Real-time Road Detection in 3D Point Clouds using Four Directions Scan Line Gradient Criterion

Ming Li, Qingquan Li

***Abstract*—Real-time road detection is the basic perceptual problem for autonomous vehicles. In urban environments, it must deal with the different scenes such as straight, curve, intersection and viaduct. Thus, the 3D geometry of the world must be considered. In this paper, we propose a method of Four Directions Scan Line Gradient Criterion *(4DSG)*. These features can not only reflect the flatness of pavement, but also reflect the distinguishing feature of point cloud on curbs in four directions. Since, the data units used to calculate the gradient is an 8-16 points, the data noise produced by vibration of autonomous vehicle can be suppressed in certain degree. Therefore, it is more stable and reliable than normal vectors, when the autonomous vehicle runs over the undulating ground. We evaluated the proposed algorithm in urban environment by SmartV-II, which is modified Chery Tiggo with the HDL-64 sensor mounted on the roof. The proposed approach has been used successfully for steering a car through narrow, dynamic urban roads. Objective test shows the recall rate is 3% performance improved compared with normal vector in different driving scenes.**

I. INTRODUCTION

Autonomous vehicle running in urban environments must contend with a number of challenging perceptual problems[1]. Roads detection is basic one, It not only explores where is road, but also distinguishes pavement form other ground such as curbs, sidewalk, ditches and so on, then deliver those information to path planner for controlling vehicle movement in real time.

Recently, the laser range finder had proven efficient for environment perception, as their resolution and field of view exceeds radar and ultrasonic sensors, providing more direct distance measurements than CCD camera[2].The 3D LiDAR have been introduced, which delivers *360 degree* horizontal field of view and *26.8* degree vertical field of view [3]. This sensors can providing more than 1 million points per second, detecting almost all directions of environment around it. Therefore it becomes the main sensor for autonomous vehicle in DARPA Urban Challenge 2007[4] and NSFC Future Challenge 2009[5].

In urban environments, road has different forms, straight, curve, intersection, viaduct and so on, and the surface of road also has undulating, separated from other grounds by curbs, ditches etc.. In order to distinguish road from other ground, its structure must be considered. Even if the autonomous vehicle has road network files (RNDF) and GPS to assisted moving control, the few autonomous vehicles still rushed on the sidewalk in the FC09, because they can not detect boundary of pavement robustly.

The moving vehicle will encounter a wide variety of static and moving obstacles in urban environments. The small drop off about 15cm may be detected by autonomous vehicle as a ditch and would reluctant to drive down. Thus, the 3D geometry of the world must be considered for driving in urban environments.

As sensors are mounted on moving vehicle, the vibration of autonomous vehicle itself will affect the detection the height of any objects. The features which use to detect road must be insensitive to those interference.

Therefore, we present a method of Four Directions Scan Line Gradient Criterion *(4DSG)*. The major contributions are:

First, these features can not only reflect the character of flatness of pavement, but also reflect the height variation of point cloud on curb in the four directions and used to detect road edge very well. Since, the data units used to calculate the gradient is an 8-16 points, the random noise of measurement errors can be suppressed in certain degree. And it is more stable and reliable than normal vectors, when the vehicle runs over the undulating, road.

Second, we also present road segment algorithm based sub-line classification. It not only segment road from point cloud, but also distinguishes pavement from other grounds. This algorithm works quite successfully even in urban environments.

This paper is organized as follows. In the next section we first give an outline of relevant works, followed by the detailed description of our approach. In section IV we provide experimental results. Section V concludes this paper and draws a conclusion.

II. PREVIOUS WORK

A simple algorithm for segment road from other objects in point cloud is to find points with similar x-y coordinates whose vertical displacement below a given threshold. However, range and calibration error are high enough so that

F. M. Li is with Wuhan University, Hubei, 430079, China. He is now with National Engineering Research Center of Multimedia Software （NERCMS） (corresponding author phone: 08627-62807329; E-mail: liming751218@whu.edu.cn).

S. Q. Li, was with Wuhan University, Wuhan, Hubei, 430079, China. He is now with the Transportation Research Center (TRC), Wuhan University, Wuhan, Hubei, 430079, China. (E-mail: qqli@whu.edu.cn).

the displacement threshold cannot be set low enough to detect curb-sized objects. An alternative to comparing vertical displacements is to compare the range returned by two adjacent beams. Sloped terrain locally compresses these rings, causing the distance between adjacent rings to be smaller than the inter-ring distance on flat terrain.

