Map Building for a Mobile Robot equipped with a 2D Laser Rangefinder

Javier Gonzalez*, Anibal Ollero** and Antonio Reina*

* Departamento de Ingeniería de Sistemas y Automática, Universidad de Málaga, Plaza El Ejido s/n, 29013 Málaga, SPAIN. E-mail: jgonzalez@ctima.uma.es

**Departamento de Ingeniería de Sistemas y Automática, E.T.S. de Ingenieros Industriales, Universidad de Sevilla, Avda. Reina Mercedes s/n, 41012, Sevilla, SPAIN. E-mail: aollero@etsii.us.es

Abstract

This paper describes a method of building a map of the environment for a mobile robot equipped with a radial laser scanner. This sensor radially scans in a plane parallel to the ground providing a two-dimensional description of the environment. From this information, the map builder produces a set of (typically) short line segments which approximate the shape of almost any kind of environment (local map). As the robot moves, the different local maps obtained are integrated into a global map, representing, thus, the whole environment observed by the robot during its navigation. In particular, we focus our attention on the update process of the global map. The proposed algorithm introduces what we call a "viewing sector" as a simple mechanism to reduce the number of local map segments to be checked for correspondence for each particular segment from the global map. A line segment fragmentation process is also used in order to manage partial correspondence between segments from both maps. We present experimental results obtained with this system that demonstrate successful map building.

1. Introduction

Map building is a dynamic process which needs the interpretation of the data supplied by external sensors in terms of the environment physical features. In general, this data refer to observations taken from different positions along the path followed by the vehicle, requiring, thus, a mechanism for integrating them into a common reference frame [4,10]. This integration process has to deal with two different kinds of information: redundant information, and new features from the environment. The procedure to distinguish them is tightly related to the correspondence process between features already known (previous observations or map known in advance), and features coming up from the sensor's last observation. Those features which can be matched with others already existing in the map are considered as redundant and integrated into it by a merging process, while the rest are considered as new and are simply incorporated into it [8, 11].

Our work is concerned with two-dimensional information provided by a radial laser scanner. Thus, the maps will consist of a set of short line segments approximating the shape of the environment, and the update process will involve a correspondence problem between segments from the current global map and segment from the local map obtained at each position. By local map we mean the representation of the environment that the sensor perceives from its current position, while the global map tries to represent the whole environment observed by the robot during its navigation. Obviously, a precise position estimation is required in order to refer both representations to a common coordinate system. The position estimator used is the one proposed by Gonzalez et al. [5].

An interesting related work is the one developed for ultrasonic range sensors by Crowley [2, 3]. Crowley proposes a simple mechanism to reinforce and decay the confidence in the line segments in the global map depending on the presence or absence of a correspondence pair in the local map. In our case, this mechanism is not necessary since the information provided by laser rangefinder is significantly more precise and reliable. In addition, while Crowley's work extends the segments whenever there is a partial correspondence with the local map segments, we propose a fragmentation process to solve it. Finally, we propose the *viewing sector* as a mechanism to reduce the number of local map segments to be checked for correspondence for a particular segment from the global map.

In the following sections we first summarize the local map building process, then we present the proposed procedure for updating the global map, and finally some experimental results are shown.

2. Local Map Building

From the scanned points provided by the radial laser rangefinder, the local map building is accomplished in four different steps [6]:

a) *Filtering*: scanned points that do not exhibit a local alignment within a tolerance are removed from the raw sensed data.

b) *Clustering*: the scan is broken at points where the distance between successive points exceeds a threshold, thereby finding occlusions.

c) *Clusters segmentation*: the range sequence of each cluster is grouped into pieces of scan suitable for a good linear fitting. This process is carried out by a recursive splitting technique.

d) *Line segment fitting*: line segments are selected through best fitting all points within the above segmented groups. This is accomplished in two steps: a) least squares line fit of each segmented group within a cluster and b) computation of segment endpoints as the intersection points with neighboring line segments.

The final result of this process is a set of line segments (short ones in case of non-structured environments) that approximate the contour of the surrounding obstacles. This kind of representation adapts to curved profiles and provides and easy and precise model of any type of environment [6].

