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Free space determination for parking slots using a 3D PMD sensor

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***Abstract*— We present an approach for parking slot detection using a 3D Range camera of PMD type. This sensor allows referring to a large number of spatial point measurements detailed representing cuts of the observed scene. The focus of this paper is on the feature extraction out of the PMD data as well as the fusion of the features defining the free space of a parking slot. The feature extraction includes reliable and exact curb detection and robust obstacle detection. The approach for the optimal feature extraction is based on the usage of an occupancy grid in combination with a feature conform definition of detection channels.**

I. Introduction

Handling a car safely under circumstances with limited space is a task that needs much imagination and experience in estimating free spaces around the vehicle. This task aggravates with increasing size of the vehicle and the complexity of the situation. To alleviate the problem, several years ago parking distance control systems (PDC) were developed. The purpose of PDCs is to determine and to give the driver acustical or optical clues about the distance of objects and obstacles detected in front of the car or behind the car while driving at low speed typical for parking maneuvers.

An application that does not only show the actual distance between the vehicle and an obstacle but a detailed map of the parking-situation beside the car including information about available space has many advantages, especially when backing into a parking slot not much larger than the car itself. In a purely information-based version, the decision whether to use the slot can be made easier for the driver. If in addition, the orientation and position of the slot can be determined, an ideal trajectory for backing into the parking space can be shown. In an advanced version, the car can control the steering motion autonomously.

There has already been a lot of research on the general problems obstacle detection and parking assistence [2] [3] [4] [5] [6]. Recently several OEMs have also been developing such applications. At the beginning of 2006, Toyota introduced a parking-assistant using a rear view camera. On a monitor in the passenger compartment, the driver has to show the system the correct parking position. At the end of 2006, Volkswagen introduced with the "Park-Assist" another parking-assistant. Below a certain speed-limit, a sensor scans the scene beside the car. Together with odometry-measurements, the position of the measurement can be assigned and thus the size of the parking slot can be computed. If the system finds a usable free space, it drives into the slot. The driver only has to control the brake and the acceleration.

Prerequisite for a good performance of a parking-assistant are accurately measured data. Besides video-cameras and radar-senors, ultrasonic-sensors, pointing perpendicular to the lateral axis of the vehicle, are most commonly used. These one-dimensional sensors typically work with a scan-rate of ca. 25 samples per second, governed by their principle of measurement. Their beam spans an angle of several degrees, leading to a coarse spatial resolution. To get more information about the vertical and horizontal position of the reflecting object significantly more effort is needed. Another possibility is to use a sensor, which provides more information about the environment. In this paper a free space detection of a parking slot using an active infrared 3D-sensor is described.

II. Our System

To scan the parking-scene, a Photonic-Mixer-Device (PMD) camera is used. A PMD camera is an active infrared 3D-sensor using a phase-shift-algorithm to determine the distance. Generally, it consists of a light source and a receiver. The light source is used to illuminate the scene with modulated infrared light. To increase the detection range and the accuracy, some more light sources can be used. The receiver detects the light which is reflected by the illuminated scene. A detailed operation breakdown of the PMD camera is described in [1]. Several challenging automotive applications are meanwhile presented as pedestrian detection [7] as well as industrial applications as performed in the german project LYNKEUS [8].

For the parking slot detection, a camera is used which scans the scene orthogonally to the lateral axis of the car and is tilted by several degrees to reduce the blind zone along the vehicle to about one metre. Two light-sources illuminate the scene. With this constellation, the sensor-system is able to detect reliably worst-case objects with low reflectivity in up to seven meters distance with an accuracy of about two centimetres. The receiving chip of the sensor has a resolution of 16×64 pixels (horizontal $\times$ vertical). For each pixel, the sensor delivers the distance and an amplitude information. With a total field-of-view of $18^\circ \times 55^\circ$ of the whole chip, this results in a detection angle of $1.1^\circ \times 0.9^\circ$

per pixel. Because of the high framerate of up to 100 frames per second (fps) and the large horizontal flare angle, there is enough overlap to scan an area several times even with a vehicle speed of over 30 km/h resulting in an increased accuracy of the virtual map. Additionally, the negative impact of environmental disturbances like rain and snow on the accuracy is reduced and even at much higher speed parking slots still can be detected.

