Camera Calibration Based on Perspective Geometry and Its Application in LDWS

Huarong Xu, Xiaodong Wang

Department of Computer Science and Technology
Xiamen University of Technology
Xiamen, China
E-mail: hrxu@xmut.edu.cn

Abstract

In this paper, we present a novel algorithm to calibrate cameras for lane departure warning system (LDWS). The algorithm only need a set of parallel lane markings and parallel lines perpendicular to the ground plane to determine the camera parameters such as the roll angle, the tilt angle, the pan angle and the focal length. Then with the camera height, the positions of objects in world space can be easily obtained from the image. We apply the proposed method to our lane departure warning system which monitors the distance between the car and road boundaries. Experiments show that the proposed method is easy to operate, and can achieve accurate results.

Keywords: camera calibration; lane departure warning; perspective geometry; vanishing point

1. Introduction

In recent years, vision-based intelligent driver assistance systems have been widely used such as lane departure warning system (LDWS). Generally, a LDWS is a mechanism designed to warn a driver when the vehicle begins to move out of its lane (unless a turn signal is on in that direction) on freeways or arterial roads. For the lane departure warning system the basic function is to extract the distance between the car and the lane markings. Therefore, Camera calibration is a necessary step in 3D computer vision in order to extract metric information from 2D images [1].

Many calibration methods have been proposed during the last few decades, we can classify those techniques roughly into two categories: traditional calibration methods, self-calibration methods. Traditional calibration methods are performed by a calibration object, whose geometry in 3D space is known. Then all camera parameters will be gotten by using image process and mathematical translation.
Traditional calibration methods can activate accuracy results, but they require special calibration apparatuses and an elaborate setup [2]. Besides, camera parameters are subject to random and sometimes significant disturbances due to motion, thermal affection, environmental variation, or other unpredictable factors, and thus, cameras must be repeatedly calibrated and it becomes a time-consuming labor to localize a large set of features at each time [3]. Self-calibration could calculate all the intrinsic parameters of the camera using only the information available in the images. However, the greatest shortcomings of self-calibration is the lack of robustness. Thus, most calibration methods utilize known features in a scene to estimate the camera parameters [4-7]. Paper [4] uses the periodicity of dashed lane markings and velocity information to determine the extrinsic camera parameters, however, the dashed lane marking based distance measurement is complex and lack accuracy. In [5], a method of the extrinsic parameters estimation based on minimizing an error function is proposed. But it still need special circle pattern to be placed on the ground plane in front of the car. In [6] and [7] lane marking based calibration methods are used. The accurate camera parameters can be obtained by using the extracted lane markings in each frame.

In this paper, a novel method is proposed to estimate the camera parameters. All we need beforehand is a few parallel line markings and parallel lines perpendicular to the ground plane such as the edges of buildings, buses, telegraph poles and so on. Then we manually marked the parallel lines to calculate the vanishing points. However, dynamic calibration can be achieved by integrating the automatic lane marking and edges recognition algorithms into the proposed method.

The rest of this paper is organized as follows. Section 2 presents the model of the camera, roadway geometry and derivation of camera calibration equations. Section 3 addresses the recovery of camera parameters, including the focal length, the tilt angle, and the pan angle. Experimental results are presented in Section 4; Section 5 summarizes the contribution of this paper and future developments.

2. THE PRINCIPAL OF PERSPECTIVE GEOMETRY FOR Camera Calibration

Camera calibration refers to the process of estimating a set of intrinsic and extrinsic parameters. The intrinsic camera parameters involve the internal camera geometric and optical characteristics, including the focal length, the image center, the skew angle, and the aspect ratio. For reducing calibration complexity and enhancing its effect, we make a natural assumption that the intrinsic camera parameters, except for the focal length, are constant. The extrinsic camera parameters relate the camera’s coordinated system to a world coordinate system and specify its position and orientation in space [3]. In this study we make an assumption that the road is planar and there are objects perpendicular to the ground in the scene, such as bus, the edges of buildings, telegraph poles and so on.

