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Using Histogram Correlation to Create Consistent Laser Scan Maps

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Abstract

The paper presents an approach to generate consistent maps in real-time using a laser range sensor. Its application scenario is the Bremen Autonomous Wheelchair "Rolland" (cf. Figure 1 and [4][10]) that is developed as an autonomous transport vehicle for hospitals. The paper consists of two parts: in the first one, a laser scan matching method is presented that improves an algorithm originally proposed by Weiß et al. [12] in several aspects. In the second part, a mapping approach is introduced that is based on the scan matching method. Using a laser scanner mounted on the wheelchair, it generates consistent maps, i.e. maps that do not have discontinuities resulting from the accumulation of errors in the mapping process. As such accumulations cannot be avoided, the resulting errors are corrected whenever the wheelchair returns to areas already mapped. An important property of the presented approach is its real-time capability. The mapping is performed on the fly and thus, the resulting maps can immediately be employed for self-localization.

Figure 1: *The Bremen Autonomous Wheelchair*

1. Introduction

Many approaches for the automatic generation of robot maps use scan-matching methods, i.e. they relate individual parts of two laser scans in order to determine the spatial offset between the two positions at which the scans were taken. To determine the relating sections of the scans, Lu and Milios [7] use a point to point assignment, and Gutmann and Schlegel [2] combine the approach with the point to line matching of Cox [1][6]. Both are iterative methods, i.e. they need relatively much processing time. Therefore, they are executed offline after all distance data was already acquired. Both approaches are based on the use of 360° scans. If the laser scanner cannot supply these, because it has, e.g., only an opening angle of 180°, the robot rotates on the spot and takes several measurements, which thereafter are combined to a single 360° scan. In contrast, Mojaev and Zell [8] inserted the scan points into local grid maps, and thereafter these local grids were matched to generate a global map. For this approach, a 360° scanner is not necessary, but the procedure requires a sufficiently precise odometry so that the local maps are consistent in themselves. In the method of Weiß *et al.* [12], histograms are matched that are calculated from the scan points (cf. Section 2).

There is only little work on consistent sensor maps. Lu and Milios [7] presented an algorithm to create consistent laser scan map, but it is too slow to be performed online. Kuipers and Byun [3] introduced the Spatial Semantic Hierarchy, according to which a robot should first acquire topological knowledge, and employ that to build a metric model of the environment afterwards. However, the only known implementation on a real robot [5] shows that a lot of model-based feature detection is required to acquire the topological information. A probabilistic approach for the generation of consistent maps is proposed by Thrun *et al.* [11].

2. Original Histogram Matching Approach

The approach presented in this paper is an extension of the method of Weiß *et al.* [12]. The basic idea of that scan correlation algorithm is to find characteristics that remain unchanged over several scans that were taken in the same environment but from different positions and from different angles. Such characteristics form a common signature between the scans to be matched, which makes them comparable. These signatures are calculated as histograms over the distribution of angles and distances in the measured scans. By the correlation of the histograms of two overlapping scans, their rotational and translational shifts can be determined.

2.1 Rotation

In a laser scan, the individual distance measurements and the angles under which the distances were measured (in the sensor's system of coordinates) can be interpreted as vectors, which correspond to the laser beams that scan the surroundings. If a scan was taken in an environment in which walls or other planar surfaces such as shelves or cabinets are visible to the sensor, many of the points described by these vectors result from measuring these surfaces. All points that are on the same surface describe a common straight line that represents this surface. If pairs of neighboring points are connected by straight lines, all the small lines that share the same surface have similar orientations. However, resulting from measurement inaccuracies, individual points have small lateral deviations to the straight line (in case of the scanner employed, approximately ±2 cm). Such a scan with lines that connect neighboring scan points is illustrated in Figure 2.

