DYNAMIC POSITIONING OF A MOBILE ROBOT USING A LASER-BASED GONIOMETER

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Abstract: Positioning is a fundamental problem in mobile robot navigation. Several approaches to cope with the dynamic positioning problem have been made. Most of them are based on the inconsistent use of the algorithm for static positioning enhanced by predictive algorithms. In this paper, a method that guarantees the consistent use of this algorithm at any time under dynamic condition is presented. It combines vehicle kinematics and laser-based goniometer data for real time simulation of the evolution of the straight lines between the laser-based goniometer and the set of artificial landmarks used. Experimental results showing the accuracy of this method are presented.

Keywords: Automated guided vehicles, Mobile robots, Positioning systems, Robot navigation, Kinematics.

1. INTRODUCTION

Mobile robots are increasingly used in flexible manufacturing industry and service environments like hospitals. The main advantage of these vehicles is that they can operate autonomously in their workspace. To achieve this automation these vehicles must include a positioning –or localization– system in order to provide the robot with position and orientation in the plane as accurately as possible (Leondes, 2000).

In the past two decades, a number of different approaches have been proposed to solve the positioning problem. These can be classified into two general groups (Borenstein, *et al.*, 1997): relative and absolute positioning. In relative positioning, dead reckoning and inertial navigation are used to calculate the robot position and orientation from an initial configuration. Odometry –which is a particular case of dead reckoning– is the most widely used positioning method because of its low cost, high updating rate, and reasonable short path accuracy. However, the main disadvantage of odometry is its unbounded growth of time integration errors.

Conversely, absolute positioning methods estimate the robot position and orientation in the workspace reference by detecting different landmarks placed in the robot environment. There are two main approaches according to the use of natural or artificial landmarks. The approach based on "natural" landmarks uses distinctive features in the environment that have a function other than robot navigation. The other approach uses distinctive "artificial" landmarks placed at known locations of the workspace with the sole purpose of enabling robot navigation. This second approach has the advantage of being more reliable than the first one, although the first is more flexible as it does not require the preparation of the environment.

In this paper a positioning method that combines the use of a laser-based goniometer –using artificial landmarks– and the vehicle kinematics is presented. Typically, laser-based goniometer positioning methods provide the position and orientation of the vehicle under static condition by using the triangulation algorithm (see Section 2).

Under robot dynamic condition, the algorithm is inconsistent because the landmarks taken into account are detected from different positions and orientations of the robot (Skewis and Lumelsky, 1994).

The presented method uses the kinematics of the vehicle to continuously calculate the landmark angles relative to the robot, between consecutive actual reflections from each landmark. As a consequence, the conventional triangulation algorithm can be consistently used under dynamic condition at any time. If needed, dead reckoning can also be used, in between positioning measurements, in order to obtain a continuous estimation of the robot position and orientation (see Sections 3 and 4).

Many approaches have been done to fuse dead reckoning with an absolute positioning system in order to solve the dynamic positioning problem. Most of these approaches use Extended Kalman Filter –EKF– to combine all measurement data (Hu and Gu, 2000; Nishizawa, *et al.*, 1995). These methods, which deal with the system and sensor errors, assume that these errors –which include the errors associated with the inconsistent use of the triangulation algorithm– can be modeled as white Gaussian noise. However, several authors agree that in real operation the signals used have nongaussian noise density (Hanebeck and Smith, 1996; Sasiadek and Hartana, 2001) and propose recursive algorithms more suitable than the EKF.

In the presented method the signal noise is not taken into account, but it is reduced by properly locating the landmarks. In Section 5 the experimental results achieved by means of it are presented.

2. ROBOT POSITIONING UNDER STATIC CONDITION

The conventional laser positioning system consists of a laser-based goniometer –a rotating laser scanner with the stator placed in the robot frame– and a group of catadioptric landmarks strategically placed on the walls of the workspace. The laser scanner emits a rotating laser beam which sweeps horizontally the environment and reflects back when it detects a catadioptric landmark. The system measures the angle of the reflected beam, relative to the vehicle, by using an incremental encoder.

