Navigation of an Outdoor Service Robot by Matching 2D Laser Scans

Jorma Selkäinaho and Pekka Forsman
Automation Technology Laboratory, Helsinki University of Technology
P.O.Box 5500, FIN-02015 TKK, Finland
jorma.selkainaho@tkk.fi, pekka.forsman@tkk.fi

Abstract – Autonomous navigation of a mobile robot is a challenging task. Much work has been done in indoor navigation in the last 10-15 years. Fewer results have been obtained in outdoor robotics. Laser range finder technology has evolved remarkably over the last decade, and offers a fast and accurate method for navigation and environment modeling. It is obvious that the use of several alternative sensors, selected according to the environment, will make the navigation system more flexible. In this paper we describe a flexible navigation system for unknown outdoor environments. The system uses all available sensor information and emphasizes those that best suit the particular operation environment. The core of the navigation system is laser odometry, which is discussed in more detail.


I. INTRODUCTION

Interest in developing mobile service robots has increased remarkably over the last decade. Most of the research has focused on developing robots for indoor use, but there is an increasing trend towards outdoor robotics. A good example of such a service robot is currently being developed at the Automation Technology Laboratory of Helsinki University of Technology. This centaur type service robot is known as WorkPartner and is intended to work together with a human operator mainly in outdoor environments. It has four wheeled legs and two hands [1]. A typical task for the service robot could be to fetch a defined object from a defined place. The human operator gives the required definitions of the task. Carrying out service tasks in an unknown environment is a challenging task for the perception system. The robot must know its local position and heading relative to the working environment. The need for increased flexibility requires that there are no limitations for the work environment. The robot should be able to operate in a new environment without previous knowledge. On the other hand, if previous knowledge exists about the working environment, e.g., from the earlier visits, the information should be exploited.

The goal of this paper is to present a navigation system for a mobile robot such as WorkPartner. The obtained results are also largely valid for other mobile robots working in unstructured outdoor environments. The robot should be capable of moving autonomously in a previously unknown environment. In unknown environments, navigation cannot rely only on predefined landmark types such as trees or sharp corners. However, if landmarks can occasionally be detected, they should be used as additional information for navigation. Usually, the environment may consist of trees, cars, or buildings. An empty field can also form an environment for the robot.

The developed navigation system does not require a structured environment. However, if structured objects exist occasionally in an environment, they will be used. The navigation system utilizes a 2D laser range finder as a main sensor and a low cost GPS receiver, a piezo-electric gyro and inclinometers can be used as alternative or additional sensors.

When WorkPartner starts to work in an unknown place, it should be able to adapt quickly to the new working environment. Transitions from feature rich environments to open fields should not cause problems. In a new environment, there are no previously known landmarks but the robot should recognize potential landmarks and use them the next time. A robot that operates in an unknown environment should be able to cope with dynamic objects such as people walking or moving cars. However, the navigation is based on static features in the environment.

The contribution of this paper is a laser range data matching method that works in unstructured environments outdoors. Similar correlation methods based on evidence grids have previously been used in structured indoor environments [2] and [3]. The new matching method does not require odometry. Odometry-free laser based navigation has been used in an outdoor environment but only with structured landmarks [4]. In what follows, Section II discusses the navigation method. In Section III experimental results of navigation related to the execution of a “snow removal” task are described. And finally, conclusions are presented in Section IV.

II. NAVIGATION OF AN OUTDOORS SERVICE ROBOT

Navigator is the part of the robot control system that keeps track of the robot position during task execution while simultaneously avoiding collision with any obstacles. In this section we are not intending to give a broad survey of recent research in mobile robot navigation but rather describing the implementation of the navigation module in the WorkPartner robot.

WorkPartner is a centaur-like mobile service robot intended for service tasks mainly outdoors. WorkPartner has four legs and wheels are used instead of shoes. Heading of the WorkPartner is controlled by a middle-joint. The basic kinematic structure of the motion platform of WorkPartner
is illustrated in Fig. 1. Currently, the robot coordinate system is fixed on the front body of the robot. This robot is equipped with a 2D laser range finder, heading gyro and inclinometers. Leg joint angles and wheel revolutions are also measured. The navigation accuracy of wheel-based odometry is not sufficient for performing service tasks.