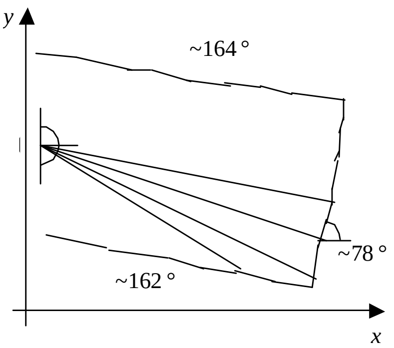

Figure 2: *Laser scan with points connected by lines*

The angles between the lines connecting two neighboring points and the *x*-axis approximately correspond to the orientations of the surfaces in the surroundings, both seen in the scanner's system of coordinates, i.e. the origin is in its center, the *x*-axis points to the front, the *y*-axis points left. A distribution statistics of the orientations of all these small lines results in the *angle histogram*. From that histogram, it can be determined, how frequently each orientation occurs in the scanned part of the environment. If many scan points result from measuring planar surfaces with the same orientation, for this certain angle, a maximum is accumulated in the histogram. An angle histogram generated from the scan depicted in Figure 2 is shown in Figure 3.

The angle histogram of a second scan taken from a somewhat shifted and turned position contains maxima that cover similar range and angles as those in the first histogram, but they are out of phase. The phase shift results from the different angles between the scanner at different positions and the measured surfaces in the environment. Since the offsets between the maxima remain constant independent of rotation and translation, they can be used as signatures. By means of a cross correlation, the phase shift between different angle histograms can be determined. This phase shift between the histograms corresponds to the rotational shift between the positions where the two scans were taken.

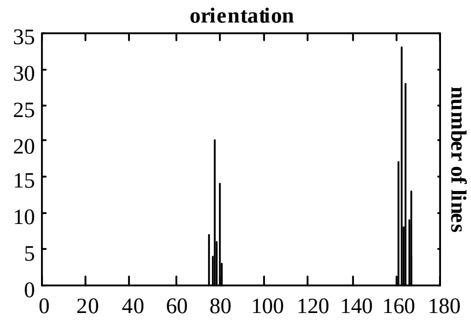

Figure 3: *Angle histogram of the scan in Figure 2*

2.2 Translation

The translational shift is calculated by generating two histograms representing the distribution of the distances of the scan points from the *x*- and *y*-axis, respectively. In such a histogram, accumulations of equal distances occur at positions, where planar structures such as walls are oriented perpendicular to the direction of the corresponding axis, i.e. the *x*-axis for the first translational histogram and the *y*-axis for the second. Since walls are not oriented perpendicular to the axis in general, the scans must be suitably rotated before.

To accomplish this, the corresponding angle histogram is searched for the *main direction*, i.e. the angle most surfaces are aligned to. If the scan point vectors are rotated by this angle, these surfaces are oriented in parallel to the *x*-axis. Therefore, the *y*-coordinates of all scan points resulting from measuring these surfaces are similar. When entering these *y*-coordinates into a histogram, a maximum is generated at the corresponding position. Analogously to the matching of angle histograms, two such distance histograms can be correlated to determine the translational shift perpendicular to the main direction. Without further rotation, the method of Weiß *et al.* [12] builds a second histogram to determine the shift along the main direction, which only works in environments with perpendicular walls.

3. Extended Histogram Matching

The extended version of the histogram matching approach provides improvements with respect to the following aspects: First, the matching is not performed with two complete scans. Instead, a *projection filter* [7] is applied two both scans first. Based on an estimated offset between both scan positions, it removes all points from one scan that result from surfaces that cannot be seen from the recording position of the other scan and vice versa (cf. Figure 4). Then, line segmentation is applied instead of only using neighboring scan points to determine the orientations of the surfaces. From the huge amount of line segmentation approaches, the generalization algorithm developed by Musto et al. [9] is employed. The lines are used to calculate the histograms. These histograms are not representing the numbers of scan points any more; instead they directly sum up the lengths of all surfaces with equal orientations or translational offsets. In order to work in non-perpendicular environments (but still with planar surfaces), two main directions are determined. Last but not least, all correlations are performed in two steps, one with a coarse resolution in a large search space, and a second with a fine resolution but a small search space.

