Camera Models Determination Using Multiple Frames

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Abstract
A new approach is proposed for determining the location and orientation of a camera mounted on an ALV (autonomous land vehicle). We choose the road boundaries and the objects with vertical edges to be the calibration objects. During the calibration process, the ALV is supposed to move with pure translation. The camera models are derived by using two or three images under the assumptions that the height of the camera and the distance during taking images are known in advance. The tilt and swing angles can be computed from the first image. The pan angle can then be derived by using the projections of vertical edges in three images. If the angle between the moving direction of the ALV and the direction of road boundaries is large enough, two images are enough to find the pan angle. Two translational parameters can be found by employing the projections of vertical edges in two or three images.

1. Introduction
Camera calibration is an important process for computer vision applications. In the past decade, significant interest has been found in the study of determining camera models, including locations and orientations. Most of these methods need special marks or knowledge about their size and coordinates. However, it is sometimes impossible to place special marks along the road in the outdoor environment. One way to solve this problem is to use the objects placed on the road as the calibration objects. These objects may have horizontal and vertical lines. In this paper, the projections of these lines are used to determine the orientation and position parameters of the camera, excluding the height, by applying the the traveling distance during taking two images.

Nearly all of these methods for camera calibration need only one monocular image with special marks, which can be divided into three classes: special man-made marks, point features and line features, including straight lines or curves. In the first approach, some restrictions must be satisfied sometimes. Fukui[1] proposed a method for determining the position of a robot from only a TV image via a standard diamond-shaped man-made mark on the wall. Magee and Aggarwal[2] proposed a method by using a calibrated sphere under the condition that the optical axis must be aligned to the center of the sphere. The second approach is to use point features[3, 4]. The worst disadvantage of point features is sensitive to noises. It is rather difficult to extract point features to subpixel precision. Using line features has no such shortcomings. Chou and Tsai[5] used house corners as marks to determine the camera location. Haralick[6] developed an algorithm for using a rectangle of unknown size to determine the camera view angle parameters. Huang, Liu and Faugeras[7] proposed that the computation of the rotation matrix and the translation vector of the camera are separable.

Using a cube as a calibration object has been proposed by Chen, Tseng and Lin[8]. Wang and Tsai[9] proposed a method by using a rectangular parallelepiped with known dimensions as the calibration object. Using a calibration object with curves to determine camera models is another approach. Haralick and Chu[10] described a method with the calibration object containing plane conic or polygon arcs. Lee et al.[11] used a semi-circle running track to determine the location of a flying object.

We aim to compute the parameters of the camera mounted on an ALV running on an outdoor road at all time. The distance during taking two images is assumed to be known, which can be obtained from an attached meter. Also the height of the camera relative to the ground plane is known beforehand and fixed. The tilt and swing angles would be derived from a single image. The pan angle would be found from two or three images, depending on the angle between the moving direction and the road boundaries. After these three angles are known, it is simple to determine other two translational parameters, depth and deviation. The proposed approach has the following advantages:

1. These marks exist commonly both in indoor and outdoor environments. This makes the proposed method more practical and flexible.
2. The results of image processing are more stable since these marks will not be sensitive to noise.
3. The solution for camera parameters can be obtained analytically.
2. Derivation of Camera Parameters

2.1 System model

There are two coordinate systems, camera coordinate system and global coordinate system, in our model. The three axes of the camera coordinate system are called u, v and w axes and those of the global coordinate system are denoted as x, y and z axes. The origin of the camera coordinate system is assumed to be the camera lens center and the w axis is supposed to be the camera optical axis. The u axis is parallel to the abscissa axis of the image plane and the v axis is parallel to the ordinate axis of the image plane. 

To fix the global coordinate system, we select the object with vertical edges to be the mark for determining camera locations. In this paper, we use “pole” to denote the object. The positive y direction is aligned with the upward direction of the pole, which is assumed to be perpendicular to the ground. Suppose that the ground is flat and the ALV moves with pure translation. The inverse translation direction is defined to be the positive z direction. The origin of the global coordinate system is the “bottom” of the vertical pole.