Most frequently, data is projected to an assumed or estimated ground plane and produces an occupancy grid map. The advantages are that several sensors can be fused easily. Many teams participating in the DARPA Urban Challenge successfully applied this method [6][7]. However, it is not suitable for detection of sloped objects like hills or curbs.

While data projection may inherently loose information, the weighted graph was usually build directly from the scan, which the weights represent the similarity between two connected nodes. Attributes used include surface direction, curvature, edges, and local smoothness constraints and more. Frank Moosmann use Local Convexity to represents as geometric criterion allowing for a generic segmenting non-flat ground and common obstacles [8].

Due to geometric features (curbs, berms, and bushes) provide important source of information for determining road boundary and shape in urban environments. The local surface properties of point cloud on curb were usually changed such as normals, gradients, principal curvatures, or higher order derivatives. The wavelet-based features were also used by CMU to detect them because it was robust to the objects variation [9].

As curbs may not discontinuity, the detected road boundaries are then tracked by a second-order Kalman filter by Team UCF[10], which ensures that broken curbs or broken lane markings do not seriously impact the estimated boundary points. If the curbs position were clear detected, this can use as useful information to fine-grained localization. Such as Junior[2] etc,

Motivated by our experiences on the normal vector based methods from the NSFC Future Challenge 2009. The features must not only reflect the character of pavement flatness, but also reflect the height changes of point cloud on curb in the different directions. When the autonomous vehicle runs over the undulating pavements, it also should be reliable. We present a method of Four Directions Scan Line Gradient Criterion (4DSG). We show that this allows for a fast algorithm and good results even in different urban environment.

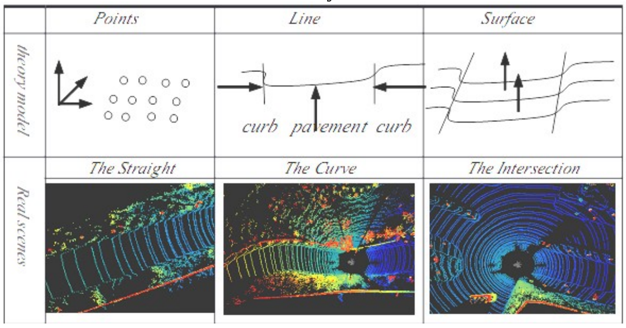
III. Problem Statement

There are two important issues of road detection: one is segmentation the pavement and the other is detection the edges of it.

The surface of pavement is flat basically in local, whether it is in a partial of scan lines, or in the adjacent two scan lines. The changes of height and distance are smaller. And variations in different directions are basically the same.

However, the characteristics of the road edge are a quite difference. In one scan line, there are significant height changes of curbs of road on both sides of vehicle. While curbs in front of the vehicle, due to the same direction and the scan lines, there are no significant height changes on one scan line, to discrimination them, the changes of the radial in circumference of different scan line must be used, such as the gradient, normal vector. And curbs locations are used to precise locate boundaries of the road.

Tab. 1 Geometry model of road



The road geometric model is set up to express the morphological changes and distinction between different objects, as Table 1. The table in two rows, the first row is the geometric models, including the object model of point, line and surface, the second is the real scene, as a reference.

In point model, the height of points on road surface is usually the same. However, it can not distinguish road from other ground such as sidewalks, curb, because the high is same. In line model, the shape of road is obvious different as compared to trees, pedestrians, which the scan line is round and irregular curves, it consists of three parts; both sides are curbs and the pavement in the middle of them. As pavement must have a certain width, therefore the middle part of scan line is a flat. If constructing a grid in different scales, it not only can express the local surface directions, but also can express difference of road from other objects, especially buildings and vehicle.

A. *Scanline Features*

The general method of point cloud segment is projected them to the occupancy grid map. Then, features of every cells of grid are extracted, such as (mean, variance, min-max, etc.). However, these features can not distinguish small objects (such as curb or ditch) on undulated road, because those objects may be covered by other points in same cells. Another method is extracted features based on the 3D-grid directly. The normal vectors of different scales are extracted on the structure of rectangular grid, which express the direction and undulation of local surface. But, these features may be disturbed by the vibration of vehicle easily.