Under static condition, it is possible to calculate the position and orientation of the mobile robot from the position where the landmarks are located and the measured angles for three of them (Fig. 1) by means of the triangulation algorithm (McGillem and Rappaport, 1989; Skewis and Lumelsky, 1994; Hanebeck and Smith, 1996).

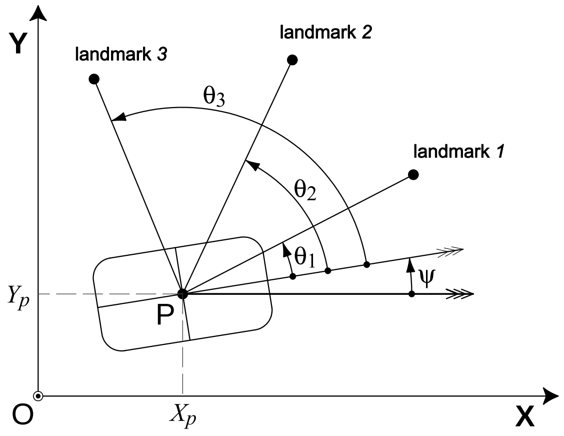

Fig. 1. Mobile robot positioning under static condition. Robot position (X_p, Y_p) and orientation (ψ) can be calculated from angles θ_1, θ_2 and θ_3. In this picture P represents the center of the laser-based goniometer.

As the accuracy of this positioning method depends upon the point of observation and the beacon arrangement (McGillem and Rappaport, 1989), more than three landmarks and an optimising algorithm can be used to improve the accuracy (Hu and Gu, 2000; Madsen and Andersen, 1998; Shimshoni, 2001).

Under dynamic condition, the static algorithm proposed in the referenced papers cannot be directly applied because each of the landmarks is detected from a different position and even from a different orientation of the vehicle. To solve this drawback, the presented method uses the kinematics of the vehicle to simulate in real time the evolution of the straight lines between the laser-based goniometer and the set of landmarks used. By doing this, the static triangulation algorithm can be consistently applied at any time under dynamic condition.

3. KINEMATICS OF THE VEHICLE

The vehicle studied in this approach is a forklift type mobile robot with a tricycle kinematics. Its main geometric parameters are shown in Fig. 2. The vehicle has two coaxial wheels located in the fork, the driving and steering wheel, and a castor wheel.

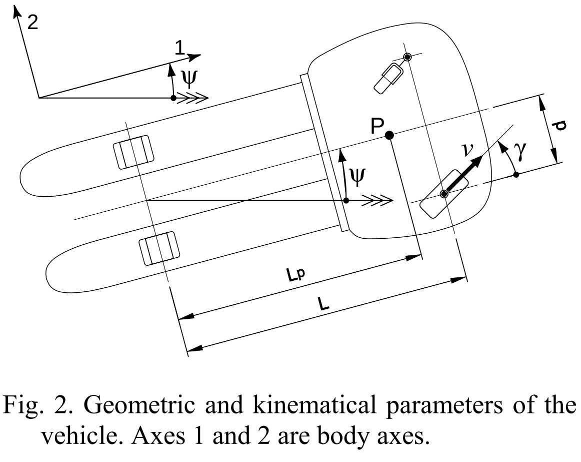

Fig. 2. Geometric and kinematical parameters of the vehicle. Axes 1 and 2 are body axes.

The velocity **v**(P) of the point P –center of the laser-based goniometer– can be calculated from the velocity v of the center of the driving-steering wheel and its steering angle γ (Fig. 2). Using axes 1-2, **v**(P) is expressed as:

$$\{\boldsymbol{v}(P)\} \equiv \begin{Bmatrix} v_{1p} \\ v_{2p} \end{Bmatrix} = v \begin{Bmatrix} \cos\gamma - \dfrac{p}{L}\sin\gamma \\ \dfrac{L_p}{L}\sin\gamma \end{Bmatrix} . \qquad (1)$$

Geometric variables p, L and L_p are defined in Fig. 2. The orientation angle of the vehicle evolves with the following angular velocity:

$$\dot{\psi} = \frac{v}{L}\sin\gamma . \qquad (2)$$

The velocity v and the angular coordinate γ can be obtained, respectively, from the driving and steering encoders on the robot.