In [3], a simple camera model was presented to estimate lane projection. In this paper, this camera model is extended by considering the roll angle of the camera. Based on this new model, some techniques have been developed. Fig. 1 shows three coordinate systems utilized in our derivation: (1) the world coordinates system O-XYZ; (2) the camera coordinate system C-XcYcZc; (3) the camera-shift coordinate system O-Uvw. Fig.1 (a) depicts the bird view of the ground plane in the world coordinate system. Lines L1, L2 represent parallel lane markings, and point O is the origin of the world coordinate system on the road plane. L3, L4 represent the parallel lines that perpendicular to the ground plane. The pan angle \( \theta \) is the angle between the Y axis and lane markings. Fig.1(b) depicts the side view of the road scene, the camera is mounted on top of the windshield with the height h and tilted down an angle \( \varphi \) and rolled angle \( \beta \). The direction of CO is perpendicular to the image plane.
According to the perspective projection theory based on the pin-hole camera model, transformation from camera coordinate \((X_c, Y_c, Z_c)\) to image coordinate \((u, v)\) can be described as:

\[
\begin{align*}
    u &= -f \frac{X_c}{Z_c} \\
    v &= -f \frac{Y_c}{Z_c}
\end{align*}
\]  

(1)

Where, \(f\) denotes the focal length.

The camera-shift coordinate system can be obtained by first rotating the world coordinate system an angle \(\varphi\) around the X axis and then an angle \(\beta\) around the Y axis. So the relationship between the world coordinate system and the camera-shift coordinate system is given by:

\[
\begin{pmatrix}
    U \\
    V \\
    W
\end{pmatrix} = \begin{pmatrix}
    \cos \beta & 0 & \sin \beta \\
    0 & 1 & 0 \\
    -\sin \beta & 0 & \cos \beta
\end{pmatrix} \begin{pmatrix}
    0 \\
    \cos \varphi - \sin \varphi \\
    \sin \varphi & \cos \varphi
\end{pmatrix} \begin{pmatrix}
    X \\
    Y \\
    Z
\end{pmatrix}
\]  

(2)

Then we can get the camera’s coordinate system by shifting the camera-shift coordinate system from point O to point C along the vector OC:

\[
\begin{pmatrix}
    X_c \\
    Y_c \\
    Z_c
\end{pmatrix} = \begin{pmatrix}
    U \\
    W \\
    -V-F
\end{pmatrix} \begin{pmatrix}
    \cos \beta & \sin \beta & \sin \varphi & \cos \varphi \\
    -\sin \beta & \cos \beta & \cos \varphi & -\sin \varphi \\
    0 & -\cos \varphi & \cos \beta & \cos \varphi
\end{pmatrix} \begin{pmatrix}
    X \\
    Y \\
    Z
\end{pmatrix} \begin{pmatrix}
    0 \\
    0 \\
    F
\end{pmatrix}
\]  

(3)
The image coordinate system is shown in Fig. 1 (c), in which the rectangular region represents the sensing area of the image sensor. Solid lines represent the lines that can be observed by the camera. Dashed lines are the same lines as the solid lines that are out of the camera’s view and cannot be observed. Two pair of parallel lines Solid line L₁, L₂ and L₃, L₄ in Fig. 1 (a) are projected onto a set of lines in Fig. 1(c) that intersect at vanishing points \( V_{hp}(u_0, v_0) \) and \( V_{vp}(u'_0, v'_0) \). We will estimate the two vanishing points in the following description.