In addition to the above assumption, we make other assumptions. First, the height of the camera relative to the ground is known. Second, tz1 and tz2, the displacements from time T1 to T2 and from T1 to T3 , respectively, are known by direct measurement. Third, there exists two parallel road boundaries with unknown directions.

2.2 Transformation of coordinate systems

Suppose the camera is located at (x0, y0, z0) with respect to the global coordinate system at time T1 . Let p be any point with global coordinate (x, y, z) and camera coordinate (u, v, w). We use the homogeneous coordinate system to describe the transformation:

\[ (u, v, w, 1) = (x, y, z, 1) \cdot T(x_0, y_0, z_0) \cdot R \cdot F \]

where

(1) \( T = \) the translation matrix between two coordinate systems.

(2) \( R = R(y, \theta) \cdot R(x, \phi) \cdot R(z, \delta) \)

where \( R(y, \theta) \) represents the rotation matrix of the x - y plane about the y axis through the pan angle \( \theta \) ; \( R(x, \phi) \), \( R(z, \delta) \) are defined similarly.

(3) \( F = \) the matrix for reversing the z axis.

Let \( p' = (u_p, v_p) \) be the projection of point \( p \) on the image plane. According to the perspective projection, we have:

\[ u_p = F \frac{u}{w} \quad (2-a) \]

where \( F \) is the focal length of the camera.

2.3 Derivation of the camera parameters

Because the lines used as calibration objects are either vertical or horizontal, the \( y_0 \) component of the translational parameters can not be found. We assume that the height of the camera is known.

2.3.1 Finding the swing and tilt angles

The tilt and swing angles can be found by using only one image, which has one projecting pole and two projecting road boundaries. Let us assume there is a straight line \( l \) whose direction is \( n \) in 3D space and its projection equation \( L \) on the image plane is

\[ u_p - m v_p - t = 0 \quad (3) \]

Substituting Eqs. (2-a) and (2-b) into Eq. (3), it yields

\[ Fu - mFv - tw = 0 \quad (4) \]

Equation (4) represents the projecting plane \( M \), formed by \( l \) and \( L \). The vector \( N = (F, -mF, -t) \) is the normal vector of the projecting plane \( M \). Because the straight line \( l \) is on the projecting plane \( M \), it is perpendicular to the normal of this projecting plane. Thus, we have

\[ N \cdot n = 0 \quad (5) \]

The direction of the vertical pole is \((0,1,0) \) in the global coordinate system and is \((\cos \phi \sin \delta, \cos \phi \cos \delta, \sin \phi) \) in the camera coordinate system. Suppose the projecting line of the pole on the first image is \( u_p' = m v_p' + t_1 \), then according to Eq. (5), we get

\[ (\cos \phi \sin \delta, \cos \phi \cos \delta, \sin \phi) \cdot (F_1, -mF_1, -t_1) = 0 \quad (6) \]

From this equation, we have

\[ \tan \phi = \frac{F_1 \sin \delta - mF_1 \cos \delta}{t_1} \quad (7) \]

Let \( A_{1p} = B_{1p} = C_{1p} = 0 \) and \( A_{1p} = B_{1p} = C_{1p} = 0 \) be the projecting equations of the left and the right road boundaries on the first image, respectively. Similar to the derivation of Eq. (4), we know the normal vectors of their projecting planes are \( N_{1p} = (F_1 A_{1p}, F_1 B_{1p}, C_{1p}) \) and \( N_{1p} = (F_1 A_{1p}, F_1 B_{1p}, C_{1p}) \), respectively. The direction of the left road boundary is perpendicular to the normal of its projecting plane and so does the right one. However, these two boundaries are parallel to each other. As a result, the direction, \( (A, B, C) \), of road boundaries relative to camera coordinate system is the cross product of the normals of these two projecting planes,

\[ (A, B, C) = (F_1 A_{1p}, F_1 B_{1p}, C_{1p}) \times (F_1 A_{1p}, F_1 B_{1p}, C_{1p}) \]