Therefore, the 8 or 16 points on same scan lines are basic units which we extracted features. The measures of variation within one unit, such as (difference, variance, and gradient)

are extracted as scan line features. That unit can also be tangential or radial direction of scan lines. In order to process in real-time, the feature extraction is based on the grid directly,

Next, the point cloud of Velodyne LiDAR is composed by 64 scans circle. So the local units of points cloud can be defined as three scan line and the six units surrounding current point. It can be extracted different features from corresponding unit, and then calculate gradient variation in four directions such as tangential, radial, and 45,135 between the tangential and radial, which is defined as the four directions scan line gradient (*4DSG*).

In Fig.1, Due to sensor's architecture, the point cloud will be gradually sparse from the near to the far, the same points spatial covered by the point have a great change, so the normalized is need for feature extraction

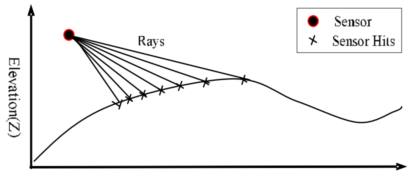
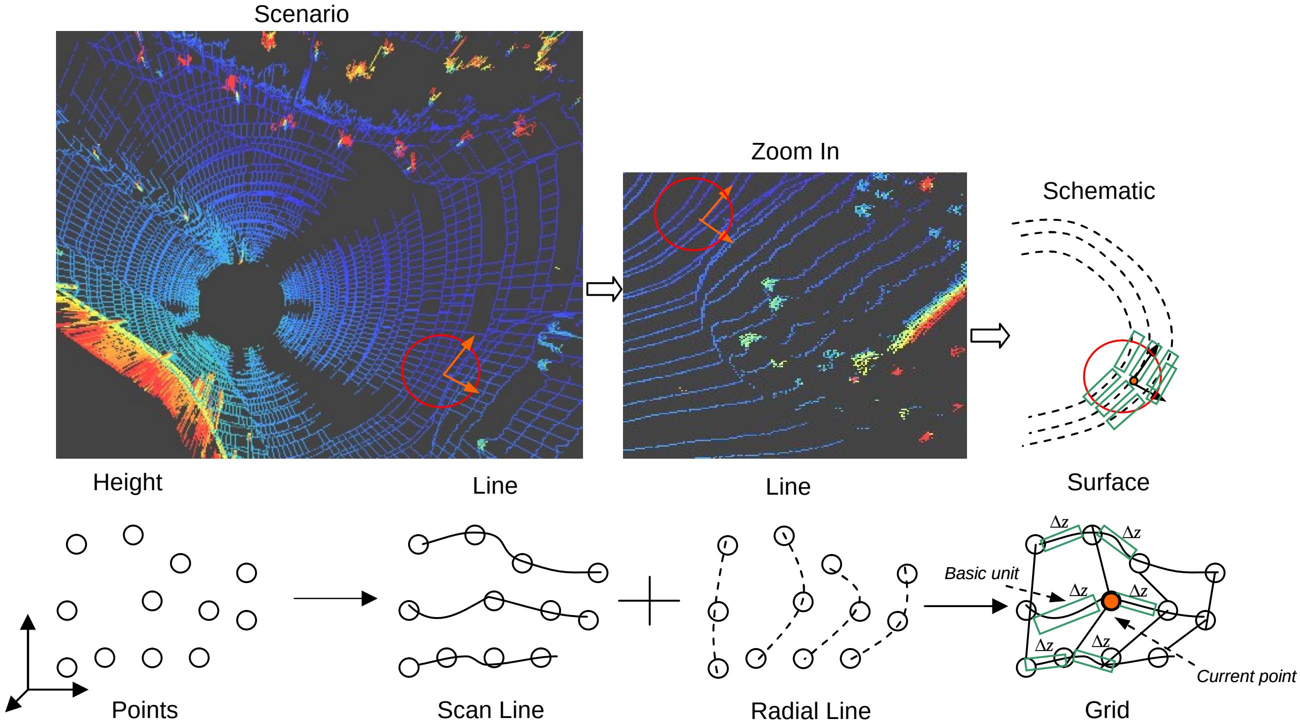


Fig. 1. Lasers rays of LiDAR

These features can not only reflect the flat character of pavement of roads in all directions, but also reflect the height changes of point cloud on curb in the four directions, which used to detect road edge very well..