The high vertical resolution of the sensor system enables a fragmentation in different zones, for example

- the road surface to calibrate the camera for vehicles with different payloads
- the curbstone to determine the orientation of the parking slot
- taller objects which occupy the parking slot.

In addition, small, thin, or flat objects like a drawbar of a trailer or a tow coupling can be detected.

III. Grid Based Approach

The field of data fusion knows in general about two ways to enhance the quality of detection systems. This is on the one hand the fusion of data coming from several sensors at the same time and on the other hand the accumulation of data coming from one or several sensors over an interval of time. The problem to solve is to assign sensor data and processing results of the sensor data to each other even if they have a different measurement time. One typical approach is to take a detection decision about the existence of an object in every measurement at every time. The object can then be tracked over time - e.g. with a Kalman Filter - and detections with an other measurement time can be assigned easily. But in the case of spatially distributed objects what is the normal case in most applications the detection decision is strongly connected with a decision about the shape of the object and the spatial pose of the object. Additionally the incompleteness of the measurement according to space makes the detection decision, whether an object is present or not often very uncertain or impossible.

A solution that combines the ideas of accumulation according to space and time is the occupancy grid that is used also in this approach. As the PMD Range Camera delivers a complete set of 3D measurements the usage of a 3D Grid seems to be advisable. But for the detection of parking vehicles and other objects around the parking space the complete regular discretization of the space is not required but the definition of certain channels of observation and accumulation. Therefore the 3D measurement points coming from the range image are assigned to these channels. For details see the chapter IV-A.

Additionally the original measurement points are stored. The used grid is therefore not only responsible to reduce the data and accumulate over time but also to store the original measurement data (points) and provide fast access to them during further processing.

To allow the exact accumulation according to space and time the knowledge about the movement of the sensor vehicle is necessary. Therefore a Kalman Filtering is used that is described in chapter IV-B.

Additionally it is necessary to provide all results relative to the actual environment of the moving vehicle. Especially if it is taken into account that also original measurements are stored. How this is solved is described in chapter IV-C.

IV. Accumulation of the Data

A. Definition of Height Channels

To recognize curbs and obstacles and to distinguish between vehicles as high obstacles and other low objects three channels of height are used to accumulate the 3D points of the Range Camera in the grid. The partitioning of the height is not disjunct but has overlapping parts according to the object types that are intended to detect in the channels. For instance parking cars normally deliver no or low measurements in the wheel space so the OBSTACLE_HIGH channel starts only at 0.4 m. Ground objects as the curbs originate from the range around zero, therefore, for the GROUND channel a symetrical height intervall with an absolute value of less than 0.3 m is used.

$$\forall\ {}^{AC}P(x,y,z) \in \text{Grid}:$$
$$\text{Channel} := \begin{cases} \text{GROUND} & \text{for} \quad |z| < 0.3\,m \\ \text{OBSTACLE\_LOW} & \text{for} \quad 0.0\,m \leq z \leq 0.4\,m \\ \text{OBSTACLE\_HIGH} & \text{for} \quad 0.4\,m \leq z \leq 2.0\,m \end{cases} \tag{1}$$

The result of this point classification can be interpreted as visualized in figure 1. Every grid element contains an occupancy value according to the channels GROUND (GR), OBSTACLE_LOW (LO) and OBSTACLE_HIGH (HI).

B. Estimating the Ego Motion

For the estimation of the movement parameters and the trajectory of the sensor vehicle an Extended Kalman filter is used. As movement model in the filter a modified constant turn rate model is used. The state space vector

$$\underline{x}(t) = \begin{bmatrix} x(t) \\ y(t) \\ \gamma(t) \\ v(t) \\ \dot{\gamma}(t) \end{bmatrix} \tag{2}$$

contains besides the position in world coordinates x and y, the orientation angle γ and the turn rate $\dot{\gamma}$ additionally the velocity v of the sensor vehicle along the trajectory (see figure 2).

