

Using 3D Laser Range Data for SLAM in Outdoor Environments

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Abstract

Robot navigation in poorly structured and uneven outdoor environments is an unsolved problem. Thus we present a SLAM (simultaneous localization and mapping) approach that is based on “leveled range scans”. The method is combining 3D perception with 2D localization and mapping. In this way established path planning and 2D navigation algorithms can be used in uneven terrain without the computational costs of full three dimensional modeling. The paper describes the processing steps data acquisition, obstacle segmentation, generation of leveled range scans and SLAM with these scans. Additionally, the paper shows experimental results in man-made outdoor environments as they are typical for civil used service robots (see video).

1. Introduction

Autonomous localization and mapping capabilities are widely accepted to be one of the key features of mobile robots. For this reason robot navigation has been an ongoing research topic for several years. Especially in recent years indoor navigation has made substantial progress. The development of simultaneous localization and mapping (SLAM) techniques, also known as CML (concurrent mapping and localization), allows the generation and localization within large consistent maps.

On the other hand navigation in outdoor environments is an open problem. The absence of simple features leads to the need for more complex perception and modeling. This mirrors in a big variety of navigation algorithms and map representations, depending on the kind of environment, the degree of structuring and the target application. Existing approaches can be roughly divided into three groups:

One group of systems act on the flat-world assumption. These systems are usually equipped with 2D laser range sensors and utilize 2D SLAM algorithms that are well known from indoor applications. As line or plane features are not applicable in outdoor environments [1], current implementations use artificial landmarks [2][3],

circular natural landmarks (trees) [4][5] or calculate the displacement by matching raw scans allowing all kinds of landmark shapes [6].

Other approaches for outdoor navigation build a 3D model of the environment. These complex and computational expensive methods are able to model completely unstructured environments as they can be found in rough natural terrain or on planetary surfaces. The most common data representation in these cases is the digital elevation map (DEM) that can model unstructured environments without overhang obstacles [7][8]. Usual perception systems in this kind of application are on one hand stereo-vision systems that provide fast, dense range images and on the other hand 3D laser range scanner that are slower but that can sense with a wider field of view.

The third category of outdoor navigation methods use 3D perception in combination with a 2D map representation [9]. These approaches combine the good performance of 2D navigation algorithms and break the constraint to flat worlds. This method is applicable in environments where a reliable determination between obstacles and the ground is possible. Thus it can not be used in rough terrain but in man-made outdoor scenes like factory sites, parks and urban environments.

This paper describes an approach that can be assigned to the third group. However, in contrast to [9] we use a different map representation and a segmentation algorithm that can also handle overhanging objects. The used SLAM algorithm is based on 2D *leveled range scans*. The output is therefore a scan based map that can model any kind of landmark shape, because it is based on raw data and has no feature extraction included.

The paper is divided into the following sections: data acquisition (section 2), generation of *leveled range scans* (section 3) including obstacle segmentation and data reduction and SLAM with *leveled range scans* (section 4). Section 5 shows experimental results of our real-time implementation within typical outdoor scenes.

2. 3D laser range scans

The 3D perception sensor we use is a laser range scanner. As there is no fast 3D scanner available at present, we use a commercial 2D Laser scanner, that works on the time of flight measurement principle and an extra servo drive to reach the 3rd dimension (see fig. 1). The alignment of the 2D laser scanner leads to a vertical base scan. The sensor is then turned around its upright z-axis to get a yawing-scan with a wide opening angle. The measured raw data is described as a point cloud that is ordered due to the scanning pattern. One scan point can be described in a cylinder coordinate system as follows:

$$\begin{aligned} P_{ij} &= (r_{ij}, \varphi_{ij}, z_{ij})^T, \\ 0 &\leq i < n, \\ 0 &\leq j < m. \end{aligned} \quad (2.1)$$

With i being the index of the vertical base scan and j being the index of the scan point within this vertical scan, ordered bottom up.



Figure 1: 3D laser range scanner

Fast 3D data collection with this type of sensor is still a challenging problem. In this case accurate synchronization of the laser measurement and the scanning device is important [10]. By using a real-time operating system to generate accurate measurement timestamps and data correlation upon this timestamps, it is possible to get undistorted point clouds within a short scanning time of 4 seconds.

