SNOWBOTS; A MOBILE ROBOT ON SNOW COVERED ICE

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ABSTRACT
We introduce snowBOTs as a generic name for robots working in snow. This paper is a study on using scanning range measuring lasers towards an autonomous snow-cleaning robot, working in an environment consisting almost entirely of snow and ice. The problem addressed here is using lasers for detecting the edges generated by "the snow meeting the road".

First the laser data were filtered using histogram/median to discriminate against falling snowflakes and small objects. Then the road surface was extracted using the range weighted Hough/Radon transform. Finally the left and right edges of the road was detected by thresholding.

Tests have been made with a laser on top of a car driven in an automobile test range just south of the Arctic Circle. Moreover, in the campus area, the algorithms were tested in closed loop with the laser on board a robotized wheelchair.

KEY WORDS
laser, snow, snowBOTs, road, edge, unmanned

1 Introduction

Detection of road boundaries are very important when running an autonomous vehicle on a road. During winter season when the landscape is covered with snow, plow machines remove snow from the road which create piles of snow on each side. These snow piles are natural boundaries for the road.

A snow covered road is constantly changing during the winter. Every time a snow plow passes the road to remove snow, the snow edges on the side of the road are moved a bit. The road surface is often rather rough, and it is expected to find small snow piles on the road, consisting of snow fallen from cars and trucks. During the winter one can also expect weather conditions that give limited visibility for a laser scanner, [1]. When developing sensing and algorithms for detection of the snow edges on the side of the road one has to consider all these conditions.

There are several different methods to detect the road boundaries using cameras and lasers, [2] and [3]. Some tests to navigate a robot in arctic conditions using a couple of different sensors have also been made, [4].

One contribution in this paper is an edge detection algorithm for snow edges. The robustness of the presented method is illustrated by the fact that we were able to run a robot, in the form of a wheelchair, on a road partly covered by snow. The robot was able to traverse a 200m long walking path several times. Even though the wheelchair was running on snow slush which made the wheels spin and the laser wiggle, it managed to correct its pose by aiming at a point a couple of meters ahead between the left and right snow edges. This test was made without a rate gyro. More information about this project is available at [5].

Figure 1. Testcar on a frozen lake used as an icetrack for automobile testing under arctic conditions. The laser sensor, tilted downwards, and a GPS antenna are mounted on the roofrack of the car.

Figure 2. Part of the icetrack seen from the inside of the car. Note the vertical marker stick near the left boundary of the road.

1.1 Paper outline

Section 2 brings up the modelling and theoretical description for the edge detection method. Section 3 describes the test area and the equipment used in the development of the method. A description on how we closed the loop and made use of the edge detection algorithm to run a robot is given in Section 4. In section 5 we give a short description of laser measurements collected during a snowfall. Furthermore, Sections 6 and 7 contain our conclusions and proposed future work respectively.

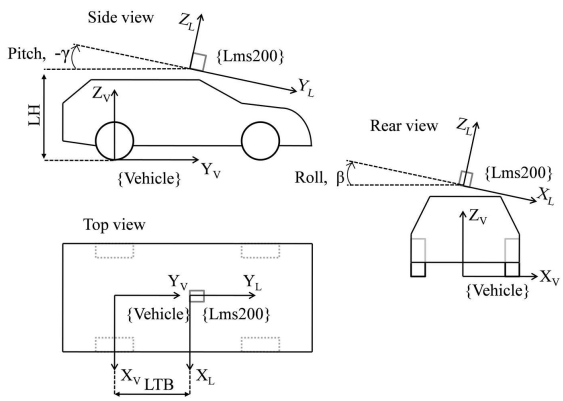

Figure 3. The coordinate systems on our test vehicle. LH is the mounting height of the laser, LTB is the distance from the laser to the rear wheel base on the vehicle. Pitch and roll angles are calculated around the X_L and Y_L axis respectively.

2 The snow edge detection method

The method presented in this section finds the snow edges on the sides of a road. This is done in a step by step process. Throughout the text we use the notation for coordinate systems described by Craig, [6].

First we detect the road surface. Then we calculate the roll and pitch angles of the laser. After that we transform the laser measurements from the laser coordinate system to vehicle coordinates, see Figure 3. Then the left and right edges on the road are found by thresholding. A block diagram describing these steps can be seen in Figure 4.

