to check the potential and the effectiveness of the developed calibration scheme of camera. The simulated test control lines, which were extracted from a cube rendered with 3D Studio, were used to describe the whole procedure of this method. The real date was used to make a comparing with the point-based method and the new one presented here. For the former, the control target was one cubic box. Figure 3 illustrated the calibrating target. Table 1 listed the simulated orientation parameters of the simulated camera.



3 (a) 3 (b) 3 (c) 3 (d)

Figure 3. Simulated Control Target.
(a). Original Image of Control Target.

(b). Edges Detected By Sobel Operator.
(c). Edges Extracted By Thinning and Following.
(d). Straight Lines (black frame) Extracted with the Least Square Fitting Method.

Table 1. Simulated Valuse of Orientation for Camera

Interior Orientation Parameters	x_o	y_o	f
	-3.692	2.972	699.42
Exteriror Orientation Parameters	Xs	Ys	Zs
	-934.10	-628.04	1555.90
	φ	ω	κ
	53.559803	57.089316	349.864286

Table 2 listed the simulated parameters of control lines and their observations on the image plane.

Table 2. Simulated Values of Control Lines

	ρ	θ	Xc	Yc	Zc	α	β	γ
L0	10.10	0.164635	100.00	100.00	0.00	0.000	0.000	1.000
L1	188.19	4.351133	100.00	0.00	0.00	0.000	1.000	0.000
L2	154.08	5.733119	0.00	100.00	0.00	1.000	0.000	0.000
L3	39.65	4.473506	100.00	0.00	600.00	0.000	1.000	0.000
L4	241.34	3.541581	100.00	1100.00	0.00	0.000	0.000	1.000
L5	172.91	2.159794	0.00	1100.00	600.00	1.000	0.000	0.000
L6	42.58	5.585684	0.00	100.00	600.00	1.000	0.000	0.000
L7	238.44	6.233983	2100.00	100.00	0.00	0.000	0.000	1.000
L8	235.29	1.558492	2100.00	0.00	600.00	0.000	1.000	0.000

The software was programmed with C++ language and executed on PC in the environment of MicroSoft WINDOWS 95. The whole process consisted of : (1) optical distortion parameters; (2) principal point coordinates; (3) affine scaling parameters; Assume the system errors of image are stable and corrected and the principal point coordinates are unknowns, and (4) exterior orientation parameters for camera. The control lines can be automatically extracted by the program at sub-pixel precision.

Table 3 lists the initial values and the calculated result.

Table 3. Result of Single Photo Resection

	Initial Value	Calculated Value
x_o	-3.692	---
y_o	2.972	---
f	699.42	---
Xs	-930.100	-934.127
Ys	-620.041	-628.043
Zs	1550.000	1555.880
φ	50.602520	53.560490
ω	60.141391	57.088574
κ	359.884333	349.864290

In order to compare the new method with other point-based ones, we used a piece of real image, which was taken with film-based 120 camera and scanned at resolution of 600 DPI (the original image shown in figure 4). The control points were measured manually with cursor on computer screen and listed in table 4. Two point-based methods DLT (Direct Linear Transformation) and SR (Space Resection) were used and the results are listed in table 5.

Figure 4. Original image used for test

Table 4. Coordinates of Control Points

Point No.	x [pixel]	y [pixel]	X [m]	Y [m]	Z [m]
1	196	915	6132.873	855.603	115.477
2	241	988	6125.498	850.850	105.256
3	244	1257	6125.608	850.856	70.128
4	721	441	5754.486	875.060	110.521
5	1854	513	5754.531	789.101	110.505
6	2353	578	5754.602	746.094	108.206
7	497	1631	5754.504	891.241	28.960
8	877	1623	5754.462	864.894	28.960
9	1991	1598	5754.471	778.866	28.950
10	735	1744	5754.521	874.942	20.772
11	2879	1353	5823.379	649.903	49.288
12	3178	1265	5783.367	644.957	56.144
13	3553	1335	5764.857	617.183	49.318
14	2864	1698	5823.420	652.165	16.158
15	3599	945	5821.447	560.807	91.456
16	3892	882	5764.506	575.348	91.460
17	2485	1711	5605.802	824.259	26.047
18	2516	1709	5606.329	822.147	26.044

Table 5. Result of Single Photo Resection

	DLT Method	Point-Based SR
x_o	83.296	83.396
y_o	-57.371	-57.371
f	239.493	239.494
Xs	5366.991	5366.991
Ys	966.396	966.396
Zs	36.896	36.896
φ	115.601898	115.601904
ω	91.394714	91.394786
κ	359.140747	359.260951

Using these control points we could get several control lines by combining two points such as 1-18, 2-17, 3-16, 4-15, and so on. In addition, four pairs of parallel lines were used here. Table 6 listed the tested result obtained with the new method. The interior parameters were provided by the former two methods.

Table 6. Result of Single Photo Resection

	Initial Value	Calculated Value
X_0	83.296	---
y_0	-57.371	---
f	239.396	---
Xs	5300.991	5366.513
Ys	900.396	966.624
Zs	30.896	37.255
φ	110.601898	115.577747
ω	90.394714	91.347435
κ	0.140747	359.280641

5. CONCLUSION

Calibration of camera has been an important component of any vision task which seeks to extract geometric information from a scene. The new method presented in this paper to determine the focal length and the exterior orientation parameters of camera is based on straight lines and their geometric constrains. The straight lines were used because they could provide excellent calibration environment for the object controls. Compared with other methods the new technique provided here possesses such advantages:

- Calibration of camera, which up to now has been point based, can be implemented on the basis of linear features. The equations then relate feature descriptors instead of point coordinates.
- Linear features, which are abundant in the 3D world due to human-made infrastructure, provide a rich set of possible geometric constraints (e.g. parallel, perpendicular, horizontal, vertical and coplanar) that can be effectively exploited in different applications, particularly in photogrametry.
- Although some techniques based on linear features have been put forward (Mikhail, 1997; Echigo, 1990; Grosky et al., 1990; Wang et al., 1991; Chen et al., 1989; Chen et al., 1991; Lee et al., 1990; Lenz et al., 1988; Liu et al., 1990; Mulawa et al., 1988; Salari et al., 1990; Tommaselli et al., 1988; Tozzi, 1996;), few of them took advantage of these excellent geometric constrains. The new method makes full use these constrains (mainly vertical parallel and horizontal lines). This can be proven both in geometric theory and mathematical basis.
- Since the calibration was divided into two steps, this can obviously reduce the relativity among the orientation parameters.
- The new method is robust and stable due to its strong geometric and mathematical relations.
- By the technique the calibration of camera can be done automatically because the straight lines can be easily extracted from the digital images at the sub-pixel accuracy.

The proposed solution was tested using synthetic and real data. From table 6 we can see that the new technique could obtain the same accuracy level result as DLT and point-based space resection. So it could be appropriate both for outdoor and for indoor computer vision applications like robot location and autonomous land vehicle guidance, because of its simplicity of environment setup and strong geometric controls. Especially in the application of the merging image with existing 3D GIS models the new method might be the most suitable way to provide the exterior orientation parameters because it is easy to provide more line objects than point from the GIS database.

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