Since the road boundaries is perpendicular to the vertical pole, we get

\[ A \cos \phi \sin \delta + B \cos \phi \cos \delta + C \sin \phi = 0 \quad (8) \]
\[
\tan \phi = \frac{A \sin \delta + B \cos \delta - C}{-C}
\] (9)

Combining Eqs. (7) and (9), we derive
\[
\tan \delta = \frac{m_1C_{F_1} - B_{t_1}}{A_{t_1} + F_1C}
\] (10)

where \( A = F_1(B_cC_{1r} - B_dC_{1l}), \) \( B = F_1(A_cC_{1r} - A_dC_{1l}), \) and \( C = F_1^2(A_dB_{1r} - A_dB_{1l}). \)

In the right part of the above equation, the variables, \( m_1, \ t_1, \ A_{t_1}, \ B_{t_1}, \ C_{1r}, \ A_{t_1}, \ B_{t_1}, \) and \( C_{1r} \) can be computed by applying the image processing techniques. Therefore, we can compute the swing angle \( \delta. \) The tilt angle can be found by substituting \( \delta \) into (7) or (9).

### 2.3.2 Finding the pan angle

#### Part 1. Finding the pan angle with two images

In an image, there exists a vanishing point of the two parallel road boundaries as long as the image plane is not parallel to the ground. We can calculate the coordinate, \((u_0, v_0)\), of the vanishing point by finding the intersection point of this two projecting lines. In 3D space the parallel lines meet only at infinity, so the vanishing point can be taken as the projection of a point at infinity. Let the direction of a line in 3D space be specified by the vector \((A, B, C)\) with respect to the camera coordinate system. The vanishing point \((u_0, v_0)\) is obtained as follows:

\[
u_0 = \frac{F_A}{C}, \quad (11-a)
\]

\[
v_1 = \frac{F_B}{C}.
\] (11-b)

The direction of the road boundaries is \((x, 0, z)\), where \(x\) and \(z\) are unknown and constant, with respect to the global coordinate system and is

\[
(A, B, C) = (x, 0, z) \cdot \begin{bmatrix} a & d & g \\ b & e & h \\ c & f & i \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{bmatrix}
\]

\[
= (ax + cz, dx + fz, -gx - iz)
\] (12)

with respect to the camera coordinate system. In the first image, from Eqs. (11-a) and (12), we have

\[
x = \frac{-F_{c}u_{c} + u_{d}}{F_{d} + u_{g}}.
\] (13-a)

In the same way, from Eqs. (11-b) and (12), we get

\[
x = \frac{-F_{d}v_{d} + v_{g}}{F_{d} + v_{g}}.
\] (13-b)

Up to now, the unknowns of the right part of Eq. (13) are \( c, d, g, f, \) and \( d \), which all depend on the only unknown variable, pan angle \( \theta. \) Let \( \theta_1, 0 \leq \theta_1 \leq \pi/2, \) denote the angle between the moving direction of the ALV and the road boundaries. In (13), the value of \( x/z \) is

\[
x/z = \pm \tan \theta_1.
\]

The equation with the negative sign is adopted when the ALV translates front–rightwards. If we can find the angle \( \theta_1 \), the pan angle can be solved immediately.

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**Fig. 1.** The ALV moves front–rightwards and selects the right road boundary to derive \( \theta_1. \) (a) The top view. (b) The front view.

We derive the angle \( \theta_1 \) by using the projections of one of road boundaries on two consecutive images. Let the projection equation of the right road boundary on the second image be denoted as

\[
A_{2} \mu_{x} + B_{2} \nu_{y} + C_{2} = 0.
\]

