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BUILDING 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" 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 in several aspects improves an algorithm originally proposed by Weiß et al. [14]. 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.

1. Introduction

Bremen Autonomous Wheelchair

The Bremen Autonomous Wheelchair "Rolland" (cf. Figure 1) is based on the commercial power wheelchair *Genius 1.522* manufactured by the German company Meyra. The wheelchair is a non-holonomic vehicle that is driven by its front axle and steered by its rear axle. The human operator controls the system with a joystick. The wheelchair is equipped with a standard PC (Pentium III 600MHz, 128 MB RAM), 27 sonar sensors, and a laser range sensor behind the seat that has an opening angle of 180° toward the backside of the wheelchair. It is able to deliver 361 distance measurements every 30 ms. The original Meyra wheelchair already provides two serial ports that allow for setting target values for speed and the steering angle as well as determining their actual values. Data acquired via this interface is used for dead reckoning. The odometry system based on these measurements is not very precise, i.e. it performs well in reckoning distances but it is weak in tracking angular changes.

Figure 1: The Bremen Autonomous Wheelchair

In the moment, the two main applications are the *Driving Assistant* and the *Route Assistant*. The Driving Assistant [6][12] provides an interface of a safe wheelchair to higher level navigation modules or the user, respectively. The principal idea is to wiretap the connection between the joystick and the motor. If the human operator issues a command that may lead to a collision with an obstacle, the wheelchair autonomously changes the dangerous command into a safe one. To be able to make this decision, the Driving Assistant maintains an occupancy grid as local obstacle map. The 27 sonar are ringwise mounted around the vehicle. The sensors deliver the distance information that is stored and processed in the map.

On the other hand, similar to GPS-navigation systems in modern automobiles, the Route Assistant [6] instructs the user to find his or her goal by indicating the next travel direction at decision points such as crossings.

Scan Matching

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 [9] used a point to point assignment, Gutmann and Nebel [3] combined the approach with the point to line matching of Cox [1][8]. 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 [10] 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.* [14], histograms are matched that are calculated from the scan points. In order to determine the rotational deviation between two scans, different orientations of lines built from neighboring scan points are represented in histograms for each scan, and these are correlated. Thereafter, the rotational offset between both scans is known. Then, the so-called *main direction* of the two scans is determined. The main direction of a scan is the orientation that is shared by most lines generated from connecting pairs of neighboring scan points. Rotating these two scans according to their main direction yields x and y histograms, the correlation of which allows to determine the spatial shifts in the two Cartesian directions. Again, this procedure is based on the use of 360° scans.

Under the basic conditions specified above, i.e. the weak odometry of the wheelchair and the 180° opening angle of the laser scanner, none of the presented approaches could be implemented on the Bremen Autonomous Wheelchair unchanged. After considering the pros and cons, an extension of the method of Weiß *et al.* [14] was developed.

Consistent Sensor Maps

There is only few work on consistent sensor maps. Lu and Milios [9] presented an algorithm to create consistent laser scan map, but it is too slow to be performed online. Kuipers and Byun [5] introduced the Spatial Semantic Hierarchy, according to which a robot should first acquire topological knowledge, and employ that to afterwards built a metrical model of the environment. However, the only known implementation on a real robot [7] 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.* [13]. However, the method is only able to work in real-time when only few sensor readings have to be processed, which is not suitable for all environments.

2. Original Histogram Matching Approach

The basic idea of the scan correlation algorithm of Weiß *et al.* [14] 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.

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.

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.

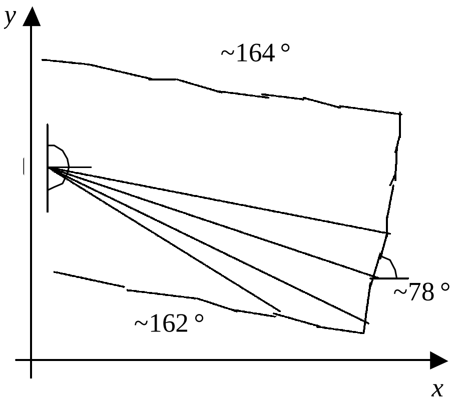

Figure 2: Laser scan with points connected by lines

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.