As measurements for the movement the vehicle velocity and the yaw rate are used in the Kalman filter. Therefore the linear measurement model

$$\underline{y}(t) = C \cdot \underline{x}(t) + \underline{w}(t)$$

$$\begin{bmatrix} v(t) \\ \dot{\gamma}(t) \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x(t) \\ y(t) \\ \gamma(t) \\ v(t) \\ \dot{\gamma}(t) \end{bmatrix} + \begin{bmatrix} w_v \\ w_{\dot{\gamma}} \end{bmatrix} \tag{3}$$

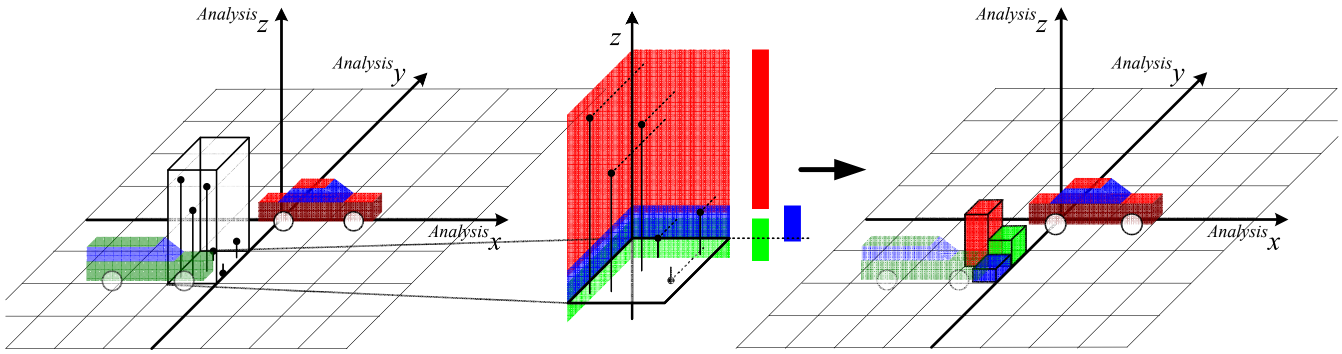

Fig. 1. Classification of Measurement Points to Height Classes

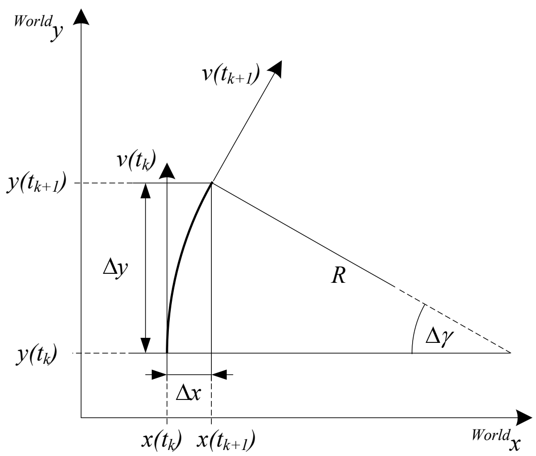

Fig. 2. State space

is used while the state transition model is non-linear.

C. The sliding Local Grid

For the subsequent detection of the parking space only a reduced section of the passed environment is needed. Therefore a local grid is used. Nevertheless the points always are stored in coordinates with respect to an according world coordinate system. The world coordinate system is defined as the system valid at the starting time of the accumulation process. It is initiated when the driver is intending to start the parking sequence. The idea to store the points in world

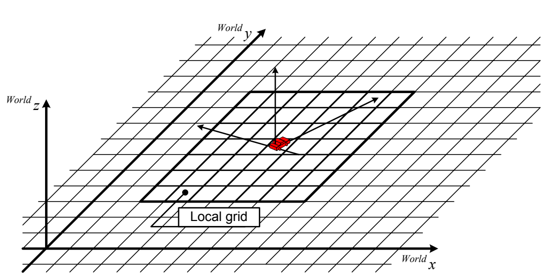

Fig. 3. Local grid

coordinates results from the intention to reduce the over all amount of position transformations. As the amount of

