LOCATING AND CROSSING DOORS AND NARROW PASSAGES FOR A MOBILE ROBOT

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Abstract: In structured indoor environment, the structural information gathered from sensors can be divided into three different levels whose features increase gradually: walls, corners and passages. Besides detecting walls and corners, the paper focuses on narrow passage detecting and crossing. The sensor employed in the robot is a laser range finder. By detecting the Complete Points in the laser map, two types of narrow passages are easy to find. Two immediate applications of the proposed approach emerge: localization for robots and automatic crossing of passages. The validity of the method is proved with experimental results.

1 INTRODUCTION

For indoor mobile robots, usually the robot has a three-step process to navigate: sensing, processing and driving. By defining a set of behaviors, the information from sensors can be directly connected with the resulting behaviors. Various methods have been developed on sensor-based localization (Lionis, 2002) and motion planning (Chung, 1992).

The idea is to develop a feature map suitable for behavior based navigation that can be further integrated by a high-level language for navigation mission specification (Santos, 2001). For most structured indoor environments, three types of features could be found: planar walls (short or long), corners (convex or concave hull), narrow passages (open or closed doors, narrow corridors). They belong to different levels in the feature map: wall is the basic element among all of the features; corner is the intersection line of two or three walls; narrow passage, which may be symbolized by corners at the entrance, could be composed of two parallel walls inside. With these three types of features, different behavior of robot could be developed. Furthermore, the features accompanied by the geometric information could also be used for localization of robots (Xiang, 2003). Since the narrow passages are the highest-level features, we focus on detecting them and consequently make use of them by localizing and navigating the robot to pass the narrow passage. Distinction between a door and a simple narrow passage can be done by using additional parameters of the algorithm such as the width, or the "quality" of the delimiting walls. That is not a major concern and from now on the terms "door" or "narrow passage" will be used interchangeably.

Several types of sensors could be used for detecting the narrow passages. Vision is good at object recognition (Davison, 2002), but it requires complex processing and relies on good illumination condition. Ultrasonic sensors are good to tell the appearance of obstacles nearby but cannot tell the accurate position due to their wide beams (Kulich, 1999). On the other hand, laser appears is an ideal sensor for our purpose and it can provide accurate 2D profiles of the surrounding environments in a mere scan. Therefore a laser scanner has been used in the present work.

The paper is organized as follows. The second part introduces our narrow passage-detecting algorithm. Section 3 presents the localization of robots by using the geometric information of passage entrance. Implementation of behavior "Crossing the passage" is described in Section 4.

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Section 5 gives some results of our experiments and section 6 concludes the paper.

2 DETECTION OF DOOR

2.1 Extracting Complete Points

In a laser scan, Complete Points (CP) represent vertical corners in the real environments. As shown in Figure 1, the ending points filled with black are all CP because they correspond to the vertical edges of the wall, while the others are not because their appearance is due to obstructing of walls in front of them.

Decision Rules of CP: For every two neighbor line segments in the laser scan, if they are connected, the intersection point of them must be a CP; if they are disconnected, between two broken points, the one that has the shorter range to the original point of laser data is a CP.

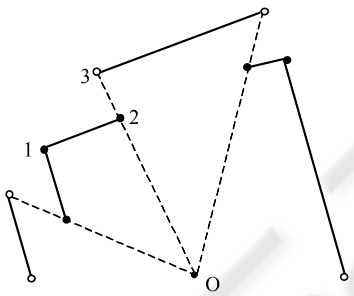

Figure 1: Interpretation of Complete Points in laser map.

In Figure 1, point 1 is the intersection point of two line segments, thus it is a CP. Between point 2 and point 3, point 2 has a shorter distance to the origin of laser, meaning that point 2 is a CP while point 3 is not.

2.2 Detecting the Entrance

Generally, in structured indoor environment, there are two types of entrance for narrow passages, namely, type I and type II, as shown in Figure 2. A type I entrance consists of two corners, and type II entrance is composed of one corner and one wall. Whichever the type of entrance, there is at least one corner as the basic element. Any corner in the real environment corresponds to CP in the laser scan.