\( M_1 \) and \( M_2 \) represent the projecting planes of the right road boundary which we choose to be the object for deriving the pan angle at time \( T_1 \) and \( T_2 \), respectively. Fig. 1(a) is the top view when the ALV moves from time \( T_1 \) to time \( T_2 \). The parallel lines represent the road boundaries. Points \( P_1 \) and \( P_2 \) represent the camera locations at time \( T_1 \) and \( T_2 \), respectively. The front view is shown in Fig. 1(b), where \( P_1P_2 \), the intersection of plane \( M_1 \) and plane \( \pi \) and \( P_1P_2 \), does that of planes \( M_2 \) and \( \pi \). In this diagram, we use other notations. \( N_1 \) denotes the normal vector of the projecting plane \( M_1 \), \( N_2 \), the normal vector of the projecting plane \( M_2 \), and \( N_3 \), the normal vector, \((b, e, -h)\), of the ground; \( \theta_2, \theta_1, \) and \( \theta_1 \) represent the angle between the projecting planes \( M_1 \) and \( M_2 \), \( M_2 \) and the normal of the ground, and \( M_1 \) and the ground, respectively; \( d_1 \) and \( d_2 \) are the distance between the camera and the right road boundary at time \( T_1 \) and \( T_2 \), respectively.

The angle between the vectors \( N_1 \) and \( N_2 \) is the same as the angle between the projecting planes \( M_1 \) and \( M_2 \). Thus, we can get \( \theta_1, \theta_2, \) and \( \theta_1 \) as follows:
\[ \theta_2 = \cos^{-1} \left( \frac{N_1 \cdot N_2}{|N_1| \cdot |N_2|} \right), \tag{14.a} \]
\[ \theta_3 = \frac{\pi}{2} - \cos^{-1} \left( \frac{N_2 \cdot N_1}{|N_2| \cdot |N_1|} \right), \tag{14.b} \]
\[ \theta_4 = \frac{\pi}{2} - \theta_2 - \theta_3. \tag{14.c} \]

Here, vectors \( N_1 \) and \( N_2 \) are obtained from the projection equations of the right road boundary in the first and the second images, respectively, and vector \( N_3 \) is \((0, 1, 0)\) in the global coordinate system. Therefore, we can compute \( \theta_2, \theta_3, \) and \( \theta_4 \) from Eq. (14).

The law of sines can be applied to triangle \( P_1P_2B_1 \). It yields
\[ \frac{t_2 \sin \theta_1}{\sin \theta_2} = \frac{2}{\sin (\frac{\pi}{2} - \theta_2 - \theta_3)} \tag{15} \]
From the right-angled triangle \( P_1P_2B_1 \), we have
\[ \sin (\theta_2 + \theta_3) = \frac{y_0}{d_2}, \tag{16} \]
where \( y_0 \) is the height of the camera. By (15) and (16),
\[ \sin \theta_1 = \frac{y_0 \sin \theta_1}{t_2 \sin (\theta_2 + \theta_3) \cos (\theta_2 + \theta_3)} \tag{17} \]
where \( y_0 \) and \( t_2 \) are known in advance and \( \theta_2, \theta_3, \) and \( \theta_4 \) are computed from Eq. (14), so the angle \( \theta_1 \) can be computed.

For convenience, let \( k = \tan \theta_1 \) or \( k = -\tan \theta_1 \), depending on the moving direction of the ALV. Equation (13.a) can be rewritten as
\[ F_1 c + u_i d + F_1 k a + u_i k g = 0. \tag{18} \]

Substituting relation (1) into (18), we obtain
\[ \tan \theta = \frac{F_1 \sin \phi \sin \delta + u_i \cos \phi + E_1 \cos \delta}{F_1 \cos \delta - F_1 \sin \phi \sin \delta - u_i k \cos \phi} \tag{19-a} \]
In the same manner, from relation (1) and (13-b), we get
\[ \tan \theta = \frac{F_1 \sin \phi \cos \delta + u_i \sin \phi - F_1 k \sin \phi \cos \delta}{F_1 \cos \delta + F_1 k \sin \phi \cos \delta + v_i k \sin \phi} \tag{19-b} \]

After obtaining the vanishing point, \((u_0, v_0)\), and \( \theta_1 \) from the first two images, we can solve the pan angle \( \theta \) from either Eq. (19-a) or (19-b).