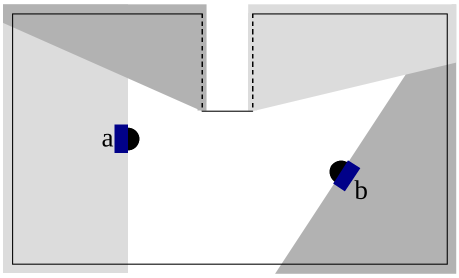

Figure 4: *Scan points removed by a projection filter. Areas marked in light gray cannot be seen from scan position (a), and areas shown in darker gray cannot be perceived from scan position (b).*

The whole matching procedure is performed in the following way: before the matching, both scans are transformed into a common system of coordinates, i.e. the one of the first scan. The second scan is transformed into that coordinate system based on odometry and previous corrections of the position estimate (cf. Section 4). Then, the correlation of the angle histograms is performed (cf. Figure 5a), determining the rotational shift between the two scans. If the estimated rotation was already correct, the calculated shift will be 0°, and no correction is required. Otherwise, the second scan is rotated according to the determined shift to align both scans (cf. Figure 5b).

After this step, the rotation is correct. Therefore, it is only necessary to determine the first main direction of one scan, i.e. the first one, because this also should be the main direction of the other scan. Based on this common main direction, both scans are aligned in parallel to the *x*-axis (cf. Figure 5c), *y*-histograms are generated, and then they are correlated. Again, if the estimated position was already correct, the correlation will result in a translational shift of 0 cm and no correction is required. Otherwise, the second scan is shifted along the *y*-axis (cf. Figure 5d). Then both scans are rotated again to align the second main direction in parallel to the *x*-axis (cf. Figure 5e), and, again, to correct the current *y* displacement (cf. Figure 5f). After the successful correlation, both scans are rotated back to the first scan's original orientation. As a result, the position of the second scan has been corrected in all three dimensions.

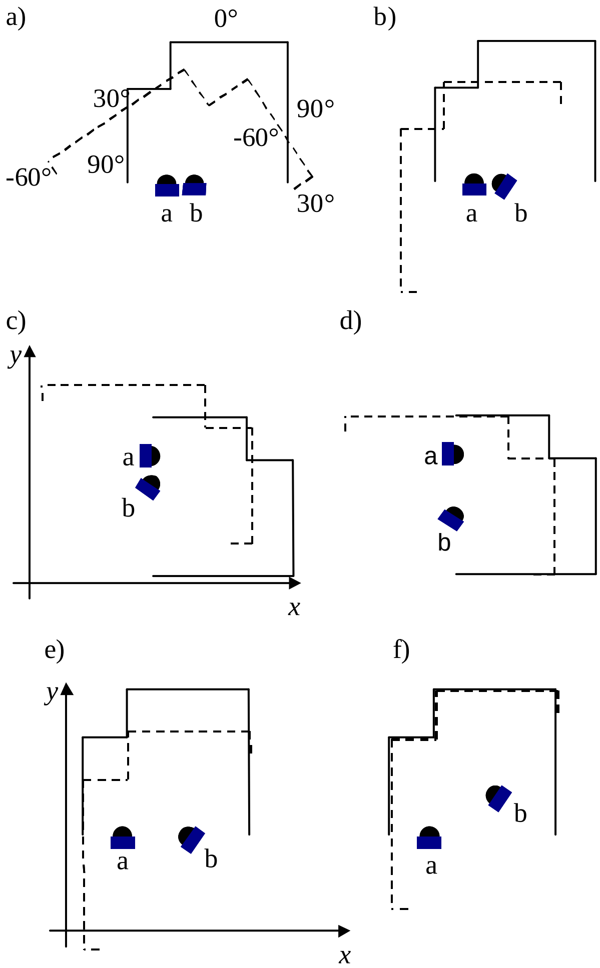

Figure 5: *Matching two scans*

In long corridors, it is not always possible to determine a unique correlation for the direction along the corridor, because perpendicular to the corridor, there are too few distinguishable features. Therefore, under normal conditions (cf. Section 4), it is allowed that the second translational correlation fails, i.e. the correlation of the best matching shift is not significantly larger than the one of the second best. In that case, this part of the position correction relies only on odometry.