Laser odometry in mobile robotics has been introduced by Bailey and Nebot [4]. They were using a 2D scanning laser range finder as the main navigation sensor. Navigation was based on matching successive landmarks like corners and vertical cylinders. Navigation of WorkPartner is mainly based on a scanning laser range finder. The incremental change in position and heading is computed by comparing successive laser scans. In practice the best match of two successive laser scans is obtained by modifying the incremental change of robot position and heading [5].

This kind of laser odometry uses raw laser scan data and does not require landmark recognition. Robot position and heading are computed by summing up the incremental changes. The incremental change in robot heading is assumed to have zero mean error and standard deviation equal to 0.3 degrees. Therefore, the error in robot heading grows slowly like in random walk but without any limit.

By using wheel odometry and heading gyro the search space is limited so that position and heading is estimated at 2 Hz. Laser odometry can also be used without wheel odometry but the laser scan matching robustness decreases.

Landmarks can be used to set limit to position and heading error of the robot. Tree trunks and walls are potential candidates for landmarks. Artificial landmarks can be used in the absence of natural ones.

A. Mathematical Description of the Navigation Method

In outdoor environments, the objects are not necessarily circular or linear. Matching of dense laser range data requires no extracted features [3]. Actually, every obstacle point that reflects the laser beam can be considered as a low level feature. Matching of laser range data cannot be used in open areas where the obstacles are beyond the maximal measurement range. The maximal range is between 30 m and 80 m depending on obstacle reflectivity when Sick LMS291 is used.

The range values obtained from the 2D scanning laser can also be presented in terms of xy-coordinates. The resulting 2D map shows objects as point groups. After the measurement interval, the next map can be computed. The robot’s rotation and translation during the measurement interval (< 1 s) is relatively small, and therefore most of the obstacle points can also be seen in the new map. If the new map is rotated and translated so that the corresponding obstacle points in successive maps coincide, the robot rotation and translation can be solved.

In principle, the xyz-coordinates of the object points in two successive range maps can also be matched by using a 3D scanning laser range finder. However, direct use of correlation type methods is not possible with current computer technology in real time.

The maximum angular and linear velocity of the robot defines the 3DOF search space for the rotation and translation. The function that is maximized during the map fitting can be constructed in many ways. When using occupancy grids, the corresponding grid probabilities are multiplied and summed over the grid [6]. Schultz and Adams used a binary match function that obtained a value equal to 1 if the corresponding cells were both occupied or both empty [2]. The match functions were then summed over all cells.

Structured landmarks are not guaranteed in outdoor environments. Therefore, a mobile robot should be able to determine its incremental position and heading from raw laser range measurements. Lu and Milios presented two methods to determine robot position and heading from raw laser range measurements [7]. The approximate rotation and translation between two successive laser range scans is defined by using odometry. The accurate matching of successive laser scans is carried out separately for the position and heading by using modified ICP. Successive laser range scan matching can be done also without odometry. Bailey and Nebot developed a method known as laser odometry, based on matching line or point features in successive range scans [4].

Now, let us present the localization method based on correlation of raw laser range scan data with respect to 3 degrees of freedom. The coordinates of an object point are written in the local coordinate system as follows

$$
x_j = r_j \cos(\beta_j - \phi_i) + x_i
$$

$$
y_j = r_j \sin(\beta_j - \phi_i) + y_i
$$

where \( r_j \) is the range to an object point and \( \beta_j \) is the corresponding bearing in laser coordinates. The robot pose is \((x, y, \phi)\), and the coordinates of the obstacle point in local coordinates are \((x_j, y_j)\). The map built by using points \((x, y, \phi)\) is known as a reference map.

When the next laser range scan is taken, the robot position and the heading have changed equal to \((\Delta x, \Delta y)\) and \(\Delta \phi\), respectively.
\[ x_k = r_k \cdot \cos(\beta_k - \phi_i - \Delta \phi) + x_i + \Delta x \]
\[ y_k = r_k \cdot \sin(\beta_k - \phi_i - \Delta \phi) + y_i + \Delta y \]  \hspace{1cm} (2)

where \( r_k \) is the range to an object point, and \( \beta_k \) is the corresponding bearing in laser coordinates. The coordinates of the object point in local coordinates are \( (x_i, y_i) \). The map built by using points \( (x_k, y_k) \) is known as a current map.

