13-26

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Lane Detection and Tracking through Affine Rectification

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Abstract

Inversion of the perspective mapping in acquired images enables an autonomous vehicle to perform vision-based navigation tasks, such as obstacle detection. We present work on affine rectification that restores the parallel property of a traffic lane, using the vanishing point of equally spaced parallel lane boundaries. Experimental results demonstrate the potential of our new algorithm.

1. Introduction

Intelligent vehicles are especially useful in applications when there are potential risks to human operators. There has been considerable recent interest in testing autonomous vehicles in real-world scenarios, as reflected for instance by the response to the DARPA Grand Challenges [12] in the U.S. The key to autonomous vehicles is navigation based on perceived environmental information [10]. In vision-based navigation systems, cameras mounted on the vehicles provide data to the path finding and planning modules.

Previous approaches that apply computer vision to vehicular navigation are often based on a stereo-vision architecture, such as the Generic Obstacle and Lane Detection (GOLD) system [8]. Assuming the intrinsic parameters of the cameras are known, an elaborate geometrical transformation was derived to undo the perspective effect from both left and right stereo images. As a result, the parallelism property of roads is recovered. The remapped stereo images are used for the detection of free-space in front of the vehicle.

Wang et al. [6] proposed a model-based lane detection and tracking algorithm using B-Snake. The mid-line of the lane is detected by using prior knowledge of the perspective parallel lines. They used B-Spline to model the lane shape based on a set of control points, which are determined by the overall forces on two sides of the lane. Their experimental results show that this method is robust against shadows and illumination variations in practice. However, the choice of the set of control points is not straightforward. In addition, the mid-line must first be determined.

A fundamental problem in analyzing images before inverting the perspective mapping is to reliably identify the lane markings of a road. As in other machine vision tasks, false positives from edge detectors must be eliminated. An effective strategy is to identify those lines that are parallel in the scene to be correct lane boundaries. In an affine space, lines that are parallel in the 3D scene are restored to be parallel. We propose a solution by introducing an affine rectification based on equally spaced parallel lane boundaries. The assumptions of our work are as follows.

1. Road lane markings are locally straight and are sufficiently well marked to be extracted by intensity edge detectors.
2. The road surface is at least locally flat, so that the straight lanes lie in one world plane and converge into a vanishing point.
3. Each roadway has at least two lanes with equal widths; i.e., the three lane boundaries of two adjacent lanes are equally spaced. When the road lanes are straight, the boundaries are parallel.

We first detect all possible edges in the captured images. The straight lanes are extracted as straight lines, which generate a vanishing point. Further, we can recover the vanishing line on the road plane from equally spaced parallel lanes. Then, the affine space can be recovered through vanishing line. Those detected lines with equal between-line distance, in the affine space, will be regarded as the road lanes.

2. Detection of Road Lane Boundaries

Our algorithm to detect the boundaries of road lanes consists of the following steps:

(1) Compute the edge maps for given images using the Canny edge detector. Fit straight lines in the edge maps through least-square method. Compute the vanishing point of road plane, which is the most dense intersection point between lines.
(2) Group those lines that generate a vanishing point by the dot product of their unit direction vectors.
(3) Choose three lines that are assumed to be equally-spaced parallel lines in scene space from three line

groups and compute the vanishing line from these three lines. Compute the affine rectification of original images.

(4) Those lines with equal between-line distance in affine space will be picked as lane boundaries. If these lines are straight, then they will become parallel and meet at infinity.

Step (1) involves basic machine vision algorithms. In the following, we describe the details of steps (2) to (4).

2.1 Grouping of straight lines

Parallel lines in the scene space meet at a vanishing point on the image plane. The vanishing point is at infinity when the projections of the parallel lines are still parallel. Vanishing points provide much useful information for 3D structure of a scene [1,2,9]. They can, for instance, be used to determine the transformation for an affine rectification [3]. Two vanishing points define a vanishing line. The affine rectification is realized by projecting the finite vanishing line into infinity. For lane detection, parallel lane boundaries or markings generate vanishing points. Since the lane markings are rectangles with one edge very long and one edge being possibly defined by a series of short lines, there may be several lines detected for one lane through edge detectors. So we need to group those lines from the same lane into one line group. The line similarity between two lines can be defined as the absolute value of dot product between their unit directions. The similarity increases as the dot product goes from 0 to 1.