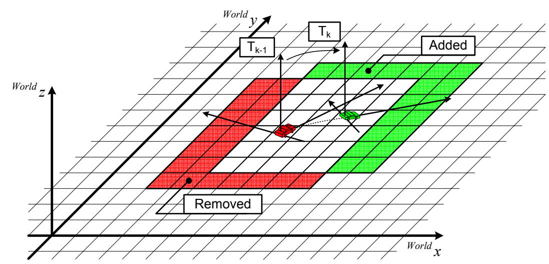

Fig. 4. Sliding Movement of the Local Grid

collected measurements is very high it is not advisable to transform all the measurements at every moment into the actual coordinate system but to transform during the collection only the actual measurements one time into the starting world coordinate system. The stored measurements do not have to be transformed again during the collection.

To reduce the stored grid frame to the local environment a sliding movement of the grid position is created. The local grid is parallel to the axis of the world coordinate system. Therefore the sliding movement can be realized by only adding new rows and columns and removing old ones (see figure 4).

V. Grid based Data Analysis

In the following subsections the developed processing algorithm is explained in detail. It consists on three steps: curb detection, obstacle detection, and free space definition.

A. Curb Detection

The implemented algorithm for curb detection is based on a model fitting approach. The procedure of this processing approach is subdivided into two steps: measurements extraction and model parameter estimation.

In the first step we strive for locating grid elements, the content of which represents some characteristics of the curb in relation to the neighbourhood. Since the object of interest occurs in this case as an edge in the GROUND-channel, the collected data of this channel are evaluated using a simple edge detection method. The basic idea of the used detector is that the elements belong to a curb, if the amount of the associated data is significantly bigger than the collected data in the elements of the local neighbourhood. This issue is illustrated in the left side of figure 5. Since the curb edge is measured by several sensor elements of the image sensor, a local maximum arises in the corresponding grid element in regard to the adjacent elements on the y-axis. The detection of such maxima is carried out using a 1×3-mask (on the right side of figure 5) and the following relationship:

$$\frac{{}^{GR}\sigma_2}{\sum_{i=1}^{3} {}^{GR}\sigma_i} > S \tag{4}$$

σ denotes the accumulation value of the corresponding grid element in the GROUND-channel and S is a suitable threshold, which depends on the type of the camera.

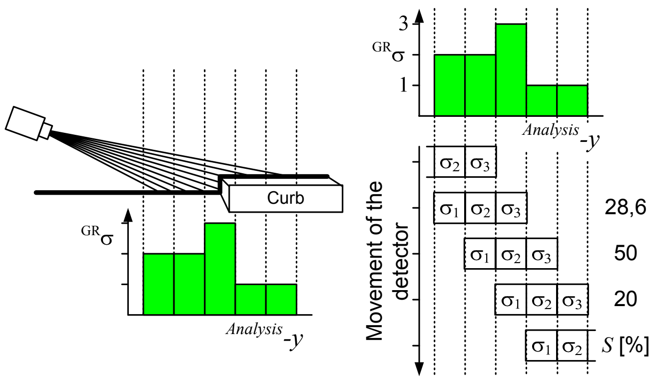

Fig. 5. Curb detection

The result of this processing step is a binary representation of the GROUND-channel. It is used in the next step as measuring domain in order to estimate the parameters of the curb model. For this purpose we apply the Hough transform, where a linear model is used. To achieve high processing performance, regarding computational costs, and detection precision a two-stage Coarse-to-Fine model fitting strategy is followed. During the first stage only the measurements created in the GROUND-channel are transformed into the Hough domain. The search for the best line in the measuring domain is then equivalent to finding the global maximum in the Hough domain. In the second stage the coordinates of the found maximum are used to select a sub domain of the local surrounding area, which has a much higher resolution than the first stage domain. The input data of the second transform are the whole collected data of the GROUND-channel, whose distance to the initial line does not exceed a defined threshold.