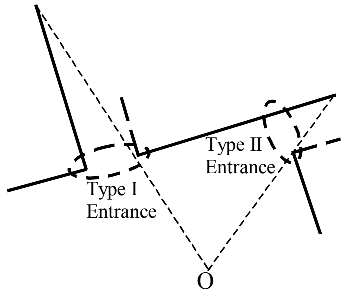

Figure 2: Illustration of two different types of entrances of narrow passages.

Type I entrance detection: Here we should check every pair of CP to see if they form a type I entrance. Several conditions could be set up for type I entrance detection:

- The distance from one CP to the line which the other CP belongs to should be less than a threshold;
- Each CP should lie on the extended part of the line segment which the other CP belongs to and neighbored with the other CP;
- The distance between two CP should be within the scope of normal width of narrow passage which robot could pass through;
- The difference of slope angle between two line segments, which the pair of CP belongs to, should be less than a predefined threshold.

If any CP belongs to more than one line segment, all of the line segments it belongs to should be checked. If there is one line segment that meets all of the above conditions, the pair of CP form a type I entrance of narrow passage.

Type II entrance detection: Unlike type I entrance, type II entrance consists of one CP and one line. Thus the conditions for forming type II entrance is like following:

- The line to be checked should be almost perpendicular to the line which the CP belongs to;
- The intersection point between the line to be checked and the line which CP belongs to should lie on the side near the CP;
- The distance between the obtained intersection point and the CP is within the scope of width of entrance.

After the above two steps, each entrance has to be checked if it is passable for the robot. Only a passable entrance will be considered as candidate to pass through.

3 LOCALIZATION OF ROBOT

If the position of the detected entrance in the global environmental map is known, it is intuitive that the entrance could be used for localization of the robot as a natural landmark. Given the position parameters of the detected entrance (x_{Gb}, y_{Gb}) and (x_{Ge}, y_{Ge}) in the global map, and the corresponding coordinates (x_{Lb}, y_{Lb}) and (x_{Le}, y_{Le}) in the local map, the position of robot (x_R, y_R, θ_R) in the global map could be computed with the following expressions:

$$\begin{cases} \theta_R = \tan^{-1}\dfrac{y_{Gb} - y_{Ge}}{x_{Gb} - x_{Ge}} - \tan^{-1}\dfrac{y_{Lb} - y_{Le}}{x_{Lb} - x_{Le}} \\ x_R = x_{Gb} - x_{Lb}\cos\theta_R + y_{Lb}\sin\theta_R \\ y_R = y_{Gb} - x_{Lb}\sin\theta_R - y_{Lb}\cos\theta_R \end{cases} \quad (1)$$

4 APPROACH AND CROSS THE PASSAGE

To cross the passage two main steps are required: reach the front of the entrance with the appropriate orientation and effectively traverse the passage.

4.1 Approach the passage

Approaching the passage can be done using one of two fundamental methods: using short-term odometry to perform some open loop motion (few meters only up to the door), or a closed-loop approach based on feature tracking, such as a Kalman filter-based technique. The later is conceptually more robust because once the door is located it can be continuously tracked while the robot moves towards its center. On the other hand, since the distances are relatively small (few meters), short-term odometry can be fairly reliable and much simpler to implement since simple motions are to be carried out. Occasional dead-reckoning errors can result in a poorer positioning near the door, which is nonetheless not relevant since door traversing is done in real time with continuous laser data and corrections will occur. Nonetheless, door locating can be done continuously and therefore door approaching can be continuously tracked as a posture tracking problem (de Wit *et al.*, 1997). This means that the desired posture near the door can be tracked as a control problem using linear and non-linear approaches. However, in this work, no such tracking control was implemented since distances are relatively small and short-term odometry clearly satisfies the demands of the problem.