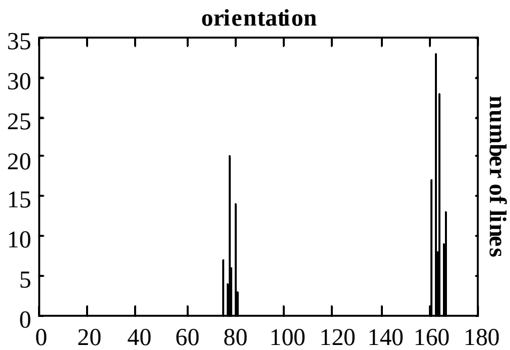

Figure 3: Angle histogram of the scan in Figure 2

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 most frequent angle, 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.* [14] built a second histogram to determine the shift along the main direction. However, this approach only works in environments with perpendicular walls. This is only one of the original algorithm's drawbacks that are removed in the extended version presented in this paper.

3. Extended Histogram Matching

The extended version of the histogram matching approach provides an improvement with respect to the following aspects: First, the matching is not performed with two complete scans. Instead, a *projection filter* 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. Then, a line segmentation is applied instead of only using neighboring scan points to determine the orientations of the surfaces. These lines are employed 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 illustrates the individual steps. For each step in one column all steps in the neighboring column to the right are performed.

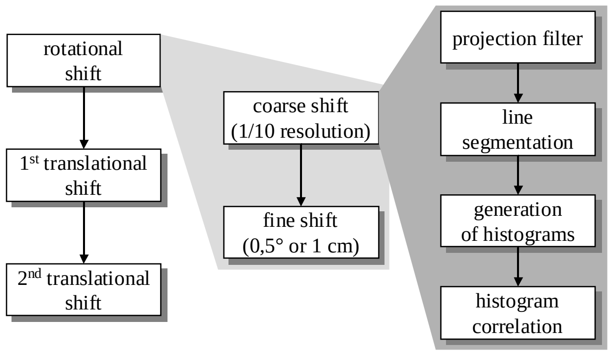

Figure 4: Extended histogram matching

Projection Filter

The employed laser range sensor of the German company Sick is able to take 180° scans. These scans only represent a part of the environment that can–depending on the position of the scanner–either be very large or quite minimal. If, for example, the scanner is located in a corner of a room and looks toward the center of the room, it can see almost the whole room. In contrast, if it is at same position but oriented toward the corner, it perceives nearly nothing of the environment. Therefore, when taking two scans from different positions, they will share only some of the characteristics of the environment, but they will also contain measurements in which they differ, because they perceive different parts of the surroundings. Such differences will have a negative impact on the generated histograms, and will therefore impede the correlation process.

Therefore, a projection filter similar to one presented by [9] is used. Based on an estimated offset between the scans to be matched, it projects all scan points measured from one position to the other position, to check whether these points may also be measured from there. Then, it filters all scan points from the processed scan that cannot be perceived by a scanner located at the other position. As an example, consider the situation shown in Figure 5. All areas marked in light gray cannot be seen from scan position (a), and all areas shown in darker gray cannot be perceived from scan position (b).

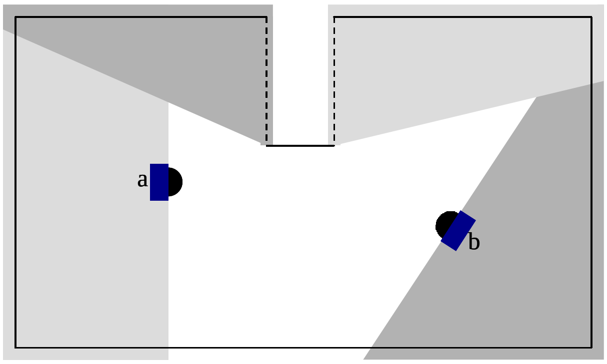

Figure 5: Scan points removed by a projection filter

Scan points can be removed for three different reasons:

Opening Angle. The opening of the Sick laser scanner is 180°. Therefore, the scanner cannot see what is behind itself. As a result, all measurements have to be removed that are behind the position, where the other scan was taken, e.g. in Figure 5, anything recorded from (a) that is behind (b) and vice versa.