Each of the line segments of the local map is represented through its two endpoints and five "fitting parameters" n_k, S_x^k, S_y^k, S_{xx}^k and S_{xy}^k used in solving the parameters of the line:

$$a_k = \frac{n_k \cdot S_{xy}^k - S_x^k \cdot S_y^k}{n_k \cdot S_{xx}^k - (S_x^k)^2} \qquad b_k = \frac{S_x^k \cdot S_y^k - S_x^k \cdot S_{xy}^k}{n_k \cdot S_{xx}^k - (S_x^k)^2}$$

where

$$S_x^k = \sum_{i=1}^{n_k} x_i, \; S_y^k = \sum_{i=1}^{n_k} y_i, \; S_{xx}^k = \sum_{i=1}^{n_k} x_i^2, \; S_{xy}^k = \sum_{i=1}^{n_k} x_i \cdot y_i$$

and $\{(x_i, y_i)\}$, $i = 1, \dots, n_k$ is the set of points corresponding to a given segmented group S_k[1].

Although the two segment endpoints are enough information to uniquely define the local map, these five additional parameters are used in order to make possible the merging process with line segments from the global map. Since this representation cannot represent vertical lines, in those cases an alternative parameter S_{yy}^k is required instead of S_{xx}^k. A similar representation has been adopted for 3D lines segments by Ayache and Faugeras [1].

Figure 1(a) shows a real scan of 1000 points taken by the Cyclone laser scanner [9] in a coal mine. Figure 1(b) shows the local map obtained from this data. The corridor

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1.- To facilitate the integration of this map into the global map, these points have been previously transformed to the absolute coordinate system by using the position and orientation provided by an iconic position estimator [5].

is about 6 meters wide and the circular icon represents the robot at the position where the scan was taken from.
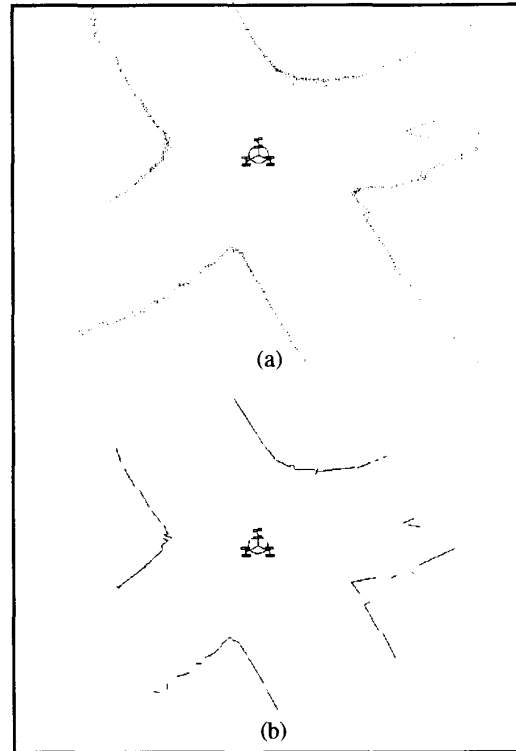

FIGURE 1. (a) Range scan provided by the Laser Rangefinder.
(b) Local map obtained.

3. Global Map Updating

The main problem when updating the global map is to solve the correspondence problem between line segments from the global map (GMS) and line segments from the local map (LMS). Figure 2 shows a simple situation where the difficulty in deciding the correspondence of the line segments labelled "l_1", "l_2" and "l_3" to the segments labelled "a", "b" and "c" is illustrated. For example, we may wonder if the segment "l_3" corresponds to the segment "b" or if it corresponds to a new feature of the environment, or, maybe, if part of "l_1" corresponds to a part of "b" while the other one corresponds to a part of "c".