4. ROBOT POSITIONING UNDER DYNAMIC CONDITION

The solution presented to cope with positioning under dynamic condition is based on the simulation, between actual reflections, of the evolution of the angle –relative to the vehicle frame– of the straight lines from the laser goniometer to the landmarks used for positioning. This simulation depends upon the kinematics of the vehicle (see Section 3).

If ρ_i stands for the distance between the point P of the vehicle (Fig. 2) and the landmark i, and θ_i is the angle between the robot longitudinal axis and the straight line from P to this landmark (Fig. 3), the evolution of these variables can be expressed, according to the vehicle kinematics, as:

$$\dot{\rho}_i = -\left(v_{1p}\cos\theta_i + v_{2p}\sin\theta_i\right) , \qquad (3)$$

$$\dot{\theta}_i = \frac{\left(v_{1p}\sin\theta_i - v_{2p}\cos\theta_i\right)}{\rho_i} - \dot{\psi} . \qquad (4)$$

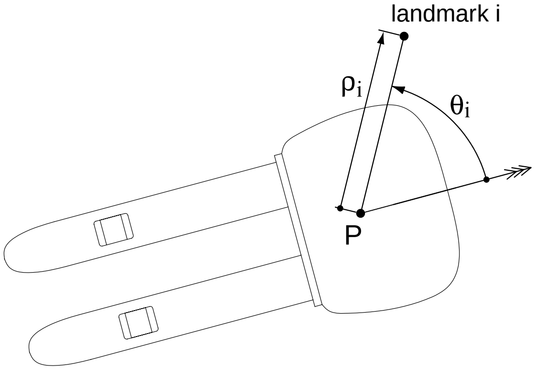

Fig. 3. Variables ρ_i and θ_i.

Time integration of equations (3) and (4) between actual measurements leads to a correct estimation of the value of ρ_i and θ_i in real time.

Note that the initialization of variables is done at different instants. The variable ρ_i is initialized every time that a positioning measurement is carried out –in our experiments, once in a laser revolution–. If t_{k-1} represents the last time an absolute positioning measurement has been done, then the value of this variable is calculated using equation (5).

$$\rho_i(t) = \rho_i(t_{k-1}) + \int_{t_{k-1}}^{t} \dot{\rho}_i dt . \qquad (5)$$

Concerning variable θ_i, it is initialized each time a reflection from landmark i occurs. If $t_{i,k-1}$ represents the time of the last reflection from landmark i, time integration of equation (4) leads to the time evolution,

$$\theta_i(t) = \theta_i(t_{i,k-1}) + \int_{t_{i,k-1}}^{t} \dot{\theta}_i dt . \qquad (6)$$

If needed, odometry can also be used to obtain a continuous estimation of robot position and orientation between positioning measurements.

5. EXPERIMENTAL RESULTS

The developed method has been tested on a forklift mobile robot (Fig. 4).

5.1 Positioning system description

The robot uses a *Guidance Control Systems Ltd.* laser-based goniometer with a head rotation frequency of 8 Hz. It delivers 65535 ticks per revolution with an accuracy of 0,095 mrad and its maximum reflection distance is 30 m. Catadioptric rectangles –retro-reflecting– that polarize the laser signal are used as landmarks.

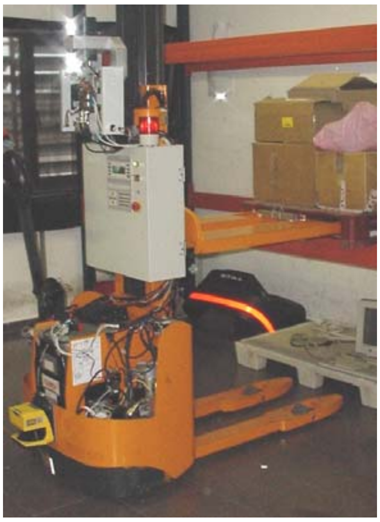

Fig. 4. Forklift prototype used for the experimental validation of the method.