Hidden Surfaces. Objects that are closer to a scan position than other object can hide parts of the environment so that the scanner cannot see them. However, from a different position, these parts of the environment may not be hidden. Therefore, all those measurements have to be dropped that–seen from the recording position of the other scan–are hidden by other scan points. As an example, consider Figure 5, where the light gray area in the upper right cannot be seen from (a), and the darker gray area in the upper left cannot be perceived from (b). To determine hidden surfaces in linear time, the depth buffer approach known from computer graphics [2] is used.

Different Sides of the Same Object. Although the depth buffer approach is principally able to determine all hidden surfaces, due to sensor noise and small errors in the estimated offset between the scan positions, it may fail to detect the case that both scans contain measurements of the same wall but from different sides. These cases can easily be detected, because such a surface is measured in a different sequence from both scan positions, i.e. if the scan points are enumerated in clockwise direction from one scan position, this sequence appears to be counter-clockwise from the other. In Figure 5, the dashed parts of the wall can be detected this way.

Line Segmentation

The measurements of the employed laser scanner vary by an amount of ±2 cm from the real distances to the objects in the environment. If neighboring scan points are connected as shown in Figure 2, the orientations of the resulting lines will deviate very heavily. Thus, an angle histogram based on such values will not be able to establish significant peaks. Therefore, a line segment filter is applied that performs two tasks: on the one hand, it determines which scan points belong to the same straight line. On the other hand, it does not connect neighboring scan points that are too far apart, i.e. it detects gaps in the laser scan. From the huge amount of line segmentation approaches, the generalization algorithm developed by Musto et al. [11] is employed. The algorithm partitions the scan based on a maximum deviation ε that, in case of the used laser range sensor, is set to 2 cm.

Histograms Representing Lengths

In the original approach by Weiß *et al.*, the number of line segments with a certain angle or the number of scan points at a certain distance from the *x*/*y* axis is inserted into the histograms. Even if different scans contain the same part of the environment, their histograms can differ significantly, because the distance to an object influences the number of scan points that fall on its surface. These differences in the histograms can considerably impede the correlation process.

In the approach presented here, the lengths of the segmented lines are inserted into the histograms. As the projection filter has already removed all different parts from the scans, the resulting histograms are comparable, even if they were taken at different positions.

Two Main Directions

The correlation algorithm of Weiß *et al.* is based on the assumption that the environment consists of right-angled objects, or at least that the two most significant directions form a right angle to each other, i.e. the second main direction is perpendicular to the first one. In many buildings, e.g. in the one the experiments for this paper where conducted in, this assumption is not valid. Therefore, the extended approach searches for two main directions, a first one as in the original method, and a second one that also has the biggest entry in the angle histogram but is at least 22.5° apart from the first one.

To ease the integration of two translational shifts that are not perpendicular, 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 position corrections (cf. Section 4). Then, the correlation of the angle histograms is performed (cf. Figure 6a), 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 6b).

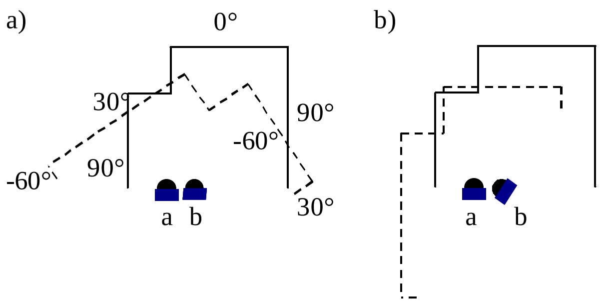

Figure 6: Correction of the rotational shift

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 to the *x* axis (cf. Figure 7a), *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 7b). Then both scans are rotated again to align the second main direction with the *x* axis (cf. Figure 8a), and, again, to correct the current *y* displacement (cf. Figure 8b). 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.