To solve those problems our method introduces a new approach based on a line segment fragmentation process and the concept of *viewing sector*. These two make possible the update process to be accomplished in a two-stage procedure. First, all GMS are updated one by one through its viewing sector. During this process, LMS which find correspondence to the GMS are removed from the local map. In the second step, all the line segments that remain

in the local map are added to the global map, representing, thus, features of the environment that have been observed for the first time.
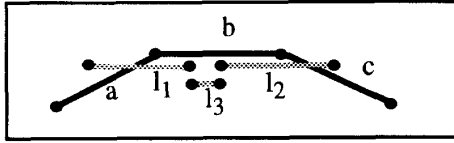
FIGURE 2. A simple situation illustrating the difficulty in the segment-to-segment correspondence.

3.1 Line Segment Fragmentation

Line segment fragmentation is the process by which a segment is split into two o more pieces (figure 3). Each of them will be considered as a new segment from the map, while the original is removed from it. This process permits partial correspondence between segments.

To describe the segment fragmentation process that has been used, let us consider the fragmentation of a line segment l_j into a set of resulting segments $\{l_{ji}\}$, $i=1,2,.....,c$.

Let $P_s^{ji}=(x_s^{ji},y_s^{ji})$ and $P_e^{ji}=(x_e^{ji},y_e^{ji})$ be the start and end-point, respectively, of the resulting segment l_{ji} (figure 3).
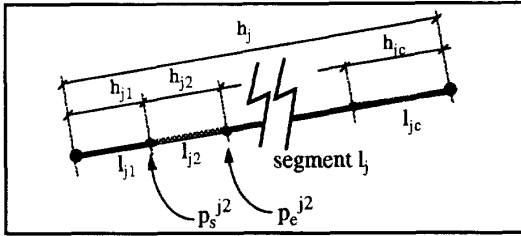

FIGURE 3. Fragmentation of a line segment l_j.

Let n_j and S_x^j, S_y^j, S_{xx}^j, S_{xy}^j be the "fitting parameters" of the line segment l_{ji}. Assuming that the points are uniformly distributed along l_j, the number of points of each new segment l_{ji} is determined by:

$$n_{ji} = n_j \frac{h_{ji}}{h_j}$$

where h_j and h_{ji} are the magnitudes of l_j and l_{ji}, respectively. Under this assumption, the "fitting parameters" of l_{ji} are given by the expressions:

$$S_x^{ji} = n_{ji}\left(\frac{x_s^{ji}+x_e^{ji}}{2}\right) \qquad S_y^{ji} = n_{ji}\left(\frac{y_s^{ji}+y_e^{ji}}{2}\right)$$

$$S_{xx}^{ji} = \frac{n_{ji}}{6(n_{ji}-1)}\left[(2n_{ji}-1)\left(x_s^{ji}+x_e^{ji}\right)-2x_s^{ji}x_e^{ji}(n_{ji}+1)\right]$$

$$S_{xy}^{ji} = \frac{n_{ji}}{6}\left[\left(3y_s^{ji}-a_j x_s^{ji}\right)\left(x_s^{ji}+x_e^{ji}\right)+2a_j x_e^{ji}+\frac{\left(x_e^{ji}-x_s^{ji}\right)^2}{n_{ji}-1}\right]$$

We have tested that, in practice, these values are a quite precise approximation of these parameters.

3.2 Viewing sector

Given a line segment l_k of the global map, the viewing sector ϕ_k is defined as the region within the scanning rays of its endpoints (figure 4).
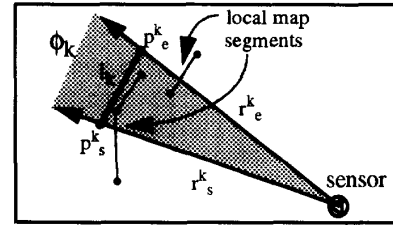

FIGURE 4. Viewing sector of a GMS l_k.

For a given viewing sector ϕ_k, the LMS are classified as follows: 1) the LMS is outside ϕ_k, 2) both endpoints of the LMS are inside ϕ_k, 3) one of the endpoints of the LMS is outside ϕ_k, 4) both endpoints of the LMS are outside ϕ_k and the LMS passes through ϕ_k.

When updating l_k, only those LMS inside ϕ_k (types 2, 3 and 4) are considered as candidates for correspondence, and, more precisely, only the piece of segment within ϕ_k. Therefore, LMS labelled as types 3 and 4 need to be fragmented to isolate the "subsegment" inside ϕ_k. Notice how the viewing sector provides a simple mechanism to reduce the number of LMS to be checked for correspondence for a particular GMS.

