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General-Purpose Road Boundary Detection with Stereo Camera

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Abstract

In this paper, we propose a simple general-purpose road boundary detection method, which can detect low height curbs, curved curbs, slopes, vegetation and ditches. Many conventional methods based on DEM (digital elevation map) can only deal with ordinary curbs because they use step-edge detection on the DEM. The proposed method detects height changes against road surface on several multi-directional scanning lines on a dense disparity map. Therefore it can detect a variety of road boundaries even with smooth edges and jagged boundaries. The experimental results show that our method can detect more kinds of road boundaries.

1 Introduction

Drivable area detection is necessary for autonomous driving systems and driver assistance systems, because they need to know where it is possible to go and where it is not. This is particularly needed in situations where lanes are not marked or where paint has faded. To detect the drivable area it is important to detect road boundaries, such as curbs, vegetation, gutters and ditches. There exist two issues related to detecting road boundaries:

First, the height of road boundary delimiters is generally low and thus difficult to detect, especially in countryside roads. In order to deal with this issue, we use a stereo camera, with a resolution that is higher than other ranging devices, and adopt a semi-global matching algorithm[4], which can provide a dense disparity output.

The second issue is the existence of a variety of road boundaries. There are many methods that deal only with ordinary curbs. However, there are few methods that are able to detect many types of road boundaries, such as vegetation, ditches, and so on.

Our approach is to deal with all possible kinds of road boundaries. Our contribution is as follows:

(1) A dedicated road edge detection approach which enables to detect not only curbs but also slopes, vegetation and ditches.

(2) A multi-directional scanning line extraction process which gives a spatially more precise road boundary detection and enables to detect curved or perpendicular road boundary to the driving direction.

The remaining of this paper is organized as follows: At first a presentation of related works on road boundary detection using stereo camera is given in Section 2. After that, the proposed method is presented in details in Section 3. Finally, the evaluation results are explained in Section 4.

Figure 1. Concept image of general-purpose road boundary detection, which enables to detect not only curbs but also slopes and vegetation, and curved or perpendicular road boundary to the driving direction.

2 Related Works

There are three types of approaches to detect road boundaries with stereo camera in the literature.

The first type [1][2][3] assumes that curbs are arranged in a linear manner. It adopts an edge detection on intensity images and uses Hough transform taking into account disparity information. [3] uses weighted Hough transform where the weight is the estimated curvature index on the range data. This type of methods is not suitable for curved curbs because of the linear assumption.

The second type [10][9] adopts a pattern matching approach. It estimates the position of curbs using the appearance of a curb. First it detects the nearest curb using either a first type method or a last type method. Then, it uses the appearance of the detected curb to extend the detection to faraway curbs using a pattern matching method. Therefore, we do not compare against this type of methods because our paper focuses not on the estimation of the position of road boundary but on its detection.

The last type [5][6][7][8] is based on digital elevation map which is created from disparity data. A digital elevation map (DEM), is a grid map having height values in each of its cells. Within the DEM, height edges are detected to determine the existence of curbs. This is a more general approach than the first type, with a better performance. However, it assumes that the shape of a curb is a step-edge, that there is no vegetation around, and that the adjacent sidewalk has the same height as the curb. As a result, this approach cannot deal with other kinds of road boundaries, such as slopes, vegetation and ditches.

In contrast, the proposed method can deal with curbs, slopes, plants and ditches, at the same time, using a dedicated edge detection method.

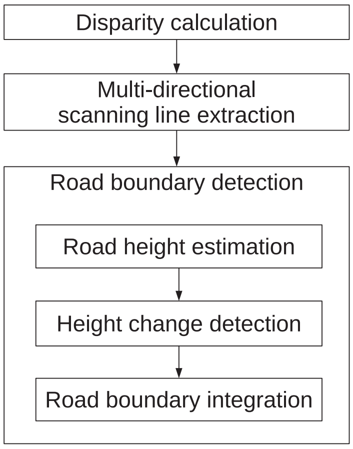

Figure 2. Processing flow of our proposed method.

3 Proposed Method

In order to detect all kinds of road boundaries, our proposed method consists of three processes: disparity calculation, multi-directional scanning line extraction, road boundary detection as shown in Figure 2.

As for the process of disparity estimation with stereo images, we use the semi-global matching[4] method that provides a dense disparity map.

After that, we extract multi-directional scanning lines, estimate the road height, detect height change on each scanning line and integrate them to road boundaries. Then, a 'winner takes all' mechanism allows determining accurately the location of road boundary. These processes will be present in details afterwards.

3.1 Multi-Directional Scanning Line Extraction

In general, one-directional scanning line is extracted perpendicular to the vehicle's traveling direction so as to detect road boundaries parallel to it. However there are curved curbs and perpendicular curbs to the traveling direction in public road, and often a leading vehicle in front of my own vehicle. Therefore a multi-directional scanning line is adopted instead.