In Fig.2, the actual data is zoomed in. and the calculation procedure of *4DSG* features is also showed here. And the formulas was listed in the tables



	Feature	Formula	Memo
Scan Line	*Height Variance of basic unit* (Δz)	$\Delta z = \frac{1}{8}(\sum_i z_i - \bar{z})$ (1)	*Average, max value or variances are extracted as basic value of scan line features.*
	Gradient in different direction (Δs)	$s(0^0) = \sqrt{(\Delta z_{i-8j} - \Delta z_{ij})^2}$ (2)	*The variation of local surface in different directions*
		$s(90^0) = \sqrt{(\Delta z_{ij-1} - \Delta z_{ij})^2}$ (3)	
		$s(45^0) = \sqrt{(\Delta z_{i-8j-1} - \Delta z_{ij})^2}$ (4)	
		$s(135^0) = \sqrt{(\Delta z_{i-8j} - \Delta z_{ij-1})^2}$ (5)	
	Gradient value (m)	$m(i,j) = \sqrt{(\Delta z_{i-8j-1} - \Delta z_{ij})^2 + (\Delta z_{i-8j} - \Delta z_{ij-1})^2}$ (6)	*The undulate of pavement*
	Gradient directions (q)	$q(i,j) = a\tan\left(\frac{(\Delta z_{i-8j-1} - \Delta z_{ij})}{(\Delta z_{i-8j} - \Delta z_{ij-1})}\right)$ (7)	*the direction of scan line gradient*

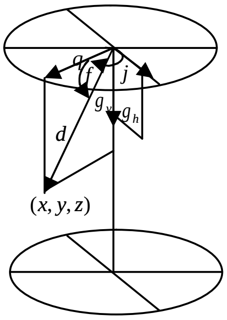
Fig. 2 Scan line features of 3D point clouds

B. Robustness

Given a set of 3D points cloud captured from a sensor the coordinates x, y, z of each point was define like this:

Tab.2 Calculation Parameter

Symbol	**Meaning**	**Memo**
x,y,z	*Coordinates*	*Every point*
Δt	*Small period of time*	*Whole sensor*
j	*Rotation angle*	*Whole sensor*
Δq	*Rotational correction angle*	*Each laser*
f	*Vertical correction angle*	*Each laser*
f'	*Noise caused by vibration*	*Each laser*
g_v	*Vertical offset*	*Each laser*
g_h	*Horizontal offset*	*Each laser*
d	*Distance*	*Each point*



$$
\begin{aligned}
f &= \Delta f + \Delta t \times f' \\
q &= j + \Delta q \\
d &= r + \Delta r \\
x &= d \times \cos(q) \times \cos(f) - g_h \times \cos(j) \\
y &= d \times \sin(q) \times \cos(f) - g_h \times \sin(j) \\
z &= d \times \sin(f) - g_v
\end{aligned}
\tag{8}
$$

Fig. 3 The formula of point cloud coordinates

It can be see that the vibrating impact of a small length of scan line is same for a relatively small period of time Δt, if the difference, variance, and gradient of this small length of scan line are used for feature extracted, you can reduce the impact of vibration.

There are two kinds of forms of the flatness of the road related to scan line: first is in the one scan line. The characteristics of variation, due to the scan line have a fixed spatial structure of points, and the amount of its differential changes can represent the surface undulated road in tangential direction. And the changes in the vehicle vibration along the cycle time (*0.1 ~ 1s*) is much greater than for 8 to 16 laser point scanning time(*10Hz*, about *2160* points one ring, $8/2160 \times 10 \approx 0.37ms$). Thus, the differential feature of local scanning lines can avoid the impact of vehicle vibration.

In the flat part of the road, the normal vector used in paper (Frank Moosmann 2009) is adjacent *6 degrees / m*, if there is a small object, such as the gravel on road surface may be exceed this limit. In fact, the flatness of road is not only refers to the road smooth transition, but also can refers to there is no large obstructions can affect the driving, we use the variance of scan lines, the noise can be average smoothed in a certain extent, and more fit to people's driving habits.

Similarly, consider variation of the adjacent scan lines, it can be determined the undulating of road surface in radial direction. First, sort of all scan lines according to different tilt angle. And taking into account the 64 scan lines, it can be considered odd and even scan lines counted separately between the radial variations to express the surface undulation characteristics in radial direction.

C. Sub-line Classification and Road Segmented

Given the 3D grid, the following region growing algorithm is executed until no more points are left.