3.3 Correspondence

Once a set of LMS is selected for a particular GMS l_k, we need to determine which of them match l_k and which don't. As a LMS may not univocally represent features from the environment, we also need to consider the possible partial correspondence between the LMS and l_k. The following four different situations are possible (figure 5):

a) if the distance of both endpoints to l_k is less than a threshold δ, a *full correspondence* to l_k exists.

b) if the distance of both endpoints to l_k is greater than δ and they lie on the same side of l_k, there is *no correspondence*.

c) if only one of the endpoints is at a distance less than δ from l_k, then the LMS is fragmented in two parts, one of which has a correspondence in l_k and the other doesn't.

d) if both endpoints lie on different sides at a distance greater than δ from l_k, the LMS is fragmented in 3 parts, one of them with correspondence in l_k (the interior one).

Situations c) and d) are referred to as *partial correspondence* and the resulting segments obtained through the fragmentation process being carried out will turn in either a full correspondence or a no-correspondence situation. The threshold δ is selected according to the expected errors in both the robot location and the sensor readings.
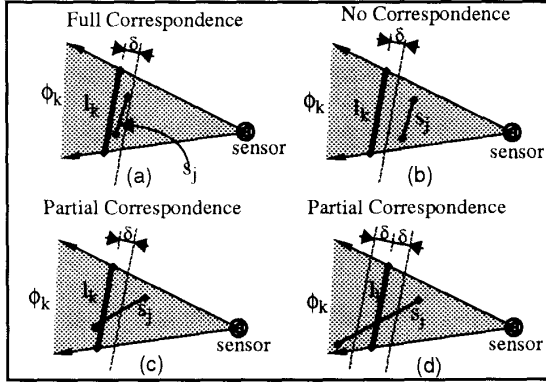

FIGURE 5. Different situations to be considered when analyzing correspondence.

3.4 Updating GMS

To update a GMS l_k, it is necessary to fragment it first by projecting all the LMS inside ϕ_k onto l_k, as shown in figure 6. Each new line segments obtained from l_k will then be modified according to 4 types of segments: *occluded, overlapped, non-observed* or *correspondence segment*. This approach will allow to efficiently manage dynamic environments.
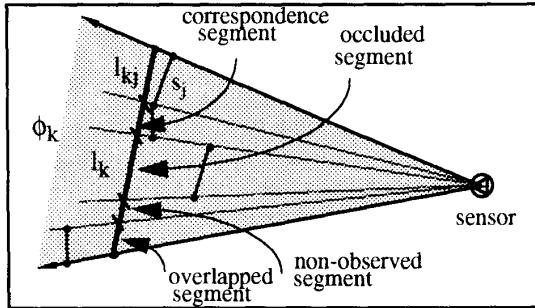

FIGURE 6. A fragmentation process over a GMS l_k.

Correspondence segment

Let (l_{kj}, s_j) be a correspondence pair, where l_{kj} is the segment fragmented from l_k through the projection of the

LMS s_j (see figure 6). In this case, both s_j and l_{kj} would represent the same feature from the environment, and therefore, they have to be merged together.

To formulate the merging process of the pair (l_{kj}, s_j), the points used in their line fit must be considered together, that is:

$$\tilde{n}_{kj} = n_{kj} + n_j \qquad \tilde{S}_x^{kj} = S_x^{kj} + S_x^j \qquad \tilde{S}_y^{kj} = S_y^{kj} + S_y^j$$

$$\tilde{S}_{xx}^{kj} = S_{xx}^{kj} + S_{xx}^j \qquad \tilde{S}_{xy}^{kj} = S_{xy}^{kj} + S_{xy}^j$$

where n_j, S_x^j, S_y^j, S_{xx}^j and S_{xy}^j are the set of "fitting parameters" of the line segment s_j while n_{kj}, S_x^{kj}, S_y^{kj}, S_{xx}^{kj} and S_{xy}^{kj} are the ones of l_{kj}. Thus, the parameters $(\tilde{a}_{kj}, \tilde{b}_{kj})$ of the line that contains the resulting segment l_{kj}, are calculated by using the expressions:

$$\tilde{a}_{kj} = \frac{\tilde{n}_{kj} \cdot \tilde{S}_{xy}^{kj} - \tilde{S}_x^{kj} \cdot \tilde{S}_y^{kj}}{\tilde{n}_{kj} \cdot \tilde{S}_{xx}^{kj} - (\tilde{S}_x^{kj})^2} \qquad \tilde{b}_{kj} = \frac{\tilde{S}_x^{kj} \cdot \tilde{S}_y^{kj} - \tilde{S}_x^{kj} \cdot \tilde{S}_{xy}^{kj}}{\tilde{n}_{kj} \cdot \tilde{S}_{xx}^{kj} - (\tilde{S}_x^{kj})^2}$$

The line segment $\tilde{l}_{kj}$ is obtained by determining its two endpoints. In general, if s_j is connected to another LMS, let us say s_l with correspondence in l_k, the resulting new segments and l_{kj} will share an endpoint, computed through the intersection of their respective lines. Otherwise, the endpoint of l_{kj} is determined intersecting the line containing it with the scanning ray passing through the s_j endpoint [7].

Finally, the LMS s_j is removed from the local map as it can no longer correspond to any other GMS.

Occluded segment

Whenever a LMS s_j blocks l_k (with no correspondence), there is not additional information about l_{kj} and, therefore, it is not modified. In this case, s_j may represent a new feature from the environment or may correspond to another segment in the global map (see figure 6).

Overlapped segment

A GMS l_{kj} blocking a LMS s_j is referred to as an overlapped segment. An overlapped segment is interpreted as the movement or disappearance of the feature which it represents (probably because it is a moving object) and, therefore, they are removed from the global map (see figure 6).

Non-observed segment

As the LMS within a viewing sector ϕ_k are projected onto the GMS l_k, it may occur that any of them project onto a particular piece of l_k. In such a case, the new SGM generated by fragmentation is said to be non-observed segment

(see figure 6). Mostly, a non-observed segment arises either from a real gap in the environment or from an unexpected disconnection in the local map (caused by the local map building process). Whatever the case, a non-observed segment is not removed from the global map, since there is not contradiction with the local map being observed.

3.5 New segments incorporation

As previously mentioned, during the updating process, LMS which obtain correspondence are removed from the local map. After being analyzed all the GMS, only those LMS which don't correspond to any other GMS remain in the global map, representing, thus, features of the environment that have been observed for the first time. These line segments are directly added to the global map.

3.6 Global Map Refinement

The different fragmentation processes carried out during the updating of the global map may increase signifincantly the number of segments in it, and consequently, the computational cost involved in processing the global map. Thus, after each global map update, segments which exhibit certain conditions of proximity and alignment are groupped together. Furthermore, line segments whose magnitude is below a tolerance are removed from the global map.

4. Experimental results

Figure 7 shows a manually-obtained map of one of the environments used for testing the map building system. The overall dimensions are 10m.x10m. The dots represent the path that the mobile robot was instructed to follow. We picked this configuration because its simplicity and reliability in being surveyed. By using synthetic data we have checked that this method works well for less structured environments. The robot, initially positioned at the beginning of the path, was programmed as follows: 1) build an initial local map from the starting position[2], 2) move 1 m. along the path, 3) estimate position, 4) build local map, 5) update current global map with local map, 6) repeat steps 2 through 6 until the navigation is complete.

The radial laser scanner mounted on the mobile robot was the *Cyclone*. The *Cyclone* was developed at the Carnegie Mellon University FRC to acquire fast, precise scans of range data over long distances (up to 50m)[3]. The resolution of the range measurements is set to be 10cm. and the accuracy is ±20cm.[9].
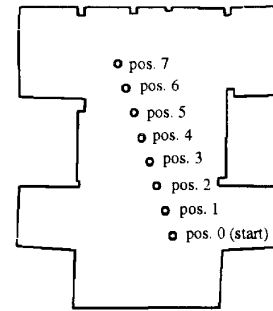
FIGURE 7. Map of the environment surveyed by a theodolite.