2.1 Vishing point \( V_{hp}(u_0, v_0) \) estimation:

Vishing point \( V_{hp} \) lie in the ground plane, so \( Z = 0 \), then apply (3) and (1) yields

\[
\begin{align*}
    u &= -f \frac{X_C}{Z_C} = -f \frac{X \cos \beta + Y \sin \beta \sin \phi}{-Y \cos \phi - F} \\
    v &= -f \frac{Y_C}{Z_C} = -f \frac{-X \sin \beta + Y \cos \beta \sin \phi}{-Y \cos \phi - F} 
\end{align*}
\]

Assuming that the \( V_{hp} \) lies at a position where \( Y \to \infty \) and \( X/Y = \tan \theta \) in the world space, we can obtain the \( V_{hp} \) by

\[
\begin{align*}
    u_0 &= \lim_{Y \to \infty} \left( -f \frac{X \cos \beta + Y \sin \beta \sin \phi}{-Y \cos \phi - F} \right) \\
        &= \lim_{Y \to \infty} \left( -f \frac{Y \tan \theta \cos \beta + Y \sin \beta \sin \phi}{-Y \cos \phi - F} \right) \\
        &= -f \tan \theta \cos \beta \sec \phi + f \sin \beta \tan \phi \\
    v_0 &= \lim_{Y \to \infty} \left( -f \frac{-X \sin \beta + Y \cos \beta \sin \phi}{-Y \cos \phi - F} \right) \\
        &= \lim_{Y \to \infty} \left( -f \frac{-Y \tan \theta \sin \beta + Y \cos \beta \sin \phi}{-Y \cos \phi - F} \right) \\
        &= -f \tan \theta \sin \beta \sec \phi + f \cos \beta \tan \phi 
\end{align*}
\]

2.2 Vishing point \( V_{vp}(u'_0, v'_0) \) estimation:

Assuming that the Vishing point lies at a position where \( Z \to \infty \) in the world space, From (1),(2), we can obtain the \( V_{vp} \) by

\[
\begin{align*}
    u &= -f \frac{X_C}{Z_C} = -f \frac{X \cos \beta + Y \sin \beta \sin \phi + Z \sin \beta \cos \phi}{-Y \cos \phi + Z \sin \phi - F} \\
    v &= -f \frac{Y_C}{Z_C} = -f \frac{-X \sin \beta + Y \cos \beta \sin \phi + Z \cos \beta \cos \phi}{-Y \cos \phi + Z \sin \phi - F} \\
    u'_0 &= \lim_{Z \to \infty} \left( -f \frac{X \cos \beta + Y \sin \beta \sin \phi + Z \sin \beta \cos \phi}{-Y \cos \phi + Z \sin \phi - F} \right) \\
        &= -f \sin \beta \cot \phi \\
    v'_0 &= \lim_{Z \to \infty} \left( -f \frac{X \sin \beta + Y \cos \beta \sin \phi + Z \cos \beta \cos \phi}{-Y \cos \phi + Z \sin \phi - F} \right) \\
        &= -f \cos \beta \cot \phi 
\end{align*}
\]
3. Algorithm Implementation of LDWS

Based on the camera model and some useful expressions presented in Section 2, in this section we estimate camera’s parameters, including \( f \), \( \theta \), \( \beta \) and \( \phi \). Then, we manually measure the camera’s height and give two calibration applications to illustrate the effectiveness of our proposed method.

3.1 Camera Parameter Estimation

Dividing (9) by (8), we have

\[
\frac{v'_0}{u'_0} = \cot \beta
\]

\[
\beta = \cot^{-1} \frac{v'_0}{u'_0}
\]

(10)

From (8), (9), we can get:

\[
\frac{v'_0}{\cot \phi} = -f \cos \beta
\]

\[
\frac{u'_0}{\cot \phi} = -f \sin \beta
\]

(11)

Then substituting (11) into (5) and (6), we obtain:

\[
u_0 + u'_0 \tan^2 \phi = -v'_0 \tan \theta \sin \phi \sec^2 \phi
\]

\[
v_0 + v'_0 \tan^2 \phi = u'_0 \tan \theta \sin \phi \sec^2 \phi
\]

(12)

(13)