2.2 Affine rectification from three equally spaced parallel lines

Given two vanishing points, we can recover the corresponding vanishing line. In images of views depicting the road ahead, one vanishing point can be easily determined; however, due to the limited field of view, two vanishing points do not always exist. Nevertheless, we can recover the vanishing line through three equally spaced parallel lines, which always exists for road lanes.

There is a planar homography between world plane and its image; furthermore, there is a planar homography among planar surfaces taken from different viewpoints [3,5], viz.

$$\mathbf{x}' = H\mathbf{x} \tag{1}$$

where $\mathbf{x}$ and $\mathbf{x}'$ are the homogeneous coordinates of the projections of a three-dimensional point X on a world plane in the first and second images, respectively. The 3 by 3 homography H can be decomposed as a product of a similarity matrix S, an affine matrix A, and a pure projective matrix P [5]; i.e.,

$$H = SAP. \tag{2}$$

In order to remove projective property and recover the affine space, we need to determine the pure projective transformation P. From [3,4], P is defined as

$$P = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ l_1 & l_2 & l_3 \end{pmatrix} \tag{3}$$

where $\mathbf{l}_\infty = [l_1 \quad l_2 \quad l_3]^T$ is the vanishing line of the plane.

The vanishing line is typically determined as the line joining two vanishing points. An alternative is that given three equally-space parallel lines $\mathbf{l}_1$, $\mathbf{l}_2$, and $\mathbf{l}_3$, the vanishing line $\mathbf{l}_\infty$ can be calculated as [7],

$$\mathbf{l}_\infty = \det(B)\mathbf{l}_3 - \det(C)\mathbf{l}_1 \tag{4}$$

where $B = [\mathbf{l}_1, \ \mathbf{l}_2, \ \mathbf{l}_a]$ and $C = [\mathbf{l}_a, \ \mathbf{l}_2, \ \mathbf{l}_3]$. Here, $\mathbf{l}_a$ can be any 3×1 vector chosen such that $\det(B) \neq 0$ and $\det(C) \neq 0$. In our lane perspective projection from visual-based navigation, those lanes do not intersect at infinity. So we can define $\mathbf{l}_a = [0 \quad 0 \quad 1]^T$, which is the line at infinity.

2.3 Verification of parallelism in affine space

By applying $D = P^{-1}$ transformation on the original image, we can transform the projective space into the affine space. The parallelism or equal between-line distance properties can be recovered in affine space.

Given two points $\mathbf{x}_1$ and $\mathbf{x}_2$ in the original image space, defining a line $\mathbf{l}_o = \mathbf{x}_1 \times \mathbf{x}_2$. After we apply $D = P^{-1}$ transformation on the original image, we can obtain the corresponding line $\mathbf{l}_o'$ of $\mathbf{l}_o$ in the affine space as

$$\mathbf{l}_o' = (D\mathbf{x}_1)\times(D\mathbf{x}_2) \cong D^{-T}(\mathbf{x}_1 \times \mathbf{x}_2) = D^{-T}\mathbf{l}_o, \tag{5}$$

where $\cong$ means "equal up to a scale".

In order to verify parallelism in affine space, we compute product of two lines. If their intersection meets at infinity, then they are parallel or equally between-line distant. They will be regarded as road lane boundaries. Given two lines $\mathbf{l}_1 = [a_1 \quad b_1 \quad c_1]^T$ and $\mathbf{l}_2 = [a_2 \quad b_2 \quad c_2]^T$; if $\mathbf{l}_1$ and $\mathbf{l}_2$ are parallel, then the third component of the intersection $\mathbf{p} = \mathbf{l}_1 \times \mathbf{l}_2$ is zero. In practice, because of the limited accuracies of edge detection and of line fitting, the third component of intersection is not exactly zero, but very small.