Figure 8 illustrates the map building process. Figures 8(a) and 8(b) show the scan taken by the Cyclone and local map at the position 1, respectively, while Figure 8(c) shows the global map obtained at position 1. The final map (at position 7) is shown in figure 8(d). Notice that even the small features from the environment (about 20 cm.) have been successfully registered.

A simple and reliable way to evaluate the performance of the map builder consists of comparing the positions and orientations estimated when using the surveyed map and the global map being built[4]. In both cases the position estimator was the iconic algorithm developed by Gonzalez et al. [5]. Figure 9 shows the computed errors (surveyed minus estimate) for both at the 7 positions along the path. When building the map, the maximum position error was 5cm. while the average was 3.8cm.

The CPU times on a Sun Sparc Station 2 were 80ms. for the local map building and 135ms. for the global map update. These times are averages over the 7 steps and the position estimation is not included[5].

5. Conclusions

An approach for building a line segment map of almost any kind of environment has been presented (including dynamic and slightly structured ones). The input to the system is the set of scanned points provided by a robot-mounted radial laser scanner. This paper emphasizes the update process of the global map proposing a two-stage procedure. First, all the segments from the global map are updated one by one through its viewing sector. During this process, LMS which find correspondence to the GMS are removed from the local map. In the second step, all the line segments that remain in the local map are considered

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2.- By "position" we mean both position and orientation of the robot.

3.- For accuracy purposes, in this application, measurements beyond 10m. are discarded.

4.- Notice that, in this case, the map does not model the whole environment, but only the part of it built until that time.

5.- The computation times for the position estimation depend on a number of factors and can be found in [5].

as new observations and therefore they are added directly to the global map, representing, thus, features of the environment that have been observed for the first time. The performance of this system has been demonstrated using real data. In particular, the accuracy of the global map was tested through the errors in the position estimates.
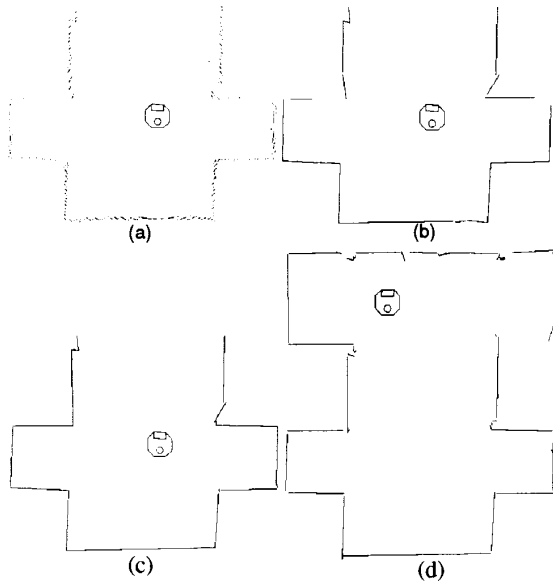

FIGURE 8. (a) Scan taken at the position 1. (b) Local map obtained at the position 1. (c) Global map at the position 1. (d) Global map at the end of the path (43 segments).
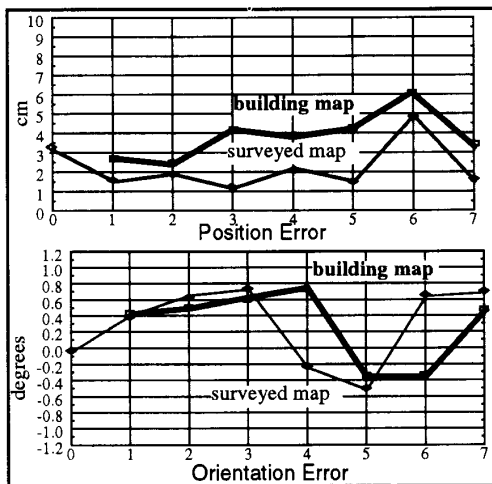

FIGURE 9. Robot position and orientation errors when using the surveyed map and the global map being built.

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