So far, we have found the pan angle by using the projection equations of the right road boundary on two consecutive frames when the ALV moves front–rightwards. When the ALV translates in other directions, we can derive similar results.

When the angle \( \theta_1 \) is large enough such that the variations of the projection of the road boundaries between two images are apparent, we need only two frames to decide the pan angle. If the variation is little, we can not extract the line features reliably. Hence, the role of road boundaries is useless for finding the pan angle. As the moving direction is parallel to the road boundaries, we can find the pan angle by using only one image. When the angle \( \theta_1 \) equals zero, the left part of Eqs. (13) are zeros also. Therefore, we have
\[ \tan \theta = \frac{F_1 \sin \phi \sin \delta + u_i \cos \phi}{F_1 \cos \delta} \]
or
\[ \tan \theta = \frac{-(F_1 \sin \phi \cos \delta + v_i \cos \phi)}{F_1 \sin \delta}. \]

**Part 2. Finding the pan angle with three images**

From the previous assumption, the \( x \) and \( z \) components of the points on the vertical pole are zeros. The points on the vertical pole can be represented by \((0, y, 0)\), where \( y \) is a finite, small and positive value which is the unknown length of the pole. The transformation of these points is
\[ (u, v, w, 1) = (0, y, 0, 1) \cdot \mathbf{T} \tag{24} \]

Using Eqs. (2-a) and (24), we obtain
\[ u_p = F_1 \left[ (by - (ax_0 + bx_0 + cz_0)) \right] - hy + \left( (bx_0 + hy_0 + iz_0) \right). \tag{25} \]

In a similar way, using Eqs. (2-b) and (24), we obtain
\[ v_p = F_1 \left[ (ey - (dx_0 + cx_0 + fz_0)) \right] - hy + \left( (bx_0 + hy_0 + iz_0) \right). \tag{26} \]

Combining (25) and (26), it yields
\[ (-cx_0 + az_0)u_p + (-fx_0 + dz_0)v_p + F_1(x_0 - z_0) = 0 \tag{27} \]

After rewriting Eq. (27) into the form \( u_p = m_1 v_p + l_1 \), we have:
\[ m_1 = \frac{-fx_0 + dz_0}{cx_0 - az_0}, \quad l_1 = \frac{F_1(x_0 - z_0)}{cx_0 - az_0} \tag{28} \]

When the ALV is moving in the negative \( z \) direction, the new location of the camera is at \((x_0, y_0, z_0 - t_2)\) in the global coordinate system at time \( t_2 \) and the pan, tilt and swing angles will not be changed. By the same process, there exists the following two equations:
\[ m_2 = \frac{-fx_0 + dx_0 - az_0}{cx_0 - az_0}, \quad l_2 = \frac{F_1(x_0 - g(z_0 - t_2))}{cx_0 - az_0} \tag{29} \]

There are four equations, (28) and (29), and three unknowns \( x_0, z_0, \) and \( g \), which are embedded in \( a, c, f, d, i, \) and \( g \). But it can be easily proved that the former parts are dependent and so are the latter parts. Thus there are only two independent equations, so it is not sufficient to obtain the above three unknowns. To find the solution, one more equation must be added. We use a third frame...
to cope with this problem. At time $t_3$, the new camera location is assumed at $(x_0, y_0, z_0 - tz_3)$. Thus, we have

$$m_3 = \frac{-f_0 + d(z_0 - tz_3)}{cx_0 - a(z_0 - tz_3)}, \quad t_3 = \frac{F_3[x_0 - g(z_0 - tz_3)]}{cx_0 - a(z_0 - tz_3)} \tag{30}$$

We choose the equations for $t$ to solve this problem because the difference among $t_1$, $t_2$, and $t_3$ is more apparent than that of $m_1$, $m_2$, and $m_3$ on the image planes.