Dividing (13) by (12), we obtain:

\[
\frac{v_0 + v'_0 \tan^2 \phi}{u_0 + u'_0 \tan^2 \phi} = -\frac{u'_0}{v'_0}
\]

\[
\phi = \tan^{-1} \left( -\frac{v_0 v'_0 - u_0 u'_0}{u'_0^2 + v'_0^2} \right)
\]

(14)

Substituting (10) and (15) into (9), we get the focal length:

\[
f = \frac{-v'_0}{\cos \beta \cot \phi}
\]

(16)

Substituting (10), (15) and (16) into (5), we get the pan angle:

\[
\theta = \tan^{-1} \frac{u_0 - f \sin \beta \tan \phi}{f \cos \beta \sec \phi}
\]

(17)

3.2 Lane Departure Measurement

The distance measurement is very important for a driver assistance system. For example, the distance between the lane marking and the host vehicle in Fig.2 (a), the distance from the host vehicle to the nearest vehicles in Fig.2 (b).

We assume that the two points to be measured are in the ground plane, which means we can ignore the Z value. After camera parameters have been recovered, we can transform the image coordinates \((u, v)\) into their 3-D coordinates \((X, Y, 0)\) using the camera calibration. Referring to (4), we have
\[ m = v \cos \phi - f \cos \beta \sin \phi \]
\[ n = u \cos \phi - f \sin \beta \sin \phi \]
\[ X = \frac{F u m - F u}{f n \sin \beta + f m \cos \beta} \]
\[ Y = \frac{f X \cos \beta - F u m}{u \cos \phi - f \sin \beta \sin \phi} \]

From Fig.1 (b) we can get the camera’s coordinate in world coordinate system \( O_c (0, -F, h) \), and the corresponding camera coordinates in the ground plane is \( O_{cp} (0, -F) \).

We extract the lane marking propose by [8], but we fit the lane marking using the linear equation, Then the lane marking is translated to the world coordinate by (18), here we assume the lane marking in the world coordinate system can be describe as: \( Ax + By + C = 0 \).

As described in Fig.2 (a) the distance between the lane marking and the bottom edge of the vehicle will be

\[ \frac{|-BF + C|}{\sqrt{A^2 + B^2}} - w \]

Where, \(-w\) is the half width of the host car.

3.3 Distance of Vehicles Measurement

The inter-vehicle distance from the driving vehicle to a preceding vehicle is a prerequisite for driver assistance systems, such as collision warning and avoidance. After camera calibration we can get the distance of vehicles as follow. Firstly, the vehicles are detected by the method proposed in [9]. After the vehicles are detected, we only choose the most nearest vehicle as the object to be processed. Then we get the image coordinates come from the bottom edges of the vehicle blobs and translate the coordinate into the world coordinate system in the ground plane \( O_v (X_v, Y_v) \).

So the distance of the vehicles is

\[ |O_{cp} - O_v| - d = \sqrt{X_v^2 + (Y_v + F)^2} - d \]

Where, \( d \) is the distance between camera center and front edge of the host vehicle.
4. Experiment results

In experiment, the evaluation of the presented calibration method is divided into three parts: calibration parameters, lane departure and the distance of the vehicles. We first estimate these quantities, then manually measure these quantities and make a comparison of the actual value and the estimations. Our experiment contains 781 frames with the resolution is 640*480, the host car is made parallel to the lane marking and the height of camera is 1.28m. Fig. 3 shows three frames in our experiment. (a) Is for camera parameters estimation, in which there are some lane markings and telegraph poles. (b) Shows the process of estimating the lane departure, the lane marking is automatically extracted. (c) Is for the distance of the vehicles estimation. The nearest vehicle in front of the host car is marked as our object to be processed.

Table 1 shows a set of result for calibration parameters. Tables 2 and 3 tabulate the values obtained for the lane departure and the distance of vehicles. Smaller errors near the host car in these estimations are obtained. This is probably due to the deviation of the camera.