2.1 Laser measurement on a vehicle, in general

The laser scanner Sick LMS200 was set to measure distance to surrounding objects in a sector of 180 degrees with an angle increment of 0.5 degrees. A complete scan consists of 361 measurements. The range span is $0 - 80$m with a resolution of 0.01m.

To be able to see the road and snow edges the laser scanner is mounted looking downwards with a small tilt/pitch angle. The angle has to be big enough so that the road surface is always visible in the laser scan. During testing an angle of at least $10°$ shows good results in both providing accurate road measurements, without limiting the range view in front of the vehicle too much.

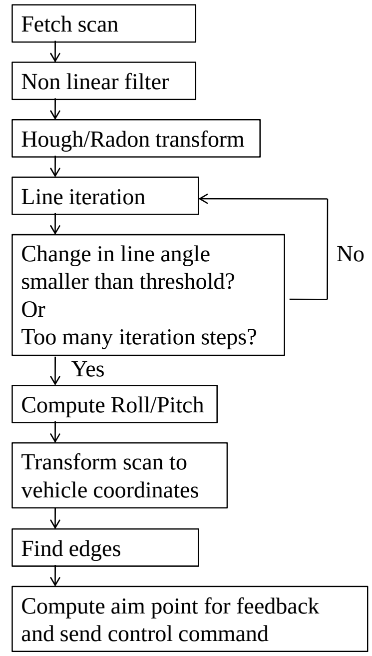

Figure 4. The block diagram gives the different steps used in the snow edge detection algorithm, for the case of one laser scan. The last step is only used during closed loop testing of the algorithm.

The vehicle is modelled to run with all four wheels attached to a perfectly flat and horizontal surface, and the X_V and Y_V axis lying flat on that surface, see Figure 3. The Z_V axis is passing through the centre of, and the X_V axis is parallel to, the rear wheel axle. Relative position changes between {L} and {V} due to movements in the vehicle suspension are not considered, and thus the origins of the laser and the vehicle coordinate systems are assumed to be fixed to each other at distances LTB and LH. Pitch and roll angle changes of the laser are however considered and the angles are calculated around the laser X_L and Y_L axis respectively.

2.2 Laser measurement in a snowy environment

The surface of a snow covered road is rather rough. There are small piles of snow and other roughness on the road that disturb the laser readings. These disturbances are not of interest since these may also produce false snow edge detections and make it harder to detect the true snow edges. Therefore a filter was applied to smooth out the roughness and remove spurious measurements, for example falling snow. The drawback with this type of filter is that it may also remove real objects in the environment, like narrow marker poles on the side of the road and other small obsta-

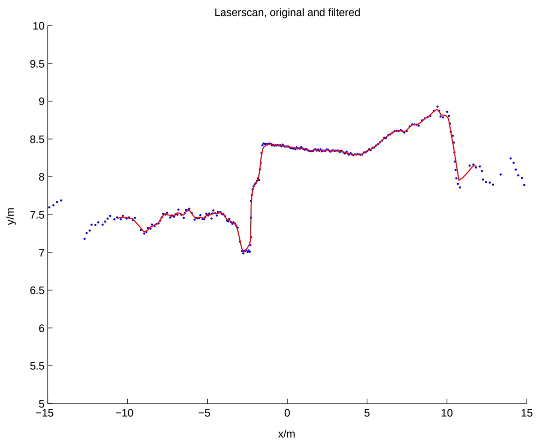

Figure 5. A example of a laserscan in laser coordinates from the icetrack. Note the different scales on the x and y axis. The dots are the actual measurements, and the line represent the filtered measurements used for ground and edge detection.

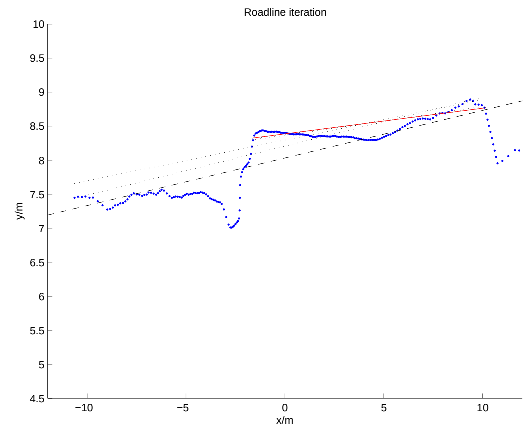

Figure 6. Roadline iteration in laser coordinates. The dashed line is the found Houghline, the dotted lines represent the iterative line steps. The solid line is the accepted roadline.

cles. This is not a serious problem in our application, since we are only interested in the snow edges.