2.1 Scanning While Driving

3D laser scanners that work on the described principle are currently only used with a fixed installation or on a standing robot. That is necessary as motion during the scanning process disturbs the measurement. On the other hand scanning while driving is essential for mobile robot navigation. Thus we contribute a method for move compensation that allows scanning while driving at walking speed.

As it is described above the 3D scan is assembled by transformation of the 2D base scans into the 3D robot coordinate system. To allow movement while scanning

it is necessary to transform these scan points into a coordinate system that is fixed to the world. The origin of this world coordinate system is set to be the robots position and heading at the start of the scan. The translation and rotation, and thus the transformation parameters, between the robot and the world frame are measured by dead-recognition. For 3D dead-recognition a combination of 3D fiber-optic gyro and wheel-encoder is used.

The result is an undistorted 3D point cloud referring to the robot position at the start of the scan. The accuracy of the point cloud depends on the accuracy, especially the orientation accuracy, of the 3D dead-recognition. The drift of dead-recognition sensors is no problem in this application as it is only used to measure the relative distance traveled during one scanning period, but still accurate synchronization and short scanning times play a major role.

3. The leveled range scan

Our approach to bring SLAM together with 3D perception is based on a data type we call *leveled range scan* that can be described in polar coordinates as follows:

$$\begin{aligned} L_i &= (r_i, \varphi_i)^T, \\ 0 &\leq i < n. \end{aligned} \quad (3.1)$$

This scan contains obstacle measurements in the surrounding of the robot, which can be used as natural landmarks. Thus it is similar to a 2D laser scan taken on a plane ground, with the difference that it is generated from a 3D laser range scan. Thereby the *leveled range scan* can be taken with a robot standing on uneven ground, independently of its orientation. Moreover, landmarks on different levels, e.g. on a hill or in a dell, can be seen, in contrast to traversable bumps and hills that are not contained. The generation of these *leveled range scans* can be divided into two steps, an obstacle/ground segmentation within the 3D point cloud and the projection of the segmented 3D measurement into the plane leveled scan. As the procedure contains no feature extraction the *leveled range scan* can be used for navigation with any kind of landmarks.

3.1 Segmentation

The classification of 3D point clouds is usually the first step to compute 3D data. For this reason, the literature knows several algorithms for obstacle-detection or rock/ground-segmentation [11][12]. In this paper we use an obstacle definition that is related to the one given in [13]. This obstacle definition is extended in a way that it knows two kinds of obstacle points: landmark-points and overhang-points. This extension brings advantages in the following projection step.

Surface points which are vertically aligned can be extracted easily and allow reliable matching from different viewpoints. Thus they are preferred as natural landmarks and are named landmark-points in our approach. Landmark-points can be found on the surface of e.g. tree trunks, poles, walls, parking cars and various other man made objects. The second kind of point is named overlap-point. This kind of point has got no direct connection to the ground and can thus be found in treetops or on roofs. This kind of obstacle is not especially addressed in other obstacle segmentation algorithms and it is not used for localization, but it needs to be treated in our approach as it would otherwise disturb the following projection step.

The obstacle definition that is the base for the used algorithm, is given as follows:

A surface point P_{ij} is an overhang-point if there is at least one point P_{ik} within the same vertical scan and with a lower angle that has a larger distance to the sensor:

$$\begin{aligned} P_{ik,r} &> P_{ij,r} + R_t, \\ 0 &\leq k < j. \end{aligned} \quad (3.2)$$

With R_t being the minimum overhang distance.

A surface point P_{ij} is a landmark-point if there is at least one point P_{ik} within the same vertical scan that is “below” P_{ij} and P_{ij} is no overhang-point. With “below” defined as:

$$\begin{aligned} H_t &< P_{ij,z} - P_{ik,z} < H_{\max}, \\ \left| \frac{P_{ij,r} - P_{ik,r}}{P_{ij,z} - P_{ik,z}} \right| &< \tan(\alpha_t), \\ 0 &\leq k < j, \\ H_{\max} &= \frac{R_t}{\tan(\alpha_t)}, \end{aligned} \quad (3.3)$$

where H_t is the minimum height of a landmark and α_t is the maximum angle misalignment.