Moreover the result of road boundary detection is largely influenced by the accuracy of disparity estimation if the scanning line is considered along a single direction. To improve the accuracy, it is important to integrate the detected road boundaries on each directional scanning line. For example, intensity of road paint in an image sometimes gets saturated and the accuracy of disparity on that region gets worse.

The scanning line is extracted at a different position and direction on two-dimensional space, a horizontal axis on image and a depth (disparity) axis. In this paper, the number of scanning lines for each direction is 60, and the position is arranged from 9[m] to 30[m]. The width of depth on each scanning line is 0.5[pixel]. The number of directions to consider is optimized in a preliminary investigation. An explanation image is depicted in Figure 3. It shows a disparity image where three-directional lines are emphasized.

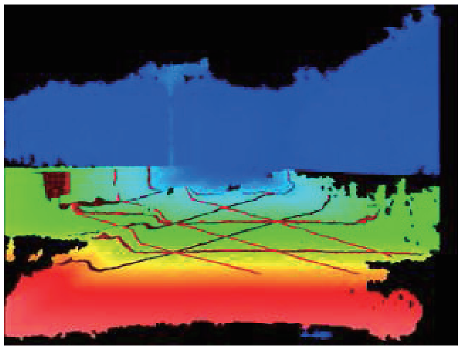

Figure 3. Concept image of multi-directional scanning line extraction, which shows three-directional lines: one perpendicular to traveling direction and two tilted ones.

3.2 Road Boundary Detection

In this process, candidate road boundaries are detected along each directional scanning line and integrated. This is divided into three processes: road height estimation, height change detection and road boundary integration.

3.2.1 Road height estimation

First of all, the height of road region is estimated for each scanning line. Our method assumes that road region is the area in front of the vehicle and a road profile is locally flat. We adopt two-dimensional principal component analysis, whose dimensions are scanning direction and surface height. The first eigenvector means dominant road angle and the second eigenvector means a variance of the height of all points. We use the inverse of the second eigenvalue as reliability value, which is the weight of integration among multiple candidate road boundaries.

3.2.2 Height change detection

Then, a candidate road boundary is detected if there is a large difference between the estimated road height and the height of a point on a scanning line. Figure 4 shows the concept image of this process. This detection approach covers not only positive road boundaries such as curbs and plants, but also negative road boundaries such as ditches, gutters, and so on. In case of negative road boundaries and curved positive boundaries, the backside of road boundary is occluded. Therefore this process is simple albeit being valid and practical.

3.2.3 Road boundary integration

For each detected candidate road boundary on a scanning line, the closest candidate road boundaries on other directional bands are extracted as well. Then, an integrated road boundary is estimated among these candidates. As an integration method, we compared two methods, a weighted average method and a 'winner-takes-all' method. The former is as follows:

$$\mathbf{p} = \sum_{i=1}^{n} \omega_i \cdot \mathbf{p}_i \qquad (1)$$

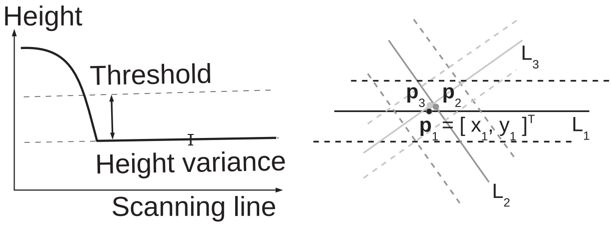

Figure 4. Concept image of height change detection (left) and integration among candidate road boundaries (right).

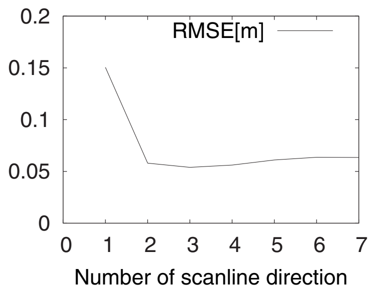

Figure 5. Performance results for several directional numbers of scanning lines

,where $\mathbf{p}$ means integrated road boundary position, $\mathbf{p}_i$ means candidate road boundary on each scanning line and n means the number of scanning line directions. The latter is as follows:

$$\mathbf{p} = \mathbf{p}_i, (i = arg\max_i \omega_i) \tag{2}$$

The set of estimated road boundaries is therefore the final output for the current disparity map.

4 Experimental Results

We evaluated the performance of the proposed method in comparison with that of a DEM-based method for different kinds of road boundaries, such as curbs, vegetation and ditches.

At first, we determined the most appropriate number for multi-directional scanning lines and the best integration method. Secondly, we evaluated the performance of the proposed method and the DEM based method. The performance indicators are the accuracy of detected position. Finally, some examples of detection results are shown as images.

4.1 Optimization

To determine the optimal number of multi-directional scanning lines, we considered a typical road boundary scene. Figure 5 shows the result of parameter optimization, and three-directional scanning line provided the best performance.