First a median/histogram filter is used on the range data to remove spurious measurements from each scan. Then an averaging/mean value filter is used to smooth the scan. Both filters work on the range data in polar coordinates.

The median filter is of length 11, which means it can remove up to 5 consecutive deviant measurement in a window of 11 measurements.

The averaging filter is of length 3, i.e. it takes the average value of three consecutive measurements. To not affect large range jumps it uses a threshold; if the average value of the three measurements differ more than 0.5m from the median value of the same measurements, the actual data point is not filtered. In this way the average filter does not affect big range jumps in the laser scan. Figure 5 shows an example of how the filter affects a raw laser scan.

2.3 Road surface detection

To be able to detect the snow edges on the sides of the road we first need to find the actual road. The road is represented with a straight line, called the roadline. The search process for the roadline is done in the laser coordinate system.

The roadline is found in a iterative process. First the range weighted Hough/Radon transform [7] is applied to find a Houghline that is used as a first rough estimate of the roadline. Since we know where the road is expected to be, we can decrease the computation time of the Hough transform by limiting the distance and angle interval.

To find the angle of, and the distance to, the Houghline corresponding to the road, we first select all the peaks that lie within 90% of the maximum value in the Hough diagram. We then pick the distance to the peak that is furthest away as the distance to the line. If there are several peaks at that distance we select the angle from the highest, and if there is several peaks with the same height but at different angles, we take the average of those angles as the angle for the Houghline.

Measurements in a distance interval around the Houghline is selected, and a least square fit of a new roadline is made to those measurements. The roadline creation process is then repeated; measurements near the last found line are selected and a least square fit of a new line to those measurements is made, see Figure 6. When the difference in angle between the last line and the new line is smaller than a specified threshold, or the process has been repeated 10 times, the process is stopped and the roadline accepted.

The equation for the roadline in laser coordinates is

$$ {}^{L}Y = A + B\, {}^{L}X, \tag{1} $$

where A is the distance from the laser to the roadline along the Y_L axis, and B is the slope of the line. For illustrative purpose in the figures the lines fitted to a data set is only plotted between the projected end points in the data set.

2.4 Pitch and roll calculations

To calculate the pitch angle of the laser we use the laser mounting height LH, and the distance A between the laser and the roadline along the Y_L axis. Since the vehicle is modelled to run on a perfectly flat surface the detected roadline should have a slope of zero degrees, if the slope differs from zero it must be due to a roll angle of the laser, the distance A to the line is not affected. We also assume the mounting height LH from the ground to the laser to be constant. The laser pitch angle, γ, is then calculated with

$$ \gamma = -arcsin(\frac{LH}{A}), \tag{2} $$

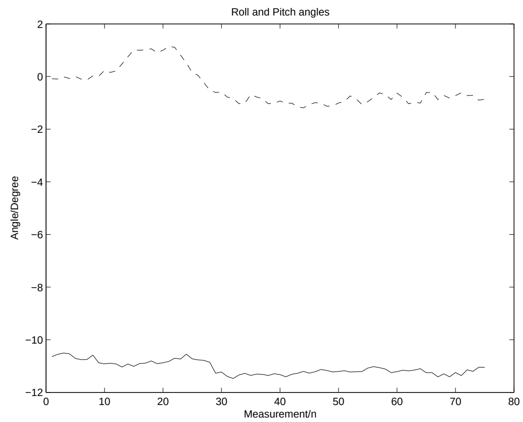

Figure 7. Calculated roll and pitch angles for 75 consecutive laser scans collected while the vehicle was moving from the right side of the road to the left side, see Figure 9. The dashed line represent the roll angle, and the solid line is the pitch angle. The big change in roll angle around scan 20 is due to the vehicle driving over the crest in the middle of the road, see Figure 8.

and the roll angle, β, of the laser is given as

$$\beta = arcsin(B\, tan(\gamma)). \quad (3)$$

A example of calculated roll and pitch angles is seen in Figure 7.