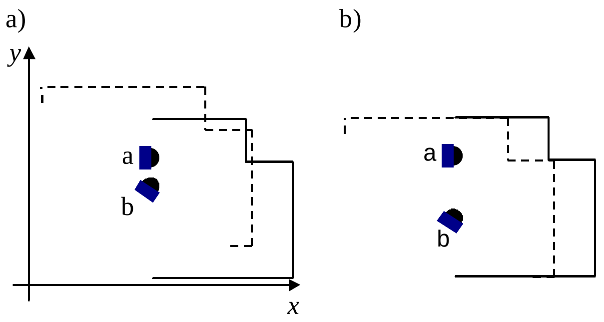

Figure 7: Correction of the first translational shift

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.

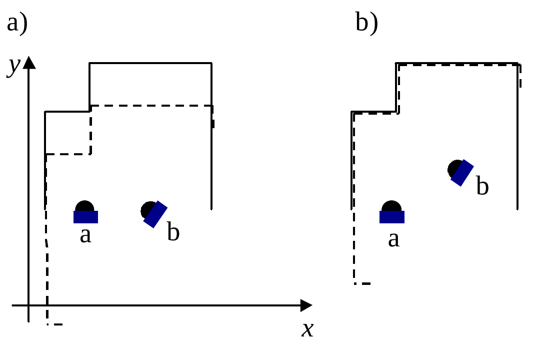

Figure 8: Correction of the second translational shift

Two Step Correlation

For the selection of the histogram's optimal resolution, two conflicting goals have to be considered: on the one hand the phase shift shall be determined with an accuracy as high as possible, on the other hand correlations with a high resolution are computationally expensive, and they bear the risk that noisy measurements prevent the histograms from accumulating clear maxima. Therefore, for each matching step, two histograms with different resolutions are used. First, the correlation between histograms with a coarse classification is determined, which guarantees that all values that only vary around a certain measuring error are inserted into the same histogram cell. For the coarse distance histograms, a cell size of 10 cm is used, the coarse angle histograms have a resolution of 5°. Afterwards, a correlation of histograms with a high resolution of 1 cm / 0.5° is carried out, which is only executed around the estimated shift given by the coarse correlation. As a result, the correlations are fast and precise.

4. Map Building

If the offset between the recording positions of two scans can be determined, this also can be performed several times consecutively with different scans. Thus, the metrical 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 (slip, 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 when the mobile system returns into an already mapped area of the environment. 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 a already known area.

The Map

The map is represented as a list. Each entry in the list consists of a laser scan, the metrical position, where is was taken, and the so-called *frame of reference* (FoR). The FoR is a value that is initialized with the tachometer 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 much was traveled between the recording 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 checked maximum shifts can be kept small.

The Mapping Process

When the mapping process begins, the current position is initialized with (x, y, rotation) = (0, 0, 0°) and the tachometer 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 scan's recording position, i.e. the current position of the wheelchair. That way, the current position is continuously corrected.

However, it is possible that the matching process for all reference scans fails, 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.

Selection of Reference Scans

There are three selection criteria for reference scans:

Old FoR. 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.

Large Overlap. 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), a third selection criterion is introduced to reduce the number of potential candidates.

Vicinity. Only those scans from the map are selected that were taken at a position in a certain radius around the current position.

The three criteria are combined by first selecting all scans in a certain radius around the current position. Then, for each direction (seen from the wheelchair), the scan that has the largest overlap with the current scan is selected. These scans are sorted by their FoR, i.e. by their age, so that it will be tried first to match the current scan with the oldest reference scan.

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.