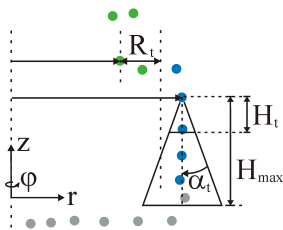


Figure 2: Definition of obstacle points (overhang-point green, landmark-point blue)

3.2 Projection

The projection step is extracting the 2D *leveled range scans* from the segmented 3D point cloud. This step is performed by selecting one landmark-point per vertical base scan and projecting these selected points parallel onto the horizontal plane. We select the first landmark-point searching bottom up:

$$\begin{aligned} L_{i,r} &= P_{ij,r}, \\ L_{i,\varphi} &= P_{ij,\varphi}, \end{aligned} \quad (3.4)$$

where j is the index of the first point in the vertical scan i which is labeled as a landmark-point.

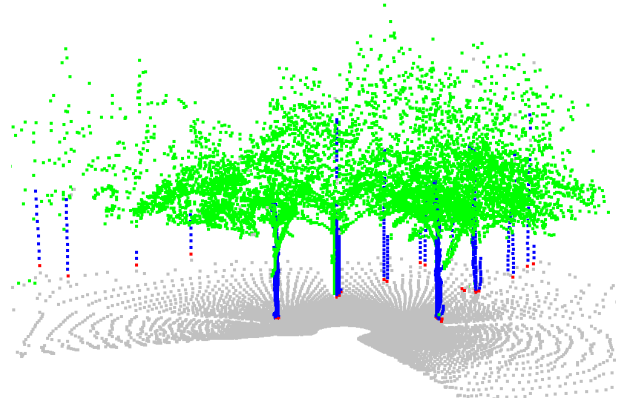


Figure 3: Segmented 3D point cloud

4. Scan based SLAM

Successful autonomous robot navigation in unknown and unstructured surroundings relies on the ability to generate environmental maps. Traditionally, the navigation problem can be divided into two separate problems: localization and mapping. However, when the robot has to navigate in an unknown environment, both the robot position and the map are unknown. In this case localization and mapping must be solved in a holistic approach and cannot be considered independently from each other. This problem is usually known as simultaneous localization and mapping (SLAM) problem.

In this work the scan based SLAM algorithm presented in [6] is used for navigation in unknown environments. This method attempts geometrically correct representing of all natural landmarks occurring in poorly structured outdoor environments.

4.1 Map representation

For environment representation the scan based map is used. Thus, instead of extracting individual geometric features from a laser range scan, it is interpreted as a partial local image from the whole environment. By overlapping all single scans, a geometrically correct

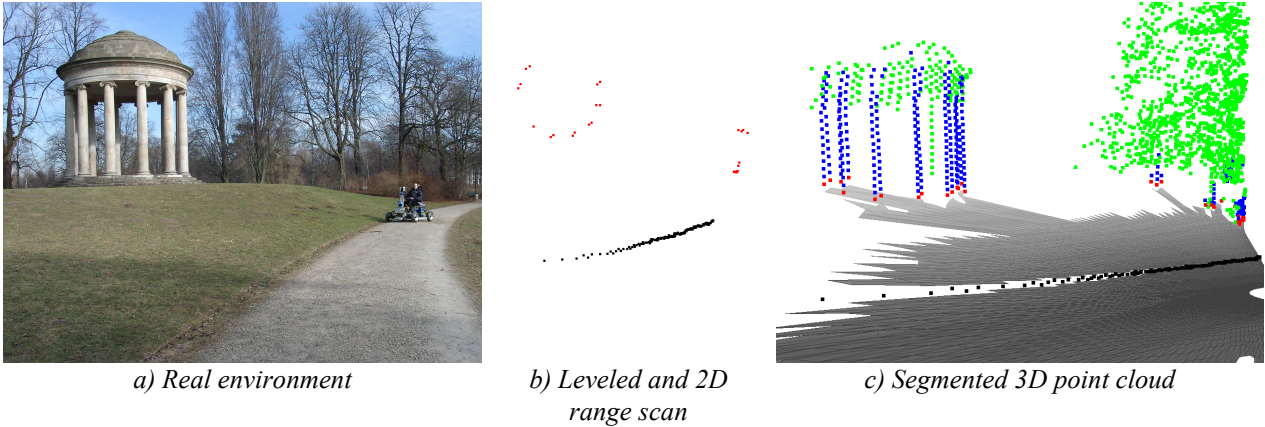


Figure 4: Comparison of 2D range scans (black) and leveled range scans (red).