2.5 Coordinate transformation

Each laser scan is transformed into the vehicle coordinate system using

$${}^{V}X = {}^{L}Xcos(\beta), \quad (4)$$

$${}^{V}Y = {}^{L}Xsin(\gamma)sin(\beta) + {}^{L}Ycos(\gamma) + LTB, \quad (5)$$

and

$${}^{V}Z = -{}^{L}Xcos(\gamma)sin(\beta) + {}^{L}Ysin(\gamma) + LH. \quad (6)$$

Where LTB is the distance from the laser to the wheel base of the vehicle, and LH is the mounting height of the laser, see Figure 3.

2.6 Edge detection

The edge detection algorithm looks at the laser data in the vehicle X_V and Z_V coordinates, see Figure 8.

The edges are detected where two consecutive measurements lies on separate sides of an imaginary threshold line, placed at certain distance above, and parallel to, the roadline. Measurements with a Z value below the threshold line are assumed to belong to the ground, and the ones above belong to the surrounding boundaries.

This algorithm may find several left and right edges. To identify the left and right bounding edges of the road we need to know where the actual road is. An estimate of the centre position of the road is computed by calculating the average position of all the measurements that the roadline is created from. When we have the centre position we can find the right and left edges corresponding to the road. This is done by selecting the closest left edge on the left side of the centre point as the detected left edge, and the closest right edge on the right side of the centre point as the detected right edge.

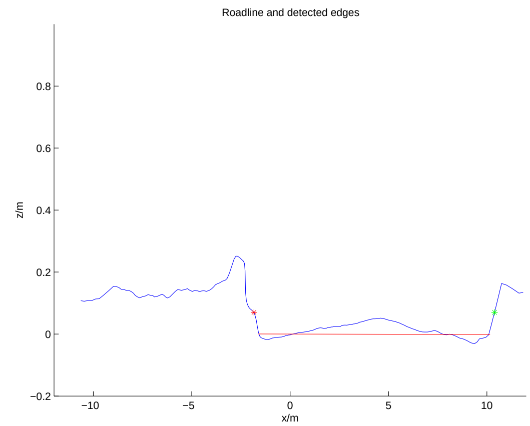

Figure 8. Roadline and detected edges in the X-Z plane seen from the vehicle. Observe the different scales in the figure. The road is about 12m wide while the snow edges on the side are approx. 0.2m high.

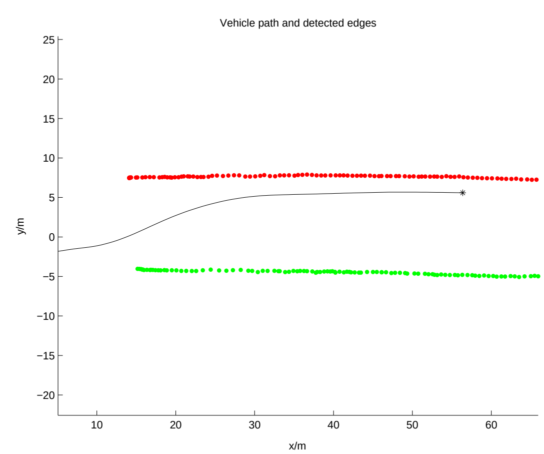

Figure 9. Detected edges when the vehicle is traversing an icetrack on a frozen lake. The curve represent the vehicle path, estimated using odometry and a low drift fiber optic gyro. The vehicle was travelling from the left to the right in the figure. The dots are the detected left and right edges on the road. Due to the tilt angle of the laser the detected edges is approx. 10m in front of the vehicle.

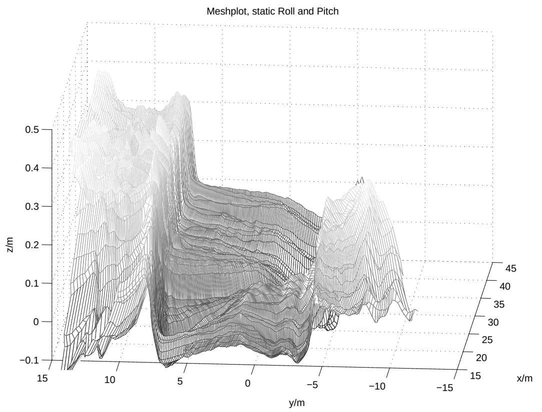

Figure 10. Meshplot of a 25m part of the icetrack. The laser scans are rotated and translated using fixed roll and pitch angles. Notice the difference to the figure where continuously updated roll and pitch angles are used.