4. Map Building

If the offset between the positions of two scans can be determined, this also can be performed several times consecutively with different scans. Thus, the metric offset relative to the initial position can be determined. In comparison to purely odometry-based dead reckoning, a significantly higher accuracy is obtained: odometry is based on the assumption that the actual movement of a mobile system is accurately reflected in the revolution of its wheels, which, however, is rarely the case for several reasons (slippage, carpet, variable wheel diameter of pneumatic tires, etc.). The method presented here uses external structures as references; therefore the movement of the system should be recognized precisely in any case. However, similar to dead reckoning, several small spatial offsets are summed up, resulting in an accumulation of errors, too. There are two possibilities to reduce such mistakes: On the one hand, because of the large measuring range of the laser scanner, scans can be correlated that were recorded several meters apart. If the offsets are large, their number can be significantly reduced, resulting in a smaller accumulation of positional errors.

On the other hand, and in contrast to odometry, scan matching provides the possibility of correcting the accumulated error. If the scans taken and successfully correlated are stored in a map, this map can be used to correct the position estimate when the mobile system returns into an area of the environment already mapped. Thereby, the error cannot grow arbitrarily. Instead, it will remain under a certain limit that results from the longest distance that can be driven without returning to an area already known.

4.3 The Map

The map is represented as a list. Each entry in the list consists of a laser scan, the metric position, at which it was taken, and the so-called *frame of reference* (FoR). The FoR is a value that is initialized with the odometer counter, i.e. with the distance already driven by the wheelchair. Therefore, when comparing the FoRs between two different scans, it can be determined how far the vehicle traveled between the recordings of these two scans. In fact, this value may differ significantly from the Euclidean distance between the positions, where the two scans were taken. The FoR is used to influence the search space during the correlation of scans, e.g., between scans with a similar FoR, the error accumulated cannot be very large, and therefore the maximum shifts that have to be checked can be kept small.

4.4 The Mapping Process

At the beginning of the mapping process, the current position is initialized with (x, y, rotation) = (0, 0, 0°) and the odometer counter is set to 0. A laser scan is taken and inserted into the map.

Then, for each further laser scan taken, the map is searched for a set of adequate *reference scans*, and the new scan is matched with each of these scans until one match is successful. As has been described in Section 3, the result of the scan matching procedure is a correction of the estimate of the scan's recording position, i.e. the current position of the wheelchair. That way, the current position estimate is continuously corrected.

However, it is possible that the matching process fails for all reference scans, because all scans have too few similarities with the current scan. In that case, the last scan that was successfully correlated is inserted into the map, i.e. the scan taken before the current one, and the selection of reference scans is repeated.

4.5 Selection of Reference Scans

There are three selection criteria for reference scans. The value of the scan's FoR shall be as small as possible, because the smaller its value is, the older the scan is. Old scans have accumulated less positional error, and are therefore better candidates for being used as a reference for the correlation with a new scan. In order to be able to match two scans, it is advantageous if they have a large overlap between their scan points. The overlap can be determined by applying the projection filter to both scans and by counting the remaining scan points. As this is a computationally expensive operation (at least if performed for all scans in the map), only those scans from the map are selected that were taken at a position in a certain radius around the current position.

4.6 Consistence

Whenever the wheelchair returns to an area already mapped, i.e. it closes a cycle, a reference scan from that region will be selected, because it is older than the reference scan previously used. Then, because of the big difference between the FoR of the current scan and the FoR of the reference scan, the search space of the correlation is large. This increases the risk of a mismatch, and therefore the results of the correlations must be very clear to be accepted. In addition, it is required that the correlations for all three dimensions (the rotational shift and both translational shifts) are successful.

a) b) c)

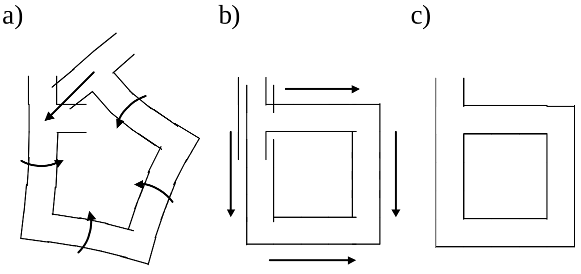

Figure 6: *Distribution of the error. a) Rotational error. b) Translational error. c) Result*