After eliminating $x_0 - az_0$ and $cx_0 - az_0$, we get

$$\frac{(t_2 - t_3)\alpha}{(t_1 - t_3)\alpha} \cos \delta = \frac{(F_k - F_j)g - \beta}{(F_k^2 - F_j^2)g}, \tag{31}$$

where $k = \frac{r_3}{r_1}$. Substituting (1) into the equation, we have

$$\tan \theta = \frac{-(t_1 - t_2)\cos \delta}{(t_1 - t_2)\sin \phi \sin \delta + (F_k - F_j)\cos \phi} \tag{32}$$

In Eq. (32), variable $k$ is obtained after $t_1$, $t_2$, and $t_3$ are computed from these three images; and angles $\phi$ and $\delta$ are computed from previous equations. Therefore, the pan angle $\theta$ can be solved.

### 2.3.3 Finding $x_0$ and $z_0$

Here, we use the difference of $u_0$ - intercept of the projection of the pole between two or among three frames to obtain these two translational parameters. Two equations are sufficient to solve these parameters because there are only two unknowns, $x_0$ and $z_0$.

For convenience, we rewrite (28-b), (29-b), and (30-b) as

$$\begin{align*}
(t_k - F_0)x_0 + (F_k - t_0)z_0 &= 0, \quad (33-a) \\
(t_k - F_0)x_0 + (F_k - t_0)z_0 &= (F_k - t_0)x_0, \quad (33-b) \\
(t_k - F_0)x_0 + (F_k - t_0)z_0 &= (F_k - t_0)z_2, \quad (33-c)
\end{align*}$$

respectively. These three equations have only two unknowns, $x_0$ and $z_0$. The above three equations are all independent of $y_0$, which makes $y_0$ unsolvable. Thus, we assume $y_0$ is known in advance. By the pseudo-inverse method, we can solve for $(x_0, z_0)$.

### 3. Extraction of Line Features

In this section, we will discuss the methods to extract the projections of calibration objects in the images under some reasonable conditions and then to compute the coefficients of line equations, which are taken as the input data for computing the camera parameters.

The Sobel edge detector is first used to compute the magnitude and direction of the gradient at each point. Then pixels with gradient magnitudes greater than the threshold value are declared as edge points. The features we are interested are the projections of vertical edges or road boundaries. If the projections of road boundaries are nearly horizontal, the pan angle approximately to 90° or the angle between the moving direction of the ALV and the direction of road boundaries is very large. The above cases are impossible in the real condition. Thus, we can remove the edge points whose direction values are smaller than 15° or larger than 165°.

Next, we draw the histogram of the direction angles of the resulting edge points. After the processing of Sobel operator, there are two peak values corresponding to the two line segments. When applying the Hough transform, we need only check the range of angle $\theta$. To find the line equation, we apply the least-square-error method.

### 4. Simulation and Experimental Results

In order to verify the theoretical derivation of the camera models, several simulations and experiments are carried out. To simplify the simulation process, the focal length of the camera is fixed and assumed to be 55mm.

The steps for generating the straight lines in an image plane are specifying the correct parameters, generating 100 points for each line, and computing the line parameters by using the least-square-error method.

The the results are shown in Table 1, where the left column specifies the parameters increasingly. The reference value of each parameter is shown on the top row.

The imaginary ALV moves front-rightwards and uses the right road boundary to find the pan angle. The distances during taking any two images are all 3 meters and the width of the road is 4.74 meters.

The proposed method is applied on the corridor. To simplify the experimental process, the focal length of the camera is fixed in 9mm. In the experiment, the camera is mounted on a tripod and is moved by an artificial method. Three consecutive images are shown in Fig. 2(a)-(c). Fig. 2(d) displays the results after applying Sobel operator and applying the Hough transform.

The orientation parameters of the camera are not known accurately in advance. Several experiments with consecutive images are made, the reference $x_0$ and $z_0$ are 178.0cm and 716cm, respectively. All the computed orientation parameters are in reasonable range and the best computed $x_0$ and $z_0$ are 164.3cm and 697.5cm, respectively.