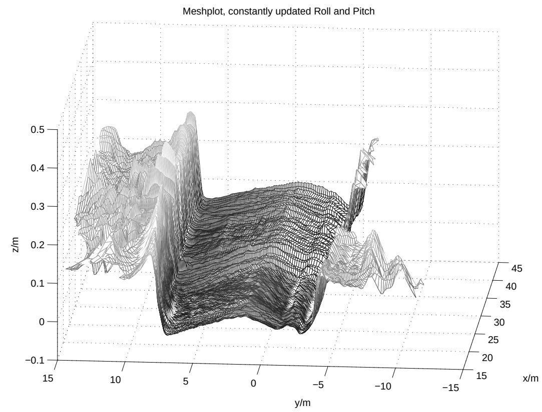

Figure 11. Meshplot of the same 25m long part as shown in Figure 10. All single scans are rotated and translated using the estimated roll and pitch angles, as described in the paper. The scans are then put together using dead reckoning. The plot is created from the same data as in Figure 9, the first part where the vehicle travels from the right to the left side of the road.

3 Test area and equipment

In this section we present a description of the test area and the test equipment used in the development of the algorithms.

3.1 Test area

The snow edge detection algorithm has been tested on data recorded at an icetrack located in the village Arjeplog in the northern part of Sweden. The icetrack is part of a large winter test facility for different car manufacturers. A part of the track is seen in Figure 2.

Since the test track is located on an ice covered lake, the assumption made that the vehicle is moving on a flat horizontal surface is fairly good. Another thing to notice is the fact that the actual road the vehicle is moving on is the lowest part in the environment. There are no ditches or holes on or beside the road, only snow and ice.

3.2 Test equipment

The test vehicle was an ordinary car, equipped with some sensors, see Figure 1: GPS receiver, wheel encoder, web camera, fiber optic rate gyro, and a laser scanner. All connected to a computer that recorded data.

The laser scanner was mounted on the roofrack on top of the car at a height, $LH = 1.65$m, and a distance, $LTB = 1.5$m from the rear wheel base. The tilt/pitch angle of the laser was approx. 11^o.

3.3 Test description

All the figures described in this section is from the same part of the testrun. The laser scans are stitched together using dead reckoning based only on the low drift fiber optical rate gyro and the wheel encoder.

Figure 7 shows the calculated pitch and roll angles for the testrun. Figure 9 shows the detected left and right edges of the icetrack as the car was driving.

Figure 10, presenting a three dimensional meshplot made from laser scans rotated using fixed roll and pitch angles shows a good example on how the motion of the car is affecting the resulting laser measurements. The influence of the vehicle motion is noticeable reduced when using the estimated roll and pitch angles, see Figure 11.

Figure 12. Robot used as platform during the closed loop testing. The LMS200 laser is seen in the front, the box behind it is a sunscreen for a laptop. The only function of the person is emergency stopping.

4 Closing the loop

A closed loop test of the edge detection algorithm was done by letting a robot follow the snow edges as estimated from the laser. The robot used in the test was a wheelchair, equipped with the necessary sensors and a computer, see Figure 12. In this test the wheelchair was not stabilized by any gyro while driving, (gyro not functional). Under these conditions the dead reckoning is very poor, especially when driving in snow slush.

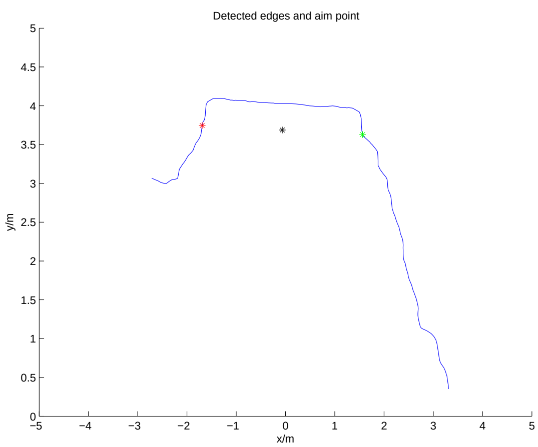

Figure 13. Detected left and right edges in one laser scan from the closed loop testrun. Note that the plot is in the X-Y plane in vehicle coordinates. The star in the middle is the aiming point for the robot, (the "rabbit"). It is located in the middle between the left and right edges.