B. Obstacle Detection

The aim of this processing step is the creation of a two dimensional distance profile in order to detect obstacles limiting the free space to be determined. The developed algorithm consists of three steps: obstacle detection using the OBSTACLE_HIGH-channel data, creating of distance profile, and precise estimation of obstacles position.

To simplify the further processing we transform the grid coordinate system, so that the x-axis becomes parallel to the curb found in the previous processing step. The first detection step can be consequently performed in terms of one-dimensional filtering along the y-axis. In the OBSTACLE_HIGH-channel we compute for each grid element the data amount relatively to the whole data of the corresponding column and represent at each grid element the percentage of all elements considered so far (Figure 6). The detector compares this percentage of each element with a predetermined threshold and marks as an obstacle position the first element with a percentage higher than the threshold.

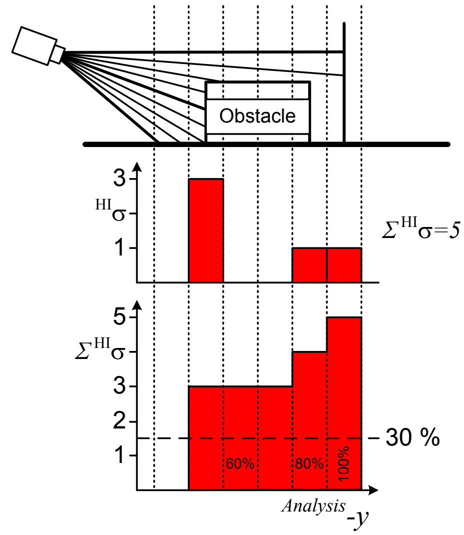

Fig. 6. Obstacle detection

In the second step a two-dimensional representation is created using the found obstacle positions. Therein the distances between the x-axis and the detected obstacles are plotted as illustrated in figure 7. We use this representation to refine the result of the first detection step. A second detector determines the distinct segments contained in the distance profile by finding the straight lines limited by a couple of subtended discontinuities. These discontinuities are located by detecting strong changes in the distance profile.

Using the complete 3D-data of a range in the OBSTACLE_HIGH-channel surrounding the initial lines we apply a linear estimation in order to obtain an optimal description of the obstacle position. In this context we use a two-dimensional line as model to be estimated and the projections of the selected 3D-data into the (x,y)-plane as measurement vector components.

C. Definition of the Free Space

To define the free space the results of the last processing steps must be carried together. In ideal case we can project the curb detected in the first step into the (x,y)-plane containing the distance profile and define a rectangle with the length of the smallest distance between the first and the second detected obstacles. However it is not guaranteed, that

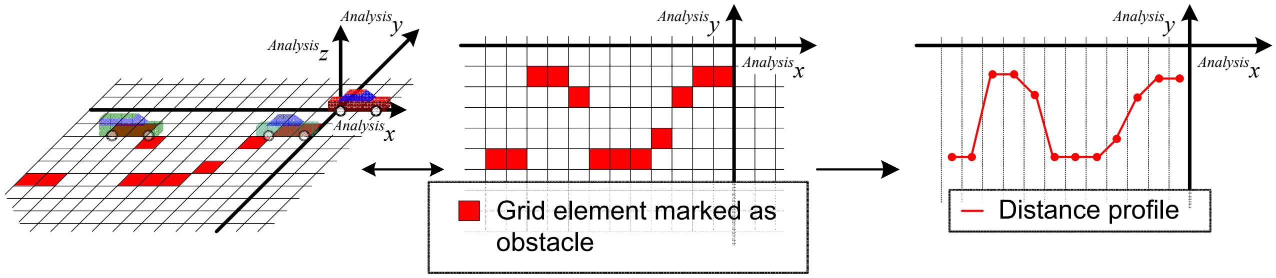

Fig. 7. Distance profile creation

the curb can be detected in each situation. In such cases a virtual curb parallel to the x-axis is placed, where the y-coordinate is calculated by means of the y-position of the first obstacle behind the sensor vehicle minus a standard vehicle width. Furthermore we evaluate the OBSTACLE_LOW-channel to make sure, that no other obstacles occur in the defined free space. For this purpose we apply the same method used for measurements extraction in the curb detection algorithm. In the case of detecting some obstacle, both the distance profile and the free space are accordingly corrected. The result of the free space definition for such instance is illustrated in figure 8.