Sub-line segment: Two points in one scan line belong to the same object based 4DSG criterion, if and only if there exists a path in the scan line connected the two nodes, segment points into sub-lines

Pavement segment: Classification sub-lines into pavement or others according the flatness in certain length.

Scan lines connected: Connect pavement in last and current scan line, according to the features changes between adjacent scan lines. The algorithm is list below.

```
For i from scanline 1 to scanline 64 do
    Select point in one scanline as a seed.
    For j form 1 to 2160 do
        Segment points based 4DSG into sub-line until no
        more points in current scanline.
        Classification sub line into pavement or others
        according the flatness in certain length.
    End for
        Connect pavement in last and current scanline
End For
```

Algorithm 1: Road Segmented based sub-line Classification

IV. EXPERIMENTS

We have evaluated the proposed algorithm in urban environment by SmartV-II, which is autonomous vehicle with the HDL-64 sensor mounted on the Chery Tiggo. The test data was collected in the FC09 Challenge. In order to evaluation classification performance, the samples of point cloud have marked as road, buildings, vehicles, pedestrians, trees, and ground. Then, the recall rate is used to evaluating performance.

Number of correct classified points, which are marked as road, is define as N_{rc},

Number of correct classified points, which are marked as other objects, is define as N_{bc} ,

Number of total point in scene is define as N , Then, the recall rate of road is define as

$$T_{road} = \frac{N_{rc} + N_{bc}}{N} \times 100\% \tag{9}$$

According to scene characteristics, the six frames are

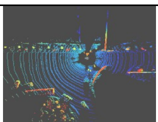
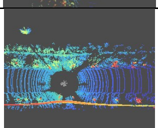
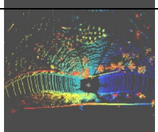
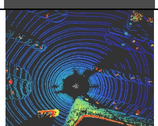
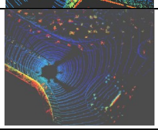
selected from the FC09 sequence as test frames, such as starting, straight, bend, junction, turn around, parking positions. Each frame has *130,000* points. The starting location of the frame is choice as a training dataset, other as a test dataset.

In order to evaluate classification performance of the 4DSG, the Bayesian, Decision Tree, KNN is chosen as classifiers. The baseline method is *Local Convexity* (Frank Moosmann, 2009). All the parameters were fixed throughout the experiment. Results are shown in table 4.

The performances of two features on the training dataset are pretty well, especially the 4DSG which reaching 100%. In different scenarios, due to the undulate, the classification performances of two features have decreased significantly in frame 802. The line features is still more than 78% accuracy due to the inherent structure of laser scanning.

The frames 1102 and 1602 are more complex scenes, the pavements are irregular shape. Obviously, curbs are borders of road. It can be used as dividing line between pavement and other ground. The patterns of curbs can be divided into two groups：One is the direction of curb perpendicular to scan line; another is the direction of curb parallel to scan line. The 4DSG can reflect the changes of point cloud on curb in the four directions, which used to detect road edge very well. Therefore, the classification performances improved about 3%.

Tab. 4 Test Results

Frame / Position	***Point Cloud***	***Classifier***	***The Discrimination (100%)***	
			Local Convexity	*4 Direction Graduate*
2 Origin		*DecTree*	*99*	*100*
		Bayes	*89*	*91*
		KNN3	*99*	*100*
302 Straights		*Dec Tree*	*91*	*96*
		Bayes	*82*	*90*
		KNN3	*90*	*95*
802 Curve		*DecTree*	*73*	*78*
		Bayes	*77*	*82*
		KNN3	*74*	*78*
1102 Intersection		*Dec tree*	*82*	*90*
		Bayes	*88*	*91*
		KNN3	*84*	*88*
1602 The U-Turn		*Dec tree*	*79*	*87*
		Bayes	*82*	*82*
		KNN3	*81*	*86*

Three examples of point cloud processing are presented here. The first is the different features of 3D point cloud in intersection. In Fig.4, the road in the center picture is split into two segments due to shadows of other vehicle breaking the connectivity. In the right picture, even the vegetation on the side of the horizontal street is well segmented. However, vegetation is very difficult to deal with, as range measurements are extremely noisy thereon. Our algorithm is able to classify them successfully.