After that, We compared with two integration methods. Table 1 shows the performance results for two integration method. The 'winner-takes-all' method (WTA) provided better performance than weighted average method.

Table 1. Performance results for integration

Index	Weighted	WTA
MSRE [px]	7.55	5.20
MSRE [m]	0.11	0.06

Table 2. Evaluation results for various curbs

Method	Index	Curb	Veg.	Ditch
Proposed method	MSRE [px]	8.2	15.3	12.1
	MSRE [m]	0.07	0.16	0.18
DEM[5]	MSRE [px]	47.7	61.9	82.3
	MSRE [m]	0.35	0.37	0.37

In the next evaluation section these determined parameter and method were adopted.

4.2 Evaluation

We evaluated the proposed method in comparison with the DEM based method in terms of accuracy of detected position for the following road boundaries: curbs, vegetation, ditches and a roundabout centers. The accuracy metric of detected position is the root mean squared error (RMSE) of position. Our system uses a 1280x960 stereo camera placed behind the rear-view mirror, with a 10[Hz] frame rate. Table 2 shows the evaluation results. Especially for vegetation, ditches and an island at intersection, the proposed method performs better than DEM based method.

4.3 Discussion

Figure 6 shows examples of detection results in comparison with the conventional method, DEM[5]. The figures on the left show the results of the proposed method. The upper and lower ends of detected road boundaries are painted on the intensity images. On the other hand, the center and right figures show the results of DEM. In the digital elevation map, the intensity at each pixel means the height and the lines on the map means an estimated road boundary and several candidates. These results show that both methods can detect curbs, but only our method can detect vegetation, ditches and roundabout centers.

Curb: DEM based on Hough-transform cannot detect the road boundary because curbs are curved in this scene and it doesn't fit the linear model. Ordinary curbs in public road are about 20[cm] height, and the proposed method can detect it effectively.

Vegetation: The second row of images in Figure 6 show the detection result for plants or vegetation in general. The proposed method can detect plants in spite of their complicated shapes, while DEM method cannot detect them because road boundary is not straight and the height is also non-uniform. Our method can detect them because there is no particular assumption on the shape.

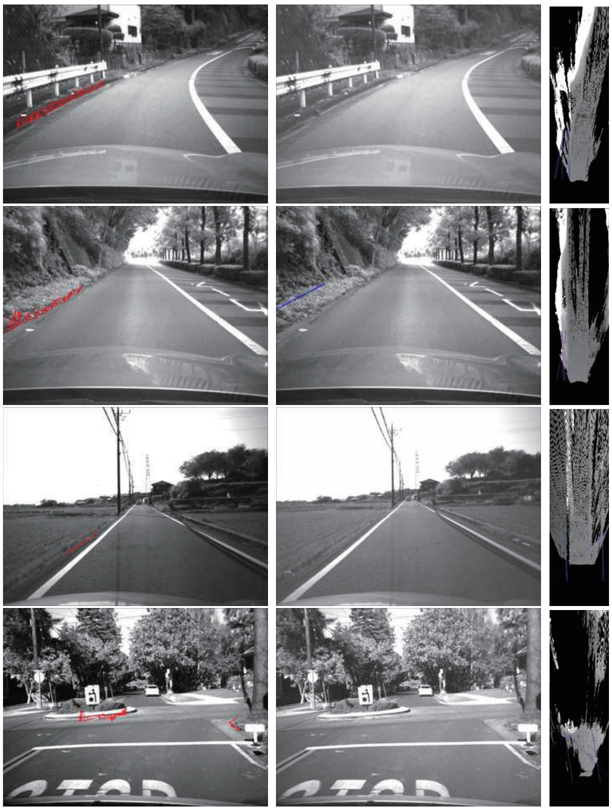

Figure 6. Detection results of proposed method (left) and DEM method (center/right). Road boundaries are curbs, vegetation, ditches and roundabout centers. (Best viewed in color)

Ditch: The third row of images in Figure 6 show the detection result for ditches. Our proposed method can detect negative road boundaries such as ditches. On the other hand, DEM method cannot detect them because disparity is not dense on the map due to occlusion with ditches as you can see the DEM results on the right. Our method can deal with ditches because we adopt a simple change of height approach.

Roundabout center: Images at the bottom in Figure 6 show the detection result for roundabout centers. Our method can detect perpendicular curbs to the driving direction, while DEM method cannot detect them because the center shape is not linear and doesn't fit the considered model.

4.4 Conclusion

The proposed method is a general-purpose road boundary detection, which can detect many kinds of road boundaries, such as curbs, vegetation and ditches.

In our method a dedicated edge detection technique is adopted, which is more effective than DEM based method for road boundaries except for step-edged shapes.

However, in order to use this output for vehicle control, a stable result is needed. The current implementation does not yet consider integration over time, which is believed to provide a more stable output. Such issues are considered in our future work.

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