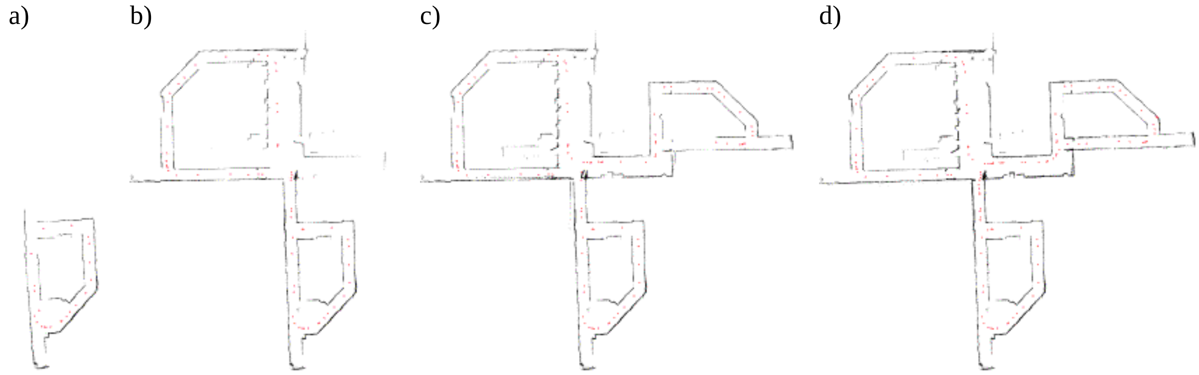

Figure 9: Four snapshots while mapping a flat

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. This can be compared to bending straight a paper-clip. Then, the *x* and *y* errors are distributed. Again, the local offsets between scans with equal FoRs remains 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 metrical 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 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 [10] 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 9. The flat that is mapped has a size of approximately 50×50 m. The wheelchair was driven manually 200 m through this environment. Starting in the upper horizontal corridor shown in Figure 9a, the wheelchair drove through the small cycle in clockwise direction until it almost returned to the start position. As can be seen in Figure 9a, a small drift had already been accumulated. It was corrected when the mapping algorithm closed the cycle. The result is depicted in Figure 9b. 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 flat. 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 9b to Figure 9c, 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 9d, 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 9d.

Figure 10 shows two other examples of maps generated by the algorithm. They were both created in the same environment, i.e. another flat of the same building, but the wheelchair followed different routes. Figure 10a depicts the two different trajectories: the map shown in Figure 10b was created while following the route drawn as solid line, whereas the map in Figure 10c 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

a) b) c)

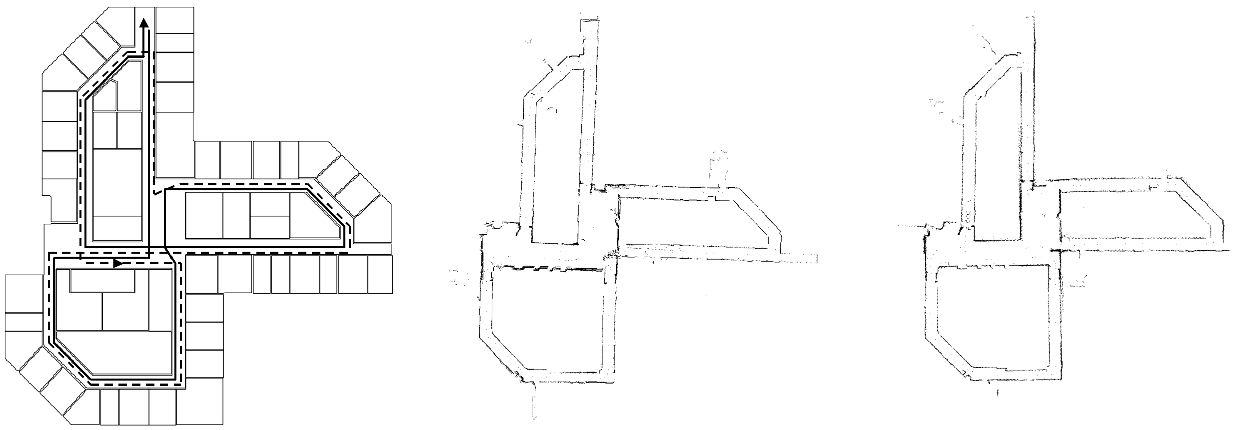

Figure 10: Two maps of the same environment generated on different routes

method originally developed by Weiß et al. [14]. It is very fast and robust.