Further results are depicted in Fig. 5. The point clouds were captured by vehicle running on undulate surface. In left picture, it can be seen the vibration of vehicles would serious affect the distribution of point cloud. In center picture, the scan line feature is will deal with this situations, the pavement of road is segmented quite well. In left picture, the gradient in four directions is used. Nevertheless, the segmentation result is very good, especially of point cloud on vegetation.

The baseline and 4DSG segment results are compared in Fig. 6, blue indicates ground, red indicates obstacle. The segment results using normal vector is show in center picture, and the segment results using gradient in four directions is also show in right picture. The walls in the right picture are well segment contrast to center picture.

We test this algorithm on IBM X32 with at 1.6 GHz using unoptimized code. The average processing times per frame are 0.219 seconds for scan line feature extracted, 0.15 seconds for segmentation and classification. With a scanning at 10Hz, this is obviously not real-time. However, the real-time performance is possible by optimizing and parallelizing code and running it on most recent hardware.

V. CONCLUSION

This paper proposed a method of Four Directions Scan Line Gradient Criterion (4DSG). These features can not only reflect the character of flatness of pavement in all directions, but also reflect the height changes of point cloud on curb in the four directions; it can also used to detect road edge very well. Since, the data units used to calculate the gradient is an 8-16 points, the random noise of measurement errors can be suppressed in certain degree. And it is more stable and reliable than normal vectors, when the vehicle driving over the undulating road.

We also present road segment algorithm based sub-line classification. It not only segment road from point cloud, but also distinguishes pavement from other grounds. This algorithm works quite successfully even in urban environments.

The method was tested on logged data acquired by the vehicle during the NSFC Future Challenge 2009. The results show average of around 3% performance improved in different scenes.

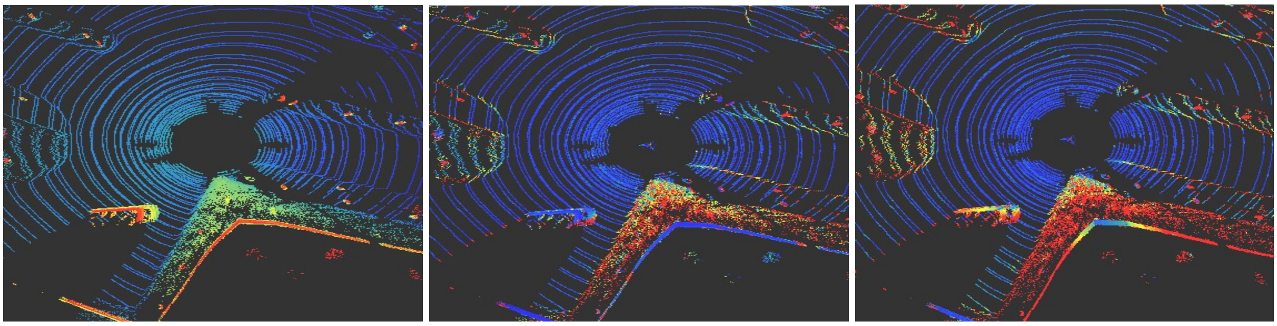


Fig. 4. The different features of 3D point cloud in intersection, best viewed in color.
(Left) Height feature of every points. (Center) The height variance of 8 points in every scan line. (Right) The gradient feature in four directions.

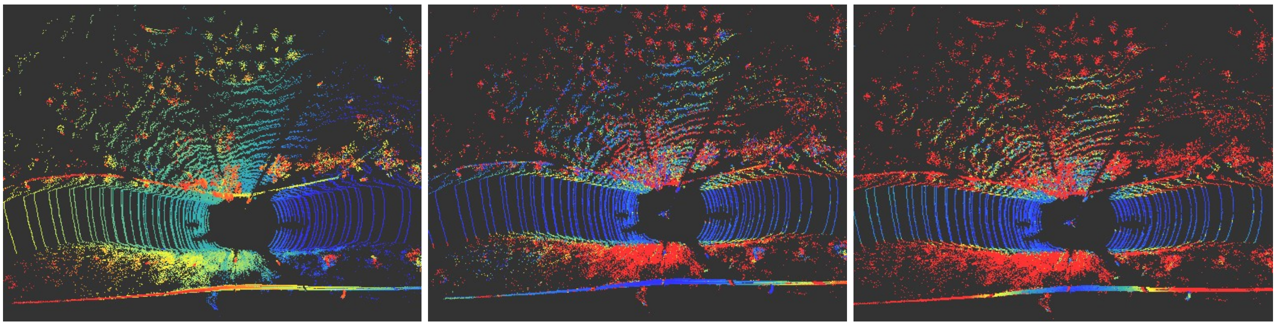


Fig. 5. Road segment while autonomous vehicle running on undulate surface, best viewed in color.
(Left) Height feature of every points. (Center) The height variance of 8 points in every scan line. (Right) The gradient feature in four directions.