In such a case, the accumulated error has to be distributed among the scans in the map that have been recorded after the current (old) reference scan and the reference scan used previously. This is done in two steps: first, the rotational error is dispersed by slightly changing the rotation between successively recorded scans that have different FoRs, keeping the relative translational offsets (cf. Figure 6a). This can be compared to bending straight a paper-clip. Then, the x- and y-errors

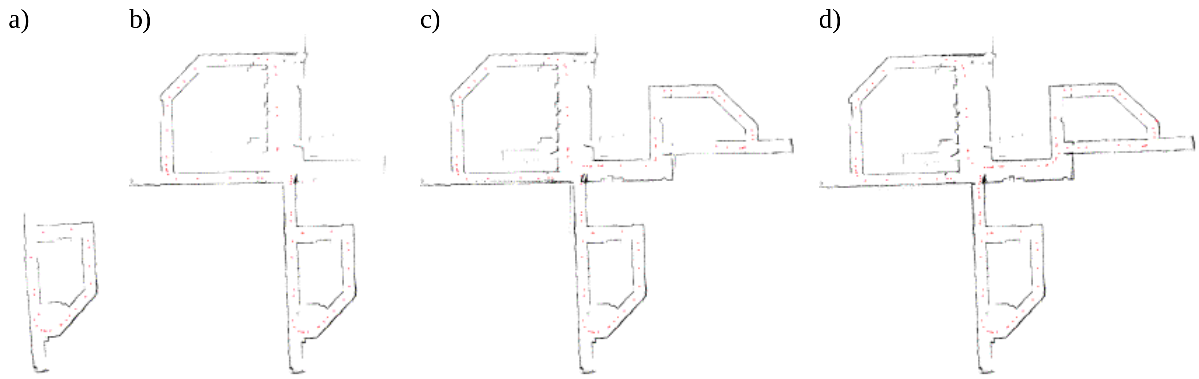

Figure 7: *Four snapshots while mapping an office floor*

are distributed (cf. Figure 6b). Again, the local offsets between scans with equal FoRs remain unchanged. The corrections are not performed uniformly; instead they are weighted by an uncertainty value that was determined during the scan matching process, before the scans were inserted into the map. After the corrections, the FoRs of all scans corrected are set to the FoR of the initial scan in the cycle, i.e. the cycle is now assumed to be consistent, and therefore all its scans share the same FoR. Note that this prevents the local metric relations between the scan positions in this cycle from being changed again, e.g. when a larger cycle is closed.

5. Results

On the Pentium III-600 computer used on the Bremen Autonomous Wheelchair, the matching algorithm is able to determine more than 14 corrections of the position estimate per second. However, this high update rate is not required. Therefore, enough computing power remains for other applications on the wheelchair. For comparison: On a similar computer, the map-building method developed by Mojaev and Zell [8] would only be able to perform five adjustments of the position per second, although it requires the rotational odometry error to be less than 4° since the last correction of the position.

The mapping process is illustrated in Figure 7. The office floor that is mapped has a size of approximately 50×50 m. The wheelchair was manually driven along a path of 200 m through this environment. Starting in the upper horizontal corridor shown in Figure 7a, the wheelchair drove through the small cycle in clockwise direction until it almost returned to the start position. As can be seen in Figure 7a, a small drift had already been accumulated. It was corrected when the mapping algorithm closed the cycle. The result is depicted in Figure 7b. It is also shown in that figure, how the generation of the map continued while the wheelchair was driving to the central crossing, turning left, and following the large corridor cycle to the left in clockwise direction. The wheelchair returned to the central crossing and turned left again, i.e. it drove to the right part of the office floor. At that moment, the algorithm was not able to detect that the wheelchair had returned to a known area, because the overlap between the actual scans and the scans stored in the map was too small. Note that the scanner is mounted at the backside of the wheelchair and can see only 180°. Therefore, from Figure 7b to Figure 7c, no correction of the map took place. The journey was continued through the small cyclic corridor on the right, again in clockwise direction. In Figure 7d, the wheelchair was driven back to its start position. The mapping algorithm had corrected the position error accumulated in the right corridor, and it also removed the deviation at the central crossing. This demonstrates that the approach is able to handle the “cycle in cycle” problem.