When the indexes \( j \) and \( k \) of corresponding points are known, the rotation and translation can be solved from Eq. (1)-(2). In practice, the solution is found by going through all possible rotation and translation values for the robot and then computing the number of corresponding points for each combination. The best match is found by maximizing the number of corresponding points \( N \) relative to translation \( (\Delta x, \Delta y) \) and rotation \( \Delta \phi \):

\[ N(\Delta x, \Delta y, \Delta \phi) = \sum_{k=1}^{361} n_k \]
\[ n_k = 1, \quad \text{if} \quad \exists j \left( (x_k - x_j)^2 + (y_k - y_j)^2 < d_k^2 \right) \]
\[ n_k = 0, \quad \text{otherwise} \]  \hspace{1cm} (3)

The obstacle points are assumed tentatively corresponding if the distance between them is less than \( d_k \).

\[ d_k = 0.6 \cdot \Delta s + 0.6 \cdot \Delta b \cdot r_k \]  \hspace{1cm} (4)

where \( \Delta b \) is the bearing search resolution in radians, and \( \Delta s \) is the position search resolution. When the robot position is searched in 10 cm steps, the maximum error in robot position is equal to 5 cm. The range measurement noise standard deviation is equal to 1 cm. The first term in Eq. (4) is the sum of these two values. When the heading is searched in \( \Delta \theta \) steps, the maximum error in heading is equal to \( 0.5^\circ \cdot \Delta b \). The laser may rotate during the 26 ms long laser range scan. A rotation speed equal to \( 4^\circ/\text{s} \) causes a heading difference equal to \( 0.1^\circ \) between the first and last laser beams. The difference relative to the middle laser beam is \( 0.05^\circ \), which is considered as error. The error caused by the heading search resolution and moderate laser sensor rotation is therefore the same as the second term in Eq. (4). The position error is obtained by multiplying the heading error by the range measurement. It was assumed that the heading search resolution \( \Delta b \) is equal to \( 0.5^\circ \). A smaller value for heading search resolution was not adequate because the laser beam width was equal to \( 0.7^\circ \).

The radius \( d_i \) in Eq. (4) correspond somewhat to half of the cell size in occupancy grid based methods. At small object distances, the diameter of a circular cell is approximately 12 cm. The object distance defines mainly the cell size when the distance is greater than 11.5 m. The search space in position and heading is constrained according to the robot’s motion range during the measurement update period. When the robot uses wheeled locomotion, it is sufficient to search the translation in front of the body surge direction. The maximum velocity of the robot defines the search space in the surge direction. The search space in heading is determined by the angular speed of the articulation angle as well as robot velocity and articulation angle.

Organizing object coordinate pairs \( (x_k, y_k) \) in ascending order along \( x_k \), and using binary search make the computation faster. Only points that fulfill \( r_k < r_{\text{max}} \) are taken into account. The search space in position and heading is selected according to the motion range coming from the vehicle dynamics. Fig. 2 shows the robot’s front body segment (arrow) in two successive positions.

When the robot moves on wheels, the one step heading difference, surge difference, and sway difference are not independent of each other. It can be seen from the above figure that when surge difference is \( \Delta y \) and heading difference is \( \Delta \phi \), then the sway difference must be as follows

\[ \Delta x = R_T - R_T \cos(\Delta \phi) \]
\[ \Delta y = R_T \sin(\Delta \phi) \]  \hspace{1cm} (5)

where \( R_T \) is the turning radius.

By using the second order approximation of trigonometric functions, we get

\[ \Delta x = R_T - R_T (1 - \Delta \phi^2 / 2) \]
\[ \Delta y = R_T \cdot \Delta \phi \]  \hspace{1cm} (6)

Substituting the \( \Delta y \) equation to \( \Delta x \) equation, we get

\[ \Delta x = \Delta y \cdot \Delta \phi / 2 \]  \hspace{1cm} (7)

Thus, the new position and heading can be searched in 2DOF space, namely in \( \Delta y \) and \( \Delta \phi \). Sway value \( \Delta x \) is computed according to the last equation.

There is no guarantee that in partially structured environments, the matching solution is always unique. Erroneous matching results have been occasionally obtained when using a constant acceptance square of size equal to 20
The acceptance circle (Eq. 4) that depends on laser range measurement works reliably. However, other sensors such as heading gyro and wheel based odometry can be used to verify the correct match.