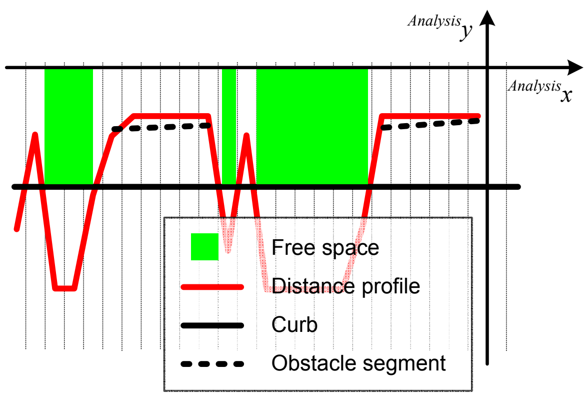

Fig. 8. Free space definition

VI. Results

A. Visualization

The current state of the measurement collection in a grid can be charted drawing each grid element in a colour value depending on its content. Therefore the colour of each is determined by the channel, which contains most of the measurements. The following colour-to-channel assignments were made:

- If the OBSTACLE_HIGH-Channel contains most of the measurements: red,
- if the OBSACLE_LOW-Channel contains most of the measurements: blue,
- if the GROUND-Channel contains the most measurements green, and
- if the grid element is empty, it's drawn white.

Following this assumption, figure 9 shows three subsequent timesteps of the summarization grid with the size 15 m × 15 m when collecting the measurements. The direction of the vehicle's movement is from top of the page to the bottom. The large green areas indicate a free space there. The red areas bounding the green horizontally are generated by parking cars. Since no measurements are available left of the car margin, a white recess is shaped.

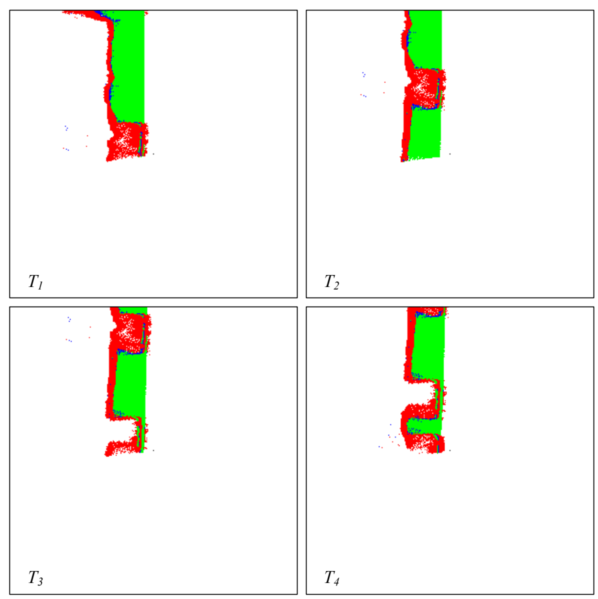

Fig. 9. Example sequence of a 15 m × 15 m summarization grid

As described in this paper, the measurement collection is followed by the curb search. Therefore, figure 10 shows the hits of the curb detector made in this analysis grid in magenta colour. Furthermore, the result line of the Hough transform is drawn.

In figure 11 the grid elements, which are marked as obstacle by the corresponding detector are coloured black. At the lowest obstacle the black grid elements are placed in the middle of the noisy measurements continously, which is an example for the robustness of the detector. The small green stripes on the left of the detected right obstacle margins are caused by the PMD sensor looking under the car.