The mobile robot used is provided with a driving encoder and a steering encoder for dead reckoning. The former –which measures the distance traveled by the center of the driving-steering wheel– provides a resolution of 45,798 ticks/mm, and the latter –which measures the steering angle– 2,122 ticks/mrad. These odometric sensors are used to determine the variables v and γ defined in Section 3.

The hardware used to support the method is an industrial PC (PC104 based) Pentium III Celeron clocked at 400Mhz smartcore. This PC runs with a real-time OS RT-Linux 3.2. For the odometric and laser signals capture, specific firmware implemented by FPGA is applied. By means of this equipment, positioning can be calculated at a rate as fast as one measurement per 120 µs.

The computational cost of the dynamic positioning algorithm is proportional to the number of dead reckoning measurements per goniometer revolution. If an optimising algorithm that chooses the best three landmarks is included, the real computational cost will increase but it will be presumably lower than the one required by means of other methods based on predictive algorithms –for instance, EKF–.

5.2 Laboratory environment description

The robot navigates through the laboratory environment shown in Fig. 5, and the same three landmarks are used for all the configurations of the vehicle in the laboratory.

Landmark positions have been topographically measured with sub-millimeter accuracy in order to reduce the uncertainties of the method.

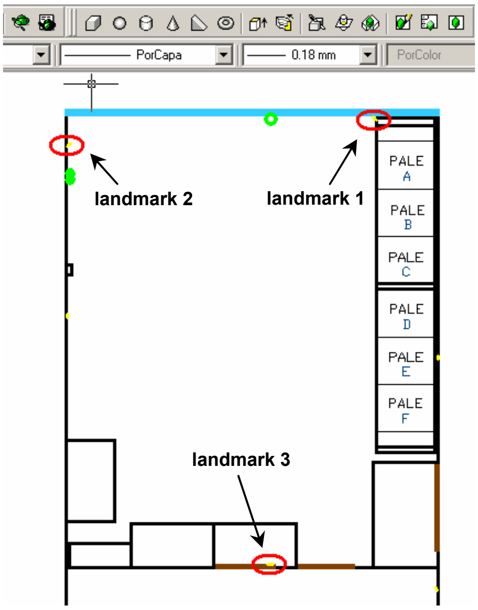

Fig. 5. CAD map of the laboratory.

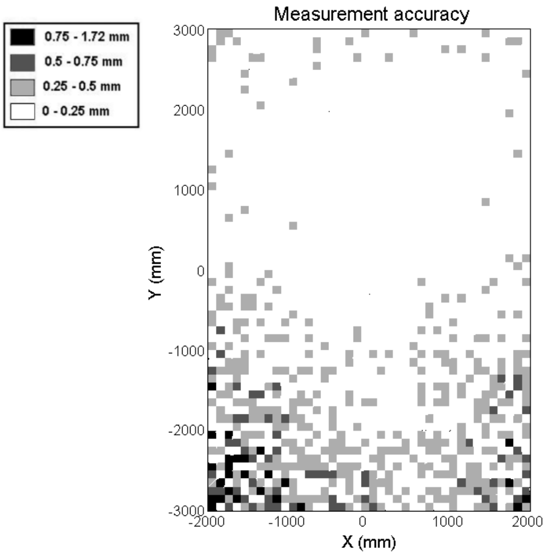

Fig. 6. Measurement accuracy of the triangulation algorithm used under static condition over the laboratory environment.

The accuracy of the triangulation algorithm depends upon the landmark arrangements, the position of the vehicle in the laboratory and the laser-based goniometer resolution. The accuracy of the positioning measurements obtained under static condition has been represented over a 10 cm grid that covers the laboratory environment accessible to the robot, and it is shown in Fig. 6.