During the journey, the Sick laser scanner delivered 9403 scans, 4208 of which could be processed, i.e. the algorithm was fast enough to use almost every second scan. Out of these 4208 scans, 122 were stored in the map. Only these scans are depicted in Figure 7d.

Figure 8 shows two other examples of maps generated by the algorithm. They were both created in the same environment, i.e. another floor of the same building, but the wheelchair followed different routes. Figure 8a depicts the two different trajectories: the map shown in Figure 8b was created while following the route drawn as solid line, whereas the map in Figure 8c was generated along the trajectory shown as dashed line.

6. Conclusion and Future Work

The paper presented an algorithm that is able to generate consistent maps from the readings of a laser range sensor in real-time. During mapping, accumulated errors are eliminated when closing cycles. The underlying scan matching approach is an extended version of a method originally developed by Weiß et al. [12]. It is very fast and robust.

Currently, it is tried to map larger regions, both indoors and outdoors. Figure 9 shows a map of the university campus, generated while traveling a 2,176m route. On such a long distance, the laser scanner is confronted

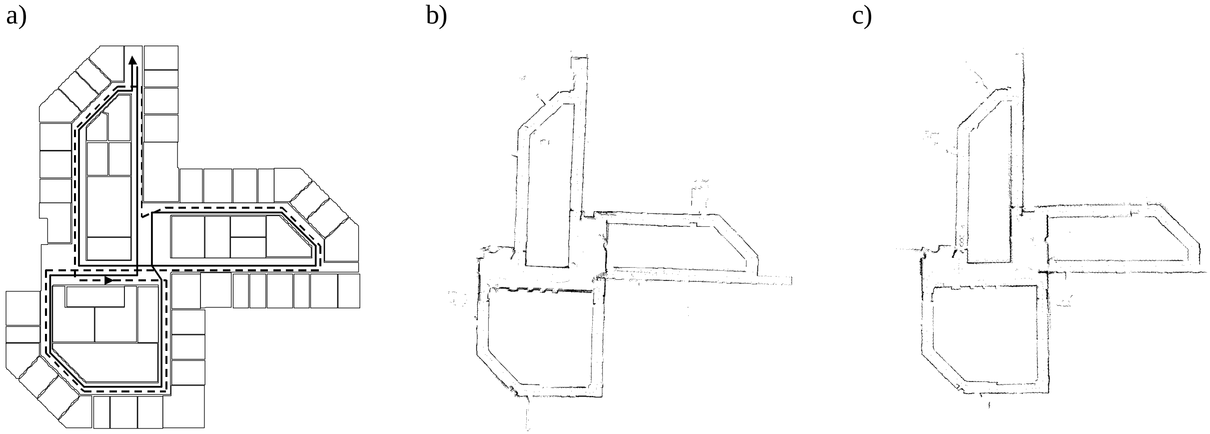

Figure 8: *Two maps of the same environment generated on different routes*

with objects that it cannot measure very well, e.g. glass and wire netting fence. Therefore sometimes, the precision of the map simply reflects that of odometry, which is very poor.

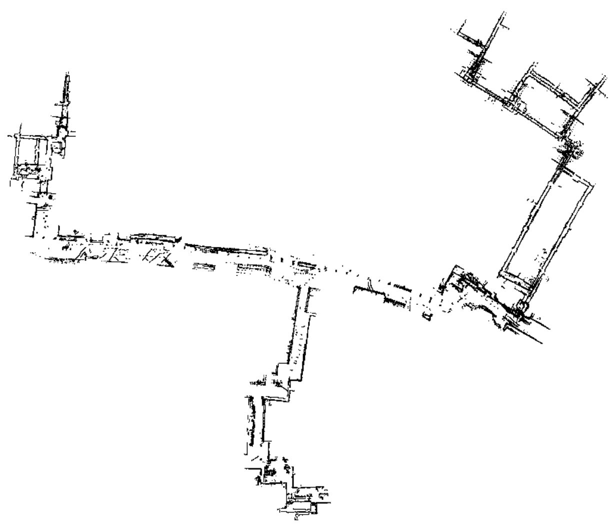

Figure 9: *A partial laser scan map of the Bremen university campus of approximately 350m × 350m in size.*

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