Approaching the door with open loop motion is however not trivial; there are practical constraints that must be taken into account. Firstly, the robot must place itself near (in front) of the door by taking into account its dimensions; it could simply rotate towards that destination point (point D in Fig.4) and move in straight line until it reaches there (using short term odometry). This approach seems reasonable for type I passages, but would fail for type II since the robot could collide with the wall in the front before reaching the front of the passage. The solution is therefore to do the approach along a circular arc as illustrated in Figure 3. Reporting to Figure 3, the door location algorithm (described in the previous sections) returns the points A(Ax, Ay) and B(Bx,By) on the robot reference frame. The point C(Cx, Cy) is immediately known (middle point), and since *Δl* is defined as a parameter for the algorithm (about 100 cm in the current approach), D(Dx, Dy) is easily obtained taking into account, for example, the following 3 conditions:

$$[CD] \perp [AB]\,,\ \|CD\| = \Delta l\,,\ \|OD\| \text{ is minimal} \quad (2)$$

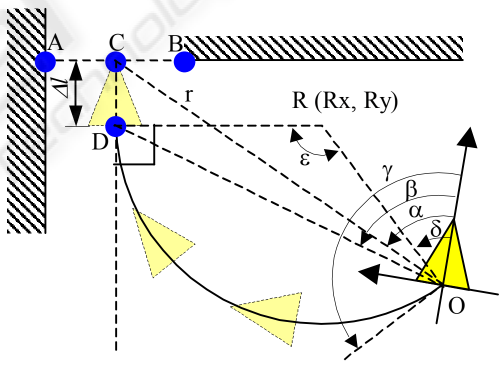

Figure 3: Illustration of the approach to a door of type II. Given A, B and the desired Δl, a preliminary rotation of angle γ followed by an arc path completes the approach which obviously also satisfies type I doors.

The conditions stated in (2) result in the following expressions ready to implement computationally for D(Dx, Dy):

$$D_x = C_x \pm \Delta l\left(A_y - B_y\right)/\|AB\| \quad (3)$$

$$D_y = C_y \mp \Delta l\left(A_x - B_x\right)/\|AB\| \quad (4)$$

where $\|AB\| = \sqrt{\left(A_y - B_y\right)^2 + \left(A_x - B_x\right)^2}$

From the two solutions obtained for D(Dx, Dy) the one that minimizes the norm of vector [OD], that is, the one that is closer to the robot, should be chosen. Knowing also that [DR] ⊥ [CD] and that D is on the circumference, it is possible to obtain the coordinates of the arc center R(Rx, Ry):

$$R_x = \frac{2D_xC_xD_y - D_x^2C_y + D_y^2C_y - D_yD_x^2 - D_y^3}{2\left(C_xD_y - C_yD_x\right)} \quad (5)$$

$$R_y = \frac{C_xD_x^2 - C_xD_y^2 - D_x^3 - D_y^2D_x + 2C_yD_yD_x}{2\left(-C_xD_y + C_yD_x\right)} \quad (6)$$

Also, the following angles are obtained: $\delta = \arctan\left(R_y, R_x\right)$, $\beta = \arctan\left(D_y, D_x\right)$ and $\varepsilon = \pi - 2\left(\beta - \delta\right)$. Finally, come the remainder parameters for the robot motion: $\gamma = \pi/2 + \delta$ and the length of the arc for the robot to move along $\Delta s = \left\|OR\right\| \times \varepsilon$.

There are however some cases where approaching the door using this method may not be physically feasible due to previously unperceived objects that become obstacles along that arc-based path. Figure 4 (left) illustrates one such situation. The solution is either to reject paths that fall out of the initial covered region by the laser (initial rotation angle γ greater that 90º) or that pass though occupied regions and make the door unreachable, or in fist place have a better perception system (360º laser).

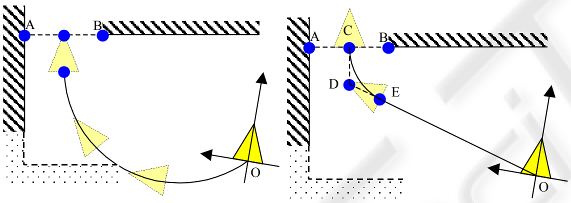

Figure 4: Planned local path turns out not feasible when further perception is available. A two-step based approach is an alternative.

An alternative, although not so elegant solution, is to set an additional point (E) in the line that connects the current position of the robot the D point extracted earlier, as shown in Figure 4 (right). The approach is done towards this point E in a straight line, and then the procedure can be repeated: if distance to door is now at range, perform the arc path calculated with the previous algorithm.