Under static condition, the maximum error –worst accuracy– is located at the bottom left-hand corner of the laboratory (Fig. 6) and its value is 1,72 mm. The best accuracy is obtained near the center of the laboratory (0 – 0,25 mm).

5.3 Experimental results

In order to validate the positioning method under dynamic condition, a photometric method –based on a high resolution photographic camera– has been used.

The actual trajectory of the robot is drawn on the floor by means of a marker that marks one point per second. Then, several photos of the trajectory are made. Each of these photos must include, at least, two reference points, the position of which has been previously measured with sub-millimeter accuracy. From these photos, the actual positions along the trajectory and the calculated positions can be compared. Even though the orientation of the vehicle is calculated by the algorithm, only the position measurement has been validated.

In the experiments the robot has followed a trajectory under manual control with a velocity v in the range of 0,14 – 0,18 ms^{-1} –which is significantly lower than the nominal velocity of 1 ms^{-1}–. The actual and calculated positions are shown in Fig. 7–8.

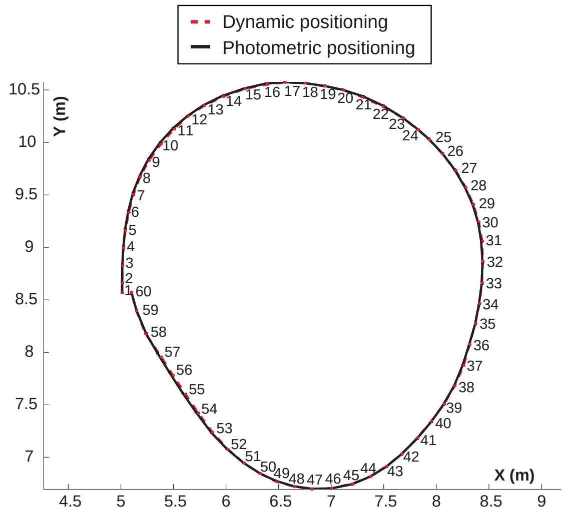

Fig. 7. Vehicle trajectory for the validation of the dynamic positioning method.

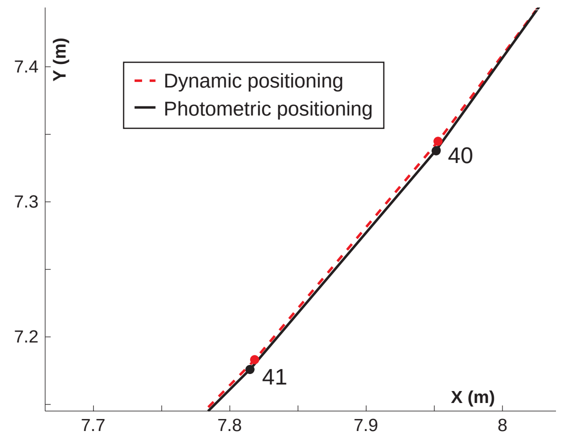

Fig. 8. A detail of the trajectory shown in Fig. 7.

As it can be seen in Fig. 9 there is a lateral error and a longitudinal error –along the trajectory direction– between the actual points obtained from photometry and the calculated points. As the longitudinal error is mainly associated with the marker time delay –and usually longitudinal errors are not relevant in the control of mobile robots–, the lateral error e_{lat} is taken as a measure of the accuracy.

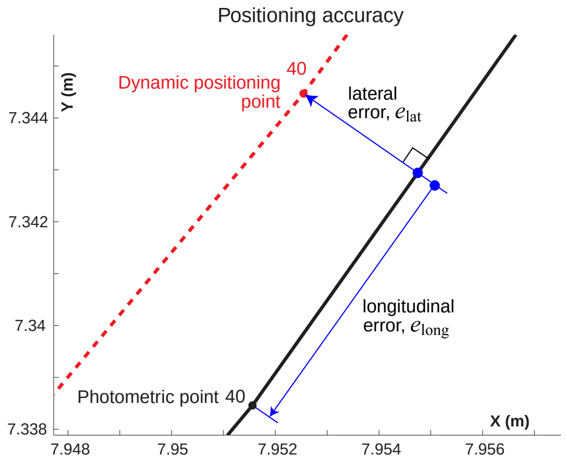

Fig. 9. Lateral error and delay of the position obtained from the presented method.