B. Simultaneous Localization and Mapping

When a mobile robot operates in the working environment, a map is needed so that the work tasks can be defined. In certain cases such as autonomous cars driving on motorways, there is usually a map available. With mobile robots, it is usually too restrictive to assume that there exists a map of the working environment. Therefore, the only possibility left for an autonomous robot is that the robot itself builds a map when it first operates in the working environment. The mapping task requires that the robot knows its position relative to objects in the environment. Simultaneous localization and mapping has been extensively studied, for example in [8].

A series of smaller laser range maps can be fused together to obtain a bigger map. A serious problem in fusing maps is the lack of consistency. Perfect consistency requires that all laser range finder positions and heading values are known at the time of scanning. In practice, when the robot is moving, some error in position and heading accumulates that compromises the map’s consistency. Thus, the same object is written many times to slightly different positions. If the position error is known, then multiple objects can be rejected from the map by checking the distance between the old object and a new candidate. The new object candidate is assumed to be identical to the old one if the distance between them is smaller than the position error. By rejecting objects in this way, some true objects are missed from the map.

III. EXPERIMENTAL RESULTS

The performance of the navigator during the execution of the “snow removal” task is presented next. The intention of this work task is to remove snow from an area defined by the human operator during the task description. The operator describes the task on the work site by bordering the area with sign markers and by giving the command “remove snow”. Thereafter WorkPartner carries out the task autonomously under the control of the “brains” of the robot, called “task planner”, which is presented in an other paper submitted for ICRA2005. The performance of navigation plays an essential role in the success or failure of the task execution.

A task to remove snow was given to WorkPartner. The robot started inside a large hall. Heading and y-directional initial position was obtained from a wall on the right side of the robot. The x-directional initial position was obtained from a large door surface. The wall direction and distance were computed by using the Hough-transform and line fitting. Total duration of the snow removal task was equal to 15 minutes. In Fig. 3 WorkPartner removing snow from the yard is shown.

The estimated position and heading of the robot is drifting because of the laser odometry. This affect on the position estimates of the observed tubes. An observed tube was recognized when its estimated position was less than 3 m away from the initial tube position. The estimated distance between the tubes was not affected by the robot position error. It was found that the variance of the estimated tube distance was less than 5 cm. Fig. 4 shows the robot trajectory when the tubes were used occasionally as landmarks. Figures 5, 6 and 7 show how much bigger position and heading error exists when the correlation based laser odometry without tube landmarks is used. The error was computed by using the robot trajectory obtained with tube landmarks. The absolute accuracy of the reference trajectory was verified by using the wall of the building and one door surface. At 12 min and 50 s from the robot start the reference trajectory position error was equal to -0,02 m in the direction of x-axis and -0,15 m in the direction of y-axis. The robot heading error was equal to 0,9 degrees at the same time. The position error has mainly accumulated after the robot has last time seen the tubes and the position error has mainly caused by the heading error.

<table>
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<th>no of points</th>
<th>Distance (m)</th>
<th>Width (deg)</th>
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<tbody>
<tr>
<td>1</td>
<td>51,92</td>
<td>0,348</td>
</tr>
<tr>
<td>2</td>
<td>36,50</td>
<td>0,494</td>
</tr>
<tr>
<td>3</td>
<td>17,24</td>
<td>1,047</td>
</tr>
<tr>
<td>4</td>
<td>12,28</td>
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<tr>
<td>6</td>
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<td>2,489</td>
</tr>
<tr>
<td>7</td>
<td>5,54</td>
<td>3,258</td>
</tr>
</tbody>
</table>
While removing snow from the given area patch the laser range measurement were stored and mapped to a common frame of reference. In Fig. 8, the 2D map generated from the raw laser measurements is depicted. Altogether 1720 laser range scans have been collected while traversing a distance of about 100 meters were used to build the map. Also the trajectory of the robot has been drawn in the figure.

In robot odometry, most of the cumulative position error is originating from heading error. Position error in forward direction is proportional to square of heading error and travelled distance. However, position error in sideways direction is proportional to heading error and travelled distance[5].

The robot motion is (Fig. 4) along the x-axis when it returns to hall. Therefore, the position error in y-axis (Fig. 7) is changing faster at the same time. This is caused mainly by the heading error shown in Fig. 5.
V. CONCLUSIONS

Navigation based on correlation of raw laser range data is useful in unknown outdoors environment. Fixed landmarks are still required in order to reduce the robot position error cumulating from laser odometry. It has been shown that the position and heading error is acceptable when landmarks have been occasionally used along the robots route. At open fields vertical cylinders can be used as artificial landmarks.

REFERENCES