representation of natural landmarks occurring in poorly structured outdoor environments is possible. In this case no restrictions concerning the geometrical contour of the landmarks are needed. All objects are faithfully reproduced, and the accuracy of the map is primarily restricted to the maximum resolution of the laser scanner.

To build a scan based map, full sets of sensor data are collected at different environment positions. Every set integrates measurements from laser range scanner, odometry and GPS. These sets of sensor data are representing network nodes [6]. The distances between two individual nodes are denoted as network edges. The value of the distances are observed from the different sensors.

4.2 Sensor observations

An extended IDC algorithm similar to [14] is used to observe the travelled distance between two data collecting positions by matching overlapped laser range scans. In addition, an extension for outdoor applications with a validation heuristic is implemented. This heuristic calculates the quality of the scan matching, which represents the estimated uncertainty of the observed distance. Because of the different structure compared to indoor environments, the original algorithm to calculate the standard deviation is not working correctly. The IDC algorithm is based on a point-to-point correspondence between scans that are compared. Two heuristics build pairs of points that are used to compute the rotation and shift between the two scans.

With odometry only relative distances between robot positions can be observed. However, the calculation of a network edges by odometry is depending on the orientation of the network node. Thus, to get only linear dependencies, odometry can only be used for successive robot positions. For other network edges the transformation gets non linear.

With GPS absolute but inaccuracy position information for every environment position is available. These data are used to observe the distances between every node of the network.

4.3 Map optimization

By solving a set of linear equations which describes the constraints of the sensor observation network an optimal solution for the environment map exists. In addition to general SLAM problems, e.g. convergence, consistency, accuracy and boundedness of the map error, the algorithm gives a high precision environment map independent of the type and the structure of available natural landmarks. That allow the use of the algorithm in unstructured outdoor environments without the explicit identification of single objects.

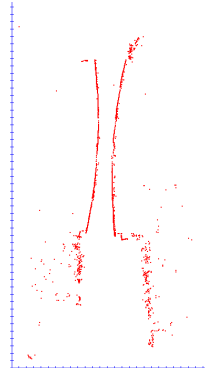
However, by using fixed mounted 2D laser range scanner localization and mapping was only possible in mostly even environments. With the integration of 2D *levelled range scans* generated from 3D environment data into the scan based SLAM algorithm, high precision localisation and mapping with natural landmarks also in hilly environments is possible.

5. Experimental results

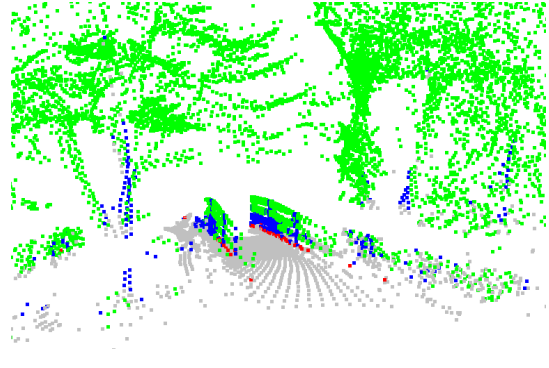
The experiments presented here were made in the park area of the University of Hannover (see video). This area is a typical man-made environment with different kinds of natural landmarks like trees, bushes, houses, bridges, park benches, hedges, cars and so on. The ground level in this area varies from flat to elevation differences of several meters within sensor range. But the environment is in general drivable with our service robot. To demonstrate the advantages of our algorithms we focus our experiments to local hilly areas of the park environment.



a) Real environment



b) Scan based map



c) Segmented 3D point cloud

Figure 5: The robot autonomously generates the scan based map while crossing the bridge