To test feedback from the edge detection algorithm we used a rather simple control law. The robot was driving with constant speed, aiming at a point a couple of meters ahead, in the middle between the estimated left and right edges, see Figure 13. If one of the edges was not found, the robot continued to drive straight forward. This control law made it necessary to always be prepared to manually stop the robot if the algorithm failed. Unwanted behaviour did occur when no snow edges where detected by the robot.

The robot was able to traverse an approx. 200m long walking path forth and back several times. Even though the wheelchair was running through snow slush which made the laser wiggle and the wheels spin, see Figure 14, it managed to correct the position and heading just by driving towards the aiming point a couple of meters ahead between the left and right snow edges.

5 Laser measurements during snowfall

Work is in progress towards model based filtering to reduce the clutter from snowflakes for outdoor robots. Below we give a hint of properties using a LMS200 laser scanner during snowfall. A wall, see Figure 15, approximately 20m away from the laser was used to get range statistics in a

Figure 14. The robot driving autonomously through snow slush on a plowed walking path in the campus area.

Figure 15. A part of this wall was used as reference object to get statistics about percentage of false detections by snowflakes, detections on the object behind, and no detections. It is possible to see falling snowflakes in the picture.

sector of 13.5^o. From 13700 range registrations approximately 19% were from snowflakes, 81% fell on the wall behind, and about 0.2% were not detected i.e. absorbed.

The histogram in Figure 16 gives the range distribution to detected snowflakes. There is a significant peak close to 1 m and almost no snowflakes are detected beyond 8 m. In another part of the scene was a wall with range changing from 1 m to 10 m. For objects close to the laser the shape of the histogram changes significantly. This is due to properties of the detector electronics.

A second laser with a narrow modulated beam was also used during the tests. This short range narrow beam laser has a better penetration between the snowflakes and gives a histogram with very few detections triggered by snowflakes. The continuous wave detector is also different.

There are many relevant parameters to study including beam divergence, modulation and detector properties, snowflake size and wind motion.

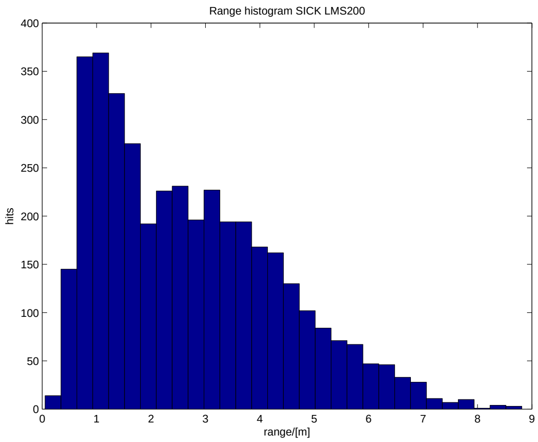

Figure 16. Histogram of detections of snowflakes from laser measurements for the scene in Figure 15. Note that there are few detections close to the laser. For clarity, the wall located approx. 20m away from the laser is left out of the histogram.

Work in progress can be summarised as:

- Median filtering gives a substantial reduction in disturbing snowflake detections.
- Histograms on projections indicate that the Radon/Hough transform will give a robust extraction of plane surface segments such as roads.
- The gamma distribution describes fairly well the distribution of detected snowflakes, see Figure 16.

6 Conclusion and discussion

The methods presented in this paper can be used to detect snow edges on the sides of a road. It is also possible to continuously calculate and update roll and pitch angles of the laser, which is very useful when stitching together several laser scans.

We tested the algorithms by using the detected snow edges as references to run a robot, and it did work, even though the surface on which the robot was running was very rough and slippery.

7 Future work

An error analysis of the roadline detection needs to be done. How does an error in the roadline propagate into the estimated roll and pitch angles?

Another noticed thing; if the roadline detection fails to detect a proper roadline the whole edge detection algorithm breaks down. An extension to the presented methods could be to apply a Kalman filter to track the roadline and roll/pitch parameters, and also include IMU information in this filter. This would probably reduce the risk of total failure in edge detection.

The disturbances of falling snow should be studied in more detail.

An interesting method to test would be the circle sector expansion method, [8]. By removing the measurements that belong to the road surface, it is possible to use that method to find the free space and the road boundaries.

8 Acknowledgement

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