### Table 1 Simulation results by using two images

<table>
<thead>
<tr>
<th>Pan Angle (°)</th>
<th>$\theta$</th>
<th>$\Phi$ (°)</th>
<th>$\delta$ (°)</th>
<th>$x_0$ (3m)</th>
<th>$z_0$ (20m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-30°</td>
<td>-29.75</td>
<td>-20.05</td>
<td>9.99</td>
<td>3.10</td>
<td>20.26</td>
</tr>
<tr>
<td>0°</td>
<td>0.14</td>
<td>-20.04</td>
<td>9.98</td>
<td>3.04</td>
<td>20.19</td>
</tr>
<tr>
<td>30°</td>
<td>30.27</td>
<td>-20.02</td>
<td>9.96</td>
<td>3.12</td>
<td>20.28</td>
</tr>
<tr>
<td>Average</td>
<td>1.07%</td>
<td>0.20%</td>
<td>0.23%</td>
<td>2.88%</td>
<td>1.19%</td>
</tr>
</tbody>
</table>

(a) The pan angle is changed from -30° to +30°.
The tile angle is changed from $-25^\circ$ to $-5^\circ$.

<table>
<thead>
<tr>
<th>tilt</th>
<th>$\theta$ ($10^\circ$)</th>
<th>$\Phi$ ($^\circ$)</th>
<th>$\delta$ ($^\circ$)</th>
<th>$x_0$ (3m)</th>
<th>$x_0$ (20m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-25^\circ$</td>
<td>9.77</td>
<td>-25.04</td>
<td>-1.03</td>
<td>2.91</td>
<td>20.07</td>
</tr>
<tr>
<td>$-15^\circ$</td>
<td>9.58</td>
<td>-15.05</td>
<td>-1.00</td>
<td>2.81</td>
<td>19.80</td>
</tr>
<tr>
<td>$-5^\circ$</td>
<td>9.88</td>
<td>-5.01</td>
<td>-0.99</td>
<td>2.99</td>
<td>20.34</td>
</tr>
<tr>
<td>average</td>
<td>1.93%</td>
<td>0.29%</td>
<td>1.30%</td>
<td>3.04%</td>
<td>1.83%</td>
</tr>
</tbody>
</table>

The swing angle is changed from $-10^\circ$ to $10^\circ$.

<table>
<thead>
<tr>
<th>swing</th>
<th>$\delta$ ($5^\circ$)</th>
<th>$\Phi$ ($-25$)</th>
<th>$\delta$ ($^\circ$)</th>
<th>$x_0$ (4m)</th>
<th>$x_0$ (20m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-10^\circ$</td>
<td>5.02</td>
<td>-25.02</td>
<td>-10.07</td>
<td>3.90</td>
<td>19.71</td>
</tr>
<tr>
<td>$0^\circ$</td>
<td>4.98</td>
<td>-25.02</td>
<td>-0.05</td>
<td>3.92</td>
<td>19.85</td>
</tr>
<tr>
<td>$10^\circ$</td>
<td>4.87</td>
<td>-25.02</td>
<td>9.78</td>
<td>3.74</td>
<td>19.26</td>
</tr>
<tr>
<td>average</td>
<td>1.71%</td>
<td>0.07%</td>
<td>1.15%</td>
<td>2.90%</td>
<td>1.39%</td>
</tr>
</tbody>
</table>

Fig. 2. Three consecutive images for computing camera parameters. (a)-(c) The original images. (d) Lines extracted by applying the Hough transform.

5. Conclusions

In this paper, we have proposed a method to determine the camera models by using multiple frames. Because the calibration process may be required anytime and anywhere, it is impossible to place man-made special marks along the road. We select the road boundaries and the objects with vertical edges to be the calibration objects.

By using the property that the direction of a line in 3D space is perpendicular to the normal of the projecting plane, the swing and tilt angles can be found. Then, the pan angle can be derived algebraically by using the projections of vertical edges in two or three consecutive images. After finding these three parameters, we compute the translational parameters by using the projections of vertical edge in two or three images.

Further researches include applying the proposed calibration method in the outdoor environment and concentrating on the extraction of road boundaries and vertical edge in natural scene.

References