Table 1 result for calibration parameters

| parameters | Estimate Value/Error |
|------------|----------------------|
| $f$        | 2244.18 +/- 7.14 (pixel) |
| $\beta$   | -1.89901 +/- 0.013 (degree) |
| $\theta$  | -0.672128 +/- 0.04 (degree) |
| $\phi$    | 2.424 +/- 0.02 (degree) |

Table 2 lane departure measurement results

| Index | Actual Value(mm) | Estimate Value(mm) | Error (%) |
|-------|------------------|--------------------|-----------|
| 1     | 522              | 501                | 3.27%     |
| 2     | 653              | 632                | 3.22%     |
| 3     | 1021             | 988                | 3.23%     |
| 4     | 1540             | 1490               | 3.25%     |
| 5     | 2178             | 2107               | 3.26%     |

Table 3 results for distance of vehicles

| Index | Actual Value(mm) | Estimate Value(mm) | Error (%) |
|-------|------------------|--------------------|-----------|
| 1     | 5201             | 5014               | 3.60%     |
| 2     | 6196             | 5972               | 3.62%     |
| 3     | 7109             | 6852               | 3.62%     |
| 4     | 8500             | 8189               | 3.66%     |
| 5     | 9859             | 9494               | 3.70%     |
5. Conclusion

A novel camera calibration method based on the lane marking and buildings is proposed. The method exhibits the advantage that no special calibration patterns are required. The method only needs the height of camera, lane marking in the road and buildings containing two edges perpendicular to the ground plane. Experiments and applications results illustrate the effectiveness of the algorithm.

In the future, the algorithm can automatically use a set of parallel lane markings and building edge to compute the camera parameters must be study, and the effect of lens distortion and nonfixed principal point needs to be handled to increase the accuracy of camera calibration.

Acknowledgements

This work was supported by Xiamen Science and Technology Planning Project (Grant Nos. 3502Z20103035), the Open Project Program of the National Laboratory of Pattern Recognition (NLPR, grant No. 201001024).

References

[1] Meng W, Xiangjing A. An Automatic Extrinsic Parameter Calibration Method for Camera-on-vehicle on Structured Road. In: Proceedings of IEEE International Conference on Vehicular Electronics on Safety, 2007, pp:1-5

[2] Jin Sun, Hongbin Gu. Research of Linear Camera Calibration Based on Planar Pattern. World Academy of Science. Engineering and Technology 60 2009.PP:627-631

[3] Kunfeng W, Hua H, Yuantao L, et al. Research on Lane-Marking Line Based Camera Calibration. In: Proceedings of the Vehicular Electronics and Safety, Beijing, CHINA:IEEE, 2007, pp:1-6

[4] Stephanie H, Steffen G, Anton K, et al. A Novel Approach for the Online Initial Calibration of Extrinsic Parameters for a Car-Mounted Camera. In: Proceedings of the Intelligent Transportation Systems, St. Louis, MO, USA:IEEE, 2009, pp:420-425

[5] Stephanie H, Christian N, Anton K. Efficient and Robust Extrinsic Camera Calibration Procedure for Lane Departure Warning. In: Proceedings of the Intelligent Vehicles Symposium, 2009, pp:382-387

[6] Bing-Fei W, Chuan-Tsai L, Yen-Lin C. Dynamic Calibration and Occlusion Handling Algorithms for Lane Tracking. In: Proceedings of the Industrial Electronics Society, 2009, pp: 1757 - 1773

[7] Todd N. S, Daniel J. D. Dynamic camera calibration of roadside traffic management cameras for vehicle speed estimation. In: Proceedings of the intelligent transportation systems, 2003, pp:90-98

[8] Kaohsiung. Edge-based Lane Change Detection and its Application to Suspicious Driving Behavior Analysis. In: Proceedings of Information Hiding and Multimedia Signal Processing, 2007, pp:415-418

[9] Banggui Z, Bingxiang T, Jianmin D. Automatic Detection Technique of Preceding Lane and Vehicle. In: Proceedings of the Automation and Logistics, Qingdao, CHINA: IEEE, 2008, pp:1370-1375