5.1 The leveled range scan

For the perception of outdoor environments a 2D laser range scanner can be used. However, this sensor is usually fixed mounted to the robot chassis and scans the environment in a horizontal plane. Thus, when the robot is moving in uneven terrain, it is not to ensure that the scanning layer at the different positions always have the same orientation. This entails the problem of different points of view of the scanner for the same environment. Especially in outdoor environments, the geometrical contours of natural landmarks are not homogeneous in height. They look different from variable perspectives and views. But to recognize the same landmark in two contiguous scans they have to look similar. So the observing perspective should be almost the same. This condition is not complied in hilly environments. Due to the different orientations of the robot while moving, the number of corresponding landmark points between two sequent scans is small. In some cases, even no landmark points are visible at all, see figure 4a. A 2D scanner that is fixed mounted one meter above the ground can only see the shape of the hill (black points in fig. 4b and 4c). Further natural landmarks are not perceptible for the scanner. Thus, reliable localization and mapping in this area with only a 2D scanner is not possible.

With the use of *leveled range scans*, landmarks on hills or in dells are visible. In the example of figure 4a, the pavilion on top of the hill is observable with the 3D scanner. After segmentation and projection, the *leveled range scan* includes extracted landmark data from the pavilion (red points in fig. 4b and 4c). This allows reliable landmark detection in areas with low landmark density and in hilly regions.

5.2 2D environment maps

To demonstrate the usability of *leveled range scans* for the navigation of autonomous service robots we present the generation of 2D maps in hilly environments. The described scan based SLAM algorithm is used to

autonomously generate an environment map while the robot is crossing a bridge (figure 5a) with continuous motion. This bridge has an overall length of 24m and an altitude difference of 2m.

For data perception a 3D laser range scanner is used. A typical 3D point cloud in this surrounding is shown in figure 5c. Here the horizontal opening angle is 270° and the vertical opening angle is 100° . The scanning time for these 27.000 range measurements is 4s. The red points in figure 5c represent the *leveled range scan*, which is used for SLAM.

The 3D data perception is done at equidistant points on the way. The spacing between two sequent scans is about 5m. For relative distant measurements the odometry is used. With this data the SLAM algorithm calculates an 2D environment map (see figure 5b). This map has a size of 25m x 50m and shows the bridge from a top view. In front of the bridge bushes and low vegetation can be seen.

6. Conclusion and future work

With this paper we presented an efficient navigation system for poorly structured outdoor scenes like parks, factory sites or urban environments. The combination of a 3D perception sensor with 2D environment modeling allows autonomous navigation in uneven and hilly environment without the computational costs of full 3D modeling.

The 3D Sensor we used is a proprietary development that is based on industrial standard products, whereas the sensor alignment and the accurate synchronization make it possible to take undistorted scans ($270^\circ * 100^\circ$) within 4s. The measured 3D point cloud is segmented to extract landmark-points, which are obstacle points that are especially suitable for landmark matching. Only special landmark-points are than projected parallel onto the horizontal plane to obtain a *leveled range scan*. As overhang-points are treated separately within our segmentation and projection algorithms, overhanging obstacles (e.g. tree tops) do not disturb the projection.

The constructed 2D *leveled range scan* is similar to a conventional 2D raw scan taken in a plane environment and can thus be used for 2D SLAM algorithms. The SLAM algorithm we used in this paper is building a scan based map. Therefore it contains no feature extraction. This enables the use of any kind of landmark shape without loss of precision.

In addition to the description of the algorithms, experimental results show the capabilities of our real-time implementation, where the test scenes are especially chosen to show the known limitations of pure 2D systems.

A 3D perception sensor is providing the robot with a huge amount of data that is rapidly reduced to allow efficient computation in our approach. Certainly this massive data reduction comes along with loss of information. Future work should therefore try to reduce the amount of data without loss of essential information, what leads to 3D feature extraction. A good feature extraction could also provide the information that is needed to solve the data association problem known from SLAM. However, a 2D map representation is sufficient in the described environments and should be kept for efficiency reasons in our opinion.

Another related research topic is 3D perception. Advances in sensor performance could allow the robot to drive faster, as the measurement time of the scanning system is currently limiting the system speed.

7. References

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