In the future, it will be analyzed, how to weight the distribution of the accumulated error when closing a cycle, in order to get optimal results. Thereby, time-consuming calculations should be avoided.

7. Acknowledgements

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8. References

[1] Cox, I. (1991). Blanche - an Experiment in Guidance and Navigation of an Autonomous Robot Vehicle. In: IEEE Transactions on Robotics and Automation 7:2. 193-204

[2] Foley, J. D., van Damm, A., Feiner, S. K., Hughes, J. F. (1990). Computer Graphics. 2nd ed., Addison-Wesley, Reading, MA.

[3] Gutmann, J.-S., Nebel, B. (1997). Navigation mobiler Roboter mit Laserscans. In: Autonome Mobile Systeme 13. Informatik aktuell. Springer. Berlin, Heidelberg, New York.

[4] Kollmann, J., Röfer, T. (2000). Echtzeitkartenaufbau mit einem 180°-Laser-Entfernungssensor. In: Dillmann, R., Wörn, H., von Ehr, M. (Eds.): Autonome Mobile Systeme 2000. Informatik aktuell. Springer. 121-128.

[5] Kuipers, B. J., Byun, Y.-T. (1991). A robot exploration and mapping strategy based on a semantic hierarchy of spatial representations. In: Journal of Robotics and Autonomous Systems 8. 47-63.

[6] Lankenau, A., Röfer, T. (2001). The Bremen Autonomous Wheelchair—A Safe and Versatile Mobility Assistant. In: IEEE Robotics and Automation Magazine (appears in March 2001 issue).

[7] Lee, W. Y. (1996). Spatial Semantic Hierarchy for a Physical Robot. PhD thesis. University of Texas at Austin.

[8] Leonard, J., Durrant-Whyte, H. F., Cox, I. J. (1990). Dynamic Map Building for an Autonomous Mobile Robot. In: Proc. IEEE Int. Workshop on Intelligent Robots and Systems. 89-95.

[9] Lu, F., Milios, E. (1997). Robot Pose Estimation in Unknown Environments by Matching 2D Range Scans. In: Journal of Intelligent and Robotic Systems 18:3. 249-275.

[10] Mojaev, A., Zell, A. (1998). Online-Positionskorrektur für mobile Roboter durch Korrelation lokaler Gitterkarten. In: Wörn, H., Dillmann, R., Henrich, D. (Eds.): Autonome Mobile Systeme. Informatik aktuell. Springer. 93-99.

[11] Musto, A., Stein, K., Eisenkolb, A., Röfer, T. (1999). Qualitative and Quantitative Representations of Locomotion and their Application in Robot Navigation. In: Proc. of the 16th International Joint Conference on Artificial Intelligence (IJCAI-99). Morgan Kaufman Publishers, Inc. San Francisco, CA. 1067-1073.

[12] Röfer, T., Lankenau, A. (2000). Architecture and Applications of the Bremen Autonomous Wheelchair. In Wang, P. (Ed.): Information Sciences 126:1-4. Elsevier Science BV. 1-20.

[13] Thrun, S., Burgard, W., Fox, D. (2000). A real-time algorithm for mobile robot mapping with applications to multi-robot and 3D mapping. In: Proc. of the Int. Conf. on Robotics and Automation 2000 (ICRA-2000).

[14] Weiß, G., Wetzler, C., von Puttkamer, E. (1994). Keeping Track of Position and Orientation of Moving Indoor Systems by Correlation of Range-Finder Scans. In: Proc. of the IROS ' 94Munich, Germany. 595-601.