3. Experimental Results

We tested our algorithm on a number of pictures and present representative results here. Note that if the vanishing points and vanishing lines exist within the picture, then only a partial area of the picture can be shown in the affine rectification. This is because that affine transformation of any points in the vanishing line will be positioned at infinity. In Fig. 1, we show the first test image, which was taken from [11]. The edges and lines are extracted and shown in Fig. 2. The original size of the image is 388(pixels) by 268(pixels), and the affine rectification area is the rectangle bounded by the points [(1, 130), (388,268)], where the first pair is the coordinate of top-left corner of the rectangle and the second pair is the coordinate of bottom-right corner. In Fig. 4, we can see that three parallel lines in affine space, corresponding to three lines generating the vanishing point, are the detected lanes as in Fig. 3.

The original size of picture 2 (Fig. 5) is 300(pixels) by 197(pixels), and the affine rectification area is rectangle [(1,1), (300,197)]. Although this is not a road image, we are interested in testing whether the affine rectification performs well when the line groups are skewed to one side of an image. In Fig. 8, we show the affine rectification and can see that three parallel lines in affine space correspond to three lines generating the vanishing point are the detected lanes.

Figure 1. Test picture 1 from [11].

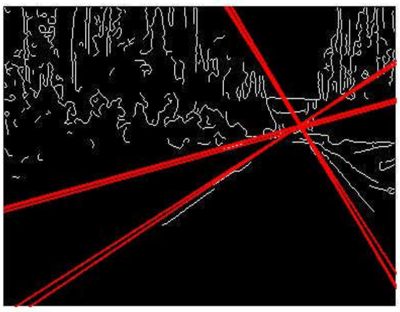

Figure 2. Canny edges and fitted straight lines extracted from Fig. 1.

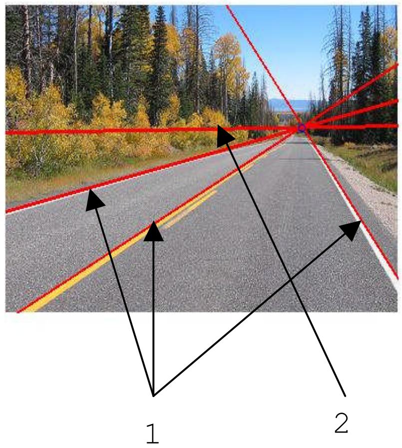

Figure 3. Vanishing line of Fig. 1. Three potential lanes (*labeled "1"*) from three line groups and the estimated vanishing line (*labeled "2"*).

Figure 4. Affine rectification recovers the original lanes in Fig. 1.

Figure 5. Test picture 2 from [13].

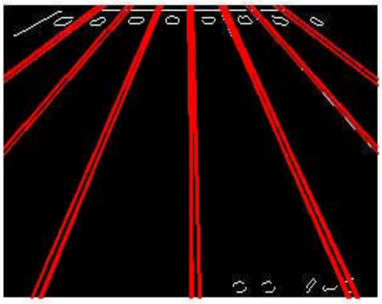

Figure 6. Canny edges and fitted straight lines extracted from Fig. 5.

Figure 7. The three leftmost lane markings are used as the three line groups. The estimated vanishing point and the estimated vanishing line are outside the image area.

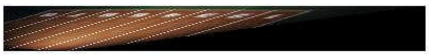

Figure 8. Affine rectification recovers the original lanes in Fig. 5.

4. Conclusions

In this paper, we gave an effective lane detection method using equally-spaced parallel lines. The first step of many machine vision algorithms for understanding road images is to extract edges from original images. Since edge detection is a low-level processing and does not contain high-level information, many false positives can result from such factors as shadows. A useful heuristic to accept potential lane boundaries is that they should be parallel on the 3D world plane. We demonstrated that we can perform this test in the rectified affine space.

Our preliminary experiments demonstrate the potential of our method. Our ongoing work includes further testing of the system and development to include a metric rectification. In addition, we are working on how to transform the original image such that we can reduce the within-image vanishing line influence and rectify more parts of the image using affine rectification.

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