After the distance profil has been created and verified, the free space is placed and metered. The results of the expample

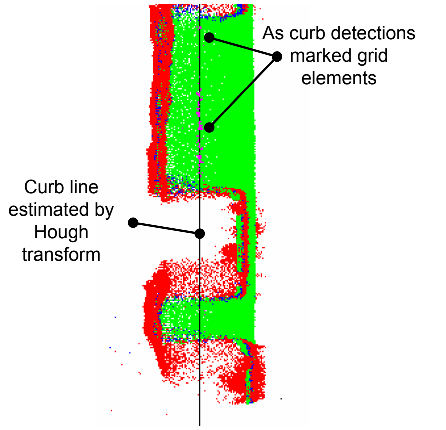

Fig. 10. Curb detection

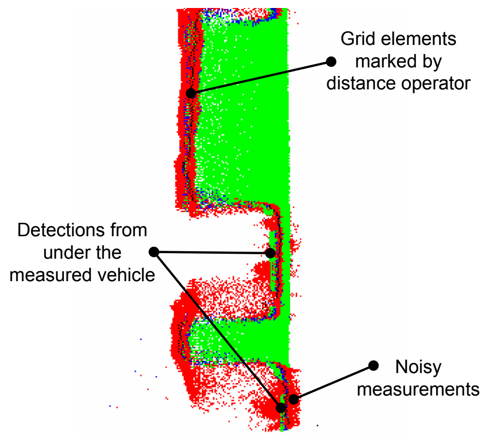

Fig. 11. Obstacle detection

used in this paper are shown in figure 12. The distance profile is plotted red, the unsteadiness detections are the blue lines.

The vertical black lines represent the preselected segements, which connect the inner jumps limiting an obstacle, as well as the LS-optimized line parameter. Since the left black line of the mid obstacle connects the blue jump endpoints, the right line shows the LS segment. You can see, that the result is very good alligned to the red plotted distance profile generated by the obstacle detector.

The demanded parking slots are marked with green colour, the x-lenghts are printed at their bottom.

B. Accuracy of estimation

To evaluate the accuracy of the parking space determination a set of measurement seqences with known sizes of the parking spaces was used. In this set, different scenes were recorded at daytime each with a few different vehicle velocities as well as different PMD sensor measurement frequencies. To make a statement about the algorithms accuracy the standard deviation of the parking space estimation was calculated. The results showed that the velocity of the vehicle does not have any strong influence on the accuracy, whereas different measurement freqency generated different result. Furthermore it is necessary, to adapt the obstacle detector

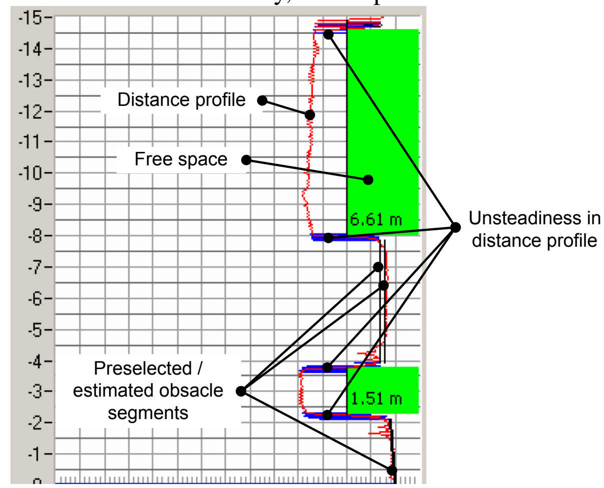

Fig. 12. Result display

threshold S depending on the measurement frequency. With a measurement frequency of 16 MHz and an threshold S of 40 % an average standard deviation of 25.2 cm was achieved for all 22 available parking slots considering all sequences. With a two frequency measurement method with alternating 16 and 0.5 MHz and an S of 30 % a standard deviation of 32.7 cm was reached. For this measurement mode 26 parking slots were available.

For the reliable detection of the curb a sufficient number of measurements is necessary. This demand is in general fulfilled by the pure 16 MHz data, which allow a perfect curb detection.

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