The lateral error is determined at each measured position –once per second–. Table 1 shows the average and the standard deviation of the absolute value of the lateral error e_{lat} for both procedures: the presented dynamic positioning method and the inconsistent use of the static triangulation algorithm –under dynamic condition–.

Table 1 Average and standard deviation of the absolute value of the lateral error e_{lat} for the presented method and for the inconsistent use of the static triangulation algorithm

Variable	**Mean**	**Standard deviation**
$\lvert e_{lat}\rvert$ (dynamic)	5 mm	4,2 mm
$\lvert e_{lat}\rvert$ (static)	10,5 mm	7,6 mm

From the results in Table 1 it can be seen that, even for the low velocity range used, the presented method reduces the average of the lateral error absolute value from 10,5 mm –using the static triangulation algorithm under dynamic condition– to 5 mm. Besides this, the standard deviation has also been reduced, which implies that the results achieved by means of the presented method are more reliable. The accuracy gain for nominal velocity should be greater.

It should be noted that the errors associated with the inconsistent use of the static triangulation algorithm presented in Table 1 are larger than the ones mentioned in Section 5.2 which were determined under actual static condition.

Fig. 10 shows the histogram of the lateral error measures along the robot trajectory when the dynamic positioning method is applied. It can be noticed that the lateral error is always smaller than 18 mm –in absolute value–. Other approaches that solve the dynamic positioning problem by means of predictive algorithms (Hanebeck and Smith, 1996) lead to measurement deviations of about 50 mm.

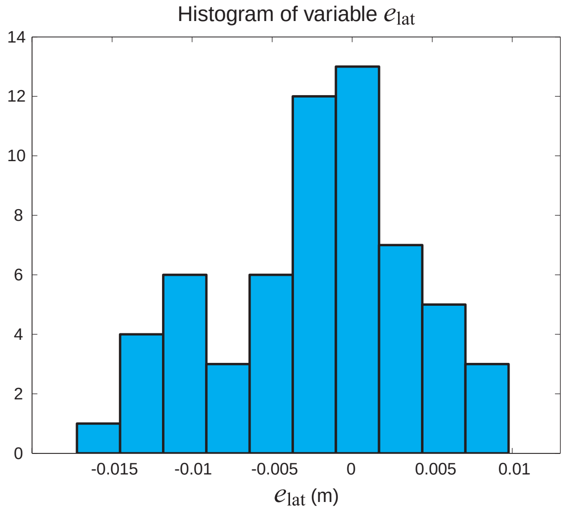

Fig. 10. Histogram of the lateral error e_{lat} (in meters).

6. CONCLUSIONS AND FURTHER WORK

In this paper, a method that copes with the dynamic positioning problem has been presented. The method combines vehicle kinematics and laser-based goniometer data to simulate in real time the straight lines between the center of the goniometer and the set of landmarks used. By doing this, the static triangulation algorithm can be consistently applied under dynamic condition at any time.

The accuracy of the proposed dynamic positioning algorithm has been experimentally tested on a real forklift prototype –equipped with a laser-based goniometer, odometric sensors and the required hardware support– navigating through a laboratory environment. A photometric method has been used to estimate the true location of the vehicle. A maximum lateral error of 18 mm between actual and calculated robot trajectories has been found.

In the future, the presented method can be improved by taking into account the odometric signal noise and by finding a parameter to evaluate in real time the accuracy of the measurement. This parameter could help to optimise the simultaneous use of more than three landmarks.

Another future line of research is the extension of the presented positioning method to vehicles with kinematics different from that of the tricycle.

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