4.2 Crossing the passage

Crossing effectively the door is done with real-time data perception and the subsequent driving of the robot continuously in order to minimize the difference of measurements on both areas on the robot sides. The algorithm is conceptually simple: in the 180º data scan it first locates apertures based on range gradient. Then it selects the widest aperture on its frontal region where the robot can fit (between ±60º but this is configurable) and evaluates its relative position and orientation. Velocity motion is generated continuously in order to drive the robot for the middle of the free pathway. Figure 5 illustrates the main procedure

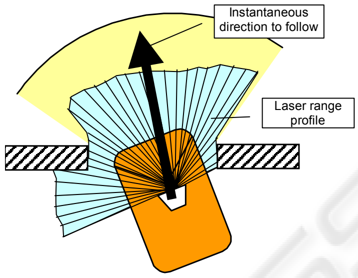

Figure 5: Crossing the door with laser range.

The trigger that detects the end of door crossing occurs when at least on one of the sides empty space appears. That is, when a range of data measurements indicates more than the normal width used for doors. This way, the algorithm drives the robot along a narrow passage regardless of its extension.

5 EXPERIMENTAL SETUP AND RESULTS

The robot used is shown in Figure 6: it is a mobile robot *Robuter* equipped, among other systems, with a SICK laser rangefinder and 24 sonar sensors distributed around the body. The laser has 180° scanning scope with a resolution of 0.5°.

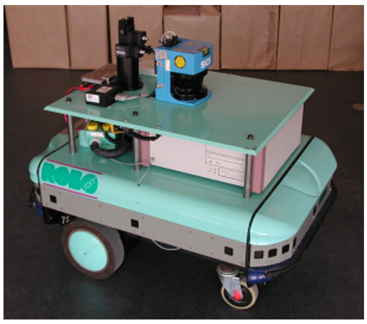

Figure 6: The experimental mobile robot: *Robuter*

Environment setups were built with cardboard boxes in order to emulate more or less complex situations. Real doors were also used but their variety is not vast (at least 95cm wide doors were required). Figure 7 shows one experimental set-up where two narrow passages were constructed with one of them blocked by some obstacles. Figure 8 shows the corresponding laser map and detection results.

Figure 7: Experimental setup with two narrow passages built with paper boxes with one of them blocked ahead.

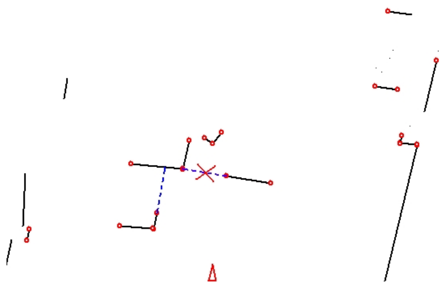

Figure 8: Laser map where two potential narrow passages were detected but one rejected due to obstruction. The triangle on the bottom represents the position of the robot.

In Figure 8 the dark lines represent the walls, and the small circles at the ends of the lines represent the Complete Points. The two detected entrances of passages were drawn with dashed lines. The results of this procedure are summarized in Tab.1.

Table1: Results of narrow passages detection from Figure 8

Type	Coordinates of Ending Points (mm)		Width (mm)	Passable (T/F)
I	(344, 2598)	(-734, 2761)	1090	False
II	(-1378, 1671)	(-1171, 2807)	1154	True

Approaching doors resulted as planned and expected since odometry demands were simple. Both the solutions depicted in Fig. 5 and Fig. 6 turned out well with the second one more efficient in cluttered environments.

Crossing the doors proved quite efficient with the configuration or robot as shown in Figure 6 but a new configuration where the laser was moved forwards for other types of data acquisition resulted less efficient. That is to be enhanced in the near future.

6 CONCLUSIONS

In this paper an algorithm to detect and cross narrow passages was described. In feature maps the passage entrances composed of two corners or one corner and one wall are the highest-level features and could be regarded as important natural landmarks that provide localization information to the robots. The implementation of the behavior was also simple and practical. Approaching doors and traverse them also proved the success of the proposed methods.

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