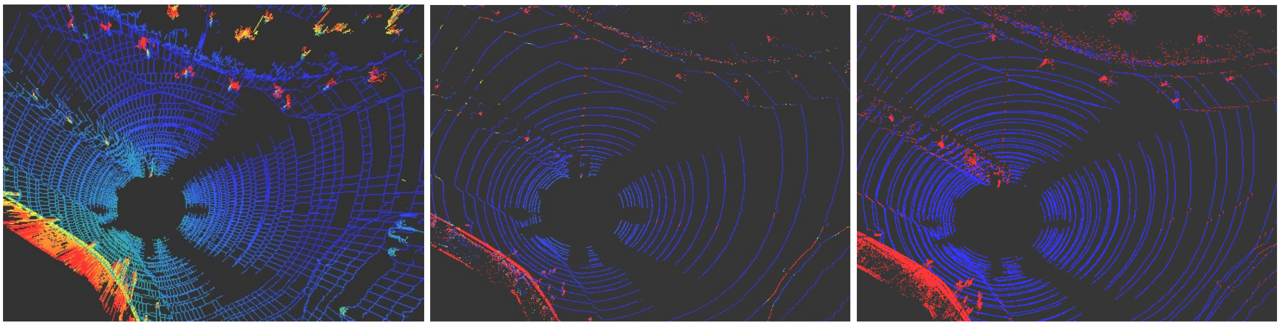


Fig. 6. Segment results are compared, blue indicates ground, red indicates obstacle.
(Left) 3D point cloud grid. (Center) The classification results using normal vector, (Right) The classification results using gradient in four directions.

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REFERENCES

[1] Michael Montemerlo, Jan Becker, Suhrid Bhat, Hendrik Dahlkamp and Dmitri Dolg, Scott Ettinger, Dirk Haehnel , "Junior: The Stanford Entry in the Urban Challenge", Journal of Field Robotics 25(9), 569–597 (2008) C, 2008

[2] F. Nashashibi and A. Bargeton, "Laser-based vehicles tracking and classification using occlusion reasoning and confidence estimation," Intelligent Vehicles Symposium, 2008 IEEE, pp. 847–852, June 2008.

[3] HDL™-64E S2, User's Manual, www.velodyne.com

[4] DARPA. (2007). Urban Challenge rules, revision Oct. 27, 2007. See www.darpa.mil/grandchallenge/rules.asp.

[5] Future Challenge 2009, http://ccvai.xjtu.edu.cn/mes.do?method=list.

[6] S.Thrun., "Learning occupancy grid maps with forward sensor models," Auton. Robots, vol. 15, no. 2, pp. 111–127, 2003.

[7] Urmson, C., Ragusa, C., Ray, D., Anhalt, J., Bartz, D., Galatali, T., Gutierrez, A., Johnston, J., Harbaugh, S., Kato, H., Messner, W., Miller, N., Peterson, K., Smith, B., Snider, J., Spiker, S., Ziglar, J., Whittaker, W., Clark, M., Koon, P., Mosher, A., Struble, J.. "A robust approach to high-speed navigation for unrehearsed desert terrain". Journal of Field Robotics,2006, 23(8):467– 508

[8] Frank Moosmann, Oliver Pink and Christoph Stiller, "Segmentation of 3D Lidar Data in non-flat Urban Environments using a Local Convexity Criterion", IEEE Intelligent Vehicles Symposium, 2009, pp. 215－220, may 2009.

[9] Chris Urmson, Joshua Anhalt, and Drew Bagnell, "Autonomous Driving in Urban Environments: Boss and the Urban Challenge", Journal of Field Robotics 25(8), 425–466 (2008)

[10] Benjamin J. Patz, Yiannis Papelis, Remo Pillat, Gary Stein, and Don Harper," A Practical Approach to Robotic Design for the DARPA Urban Challenge" , Journal of Field Robotics 25(8), 528–566 (2008)