A NEW APPROACH TO AVOID OBSTACLES IN MOBILE ROBOT NAVIGATION: TANGENTIAL ESCAPE

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Abstract: This paper proposes a new strategy for obstacle deviation when a mobile robot is navigating in a semi-structured environment. The proposed control architecture is based on a reactive approach, thus demanding low computational effort. It allows the robot to navigate from a starting point to a destination point without colliding to any obstacle in its path. The deviation from an obstacle is performed according to an escape angle calculated so that the new robot orientation is tangent to the obstacle. It is shown that such strategy generates more efficient trajectories, in the sense that the destination point is reached in less time while saving energy and reducing the demand on the robot motors. Another meaningful feature of the proposed strategy is that it also allows to implement the behaviors *Wall Following* and *Corridor Following* with no additional computation.

1 INTRODUCTION

When a mobile robot is navigating in an unstructured environment it is very important to assure that it will not collide to any obstacle. Several methods, like Edge Detection (Kuc and Barshan, 1989), Certainty Grid (Elfes, 1987), Potential Field (Khatib, 1986), Virtual Force Field (VFF) (Borenstein and Koren, 1989), Vector Field Histogram (VFH) (Borenstein and Koren, 1991) and Nearness Diagram (ND) (Minguez and Montano, 2004), have been used to avoid obstacles in mobile robot navigation. Some of them are tailored for reactive navigation and others are more suitable to deliberative navigation, where a map of the robot working environment is built (Fox et al., 1997; Brock and Khatib, 1999; Althaus and Christensen, 2002).

The VFH, VFF and Certainty Grid methods are tailored for deliberative navigation. They use data coming from the robot sensors to build a detailed map of the environment, which is used to plan the trajectory the vehicle should follow. Such methods generally require a lot of computation and loose effectiveness upon any change in the robot working environment.

Regarding reactive navigation, the robot has no *a priori* knowledge about the environment surrounding it, except, perhaps, that it is a plain indoor environment. Then, to plan a trajectory is not possible, since a map of the environment is not available. The idea is that perceptions are tightly related to actions, resulting in simplicity and low computational effort. Environmental changes are not a problem as well, when reactive navigation is adopted. Therefore, reactive navigation is more suitable to semi-structured environments, while deliberative navigation is more suitable to structured environments. The Edge Detection and the Potential Field methods, among those previously mentioned, are methods compatible to reactive navigation.

This paper recalls obstacle avoidance in mobile robot navigation, and proposes a new approach to this topic, as it will be detailed in the sequence. For being extensively used as a reactive control architecture, the *Impedance Based Control* (Hogan, 1985; Secchi et al., 2001), which uses the concept of Artificial Potential Field, is adopted as the starting point. Thus, Section 2 describes this obstacle avoidance method and presents a simulated example using it. In the sequence, Section 3 describes a modification here proposed to the impedance based control and presents a simulated example using the new strategy for avoiding obstacles. Next, Section 4 presents two experiments using the new strategy here proposed to avoid obstacles. Finally, Section 5 highlights the main conclusions.

The simulations presented in Section 2 and Sec-

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tion 3 were accomplished using the simulator that accompanies the Pioneer 2-DX mobile robot, while the experimental results were obtained using the Pioneer 2-DX itself, with an onboard computer based in the Intel Pentium MMX 266 MHz processor having 128 MBytes of RAM and running the Linux operating system. The sensors used are 16 ultrasonic sensors in a ring distributed like depicted in Fig. 1.

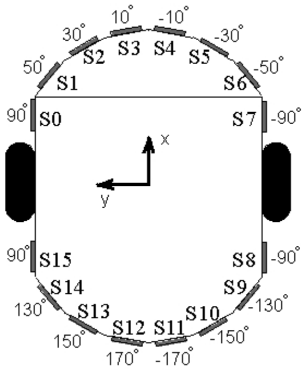

Figure 1: Sonar distribution for the Pioneer 2-DX platform.

2 THE IMPEDANCE-BASED CONTROL SYSTEM

This control system uses the concept of generalized or extended impedance to represent the relationship between the robot movement and a fictitious repulsive force (Hogan, 1985; Secchi et al., 2001). Such a repulsive force is a function of the distance robot-obstacle. A contact robot-obstacle should be avoided, what is accomplished by generating a repulsive force that increases when the robot gets closer to the obstacle.

2.1 Describing the Impedance Based Control System

Fig. 2 shows a situation in which an obstacle is detected by the robot sensors. The repulsive force F is generated, causing a temporary displacement of the goal point x_d, which allows the robot to avoid the obstacle by changing its heading angle. The components of the force F — F_t (the component coinciding with the robot orientation) and F_r (the component normal to the robot orientation) — are also represented.

The magnitude of the repulsive force F the obstacle exerts on the robot is calculated as (Secchi et al., 2001)

$$F = a - b[d - d_{min}]^2, \qquad (1)$$

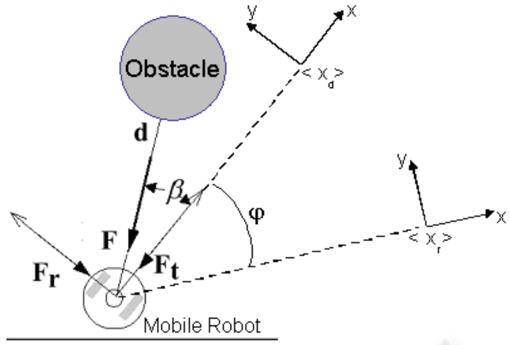

Figure 2: The fictitious force generated by an obstacle.

where a and b are positive constants related by $a = b[d_{max} - d_{min}]^2$, d_{min} is the minimum distance the sensors are able to measure, d_{max} is the maximum distance intended to cause a nonzero fictitious repulsive force and d is the smallest robot-obstacle distance currently measured by the robot sensors. Notice that $d_{min} < d < d_{max}$, and d_{max} characterizes the repulsion zone, defined as the region inside which the fictitious repulsive force has a non-zero value.

An impedance $Z(s)$ is then defined as

$$Z(s) = Bs + K, \qquad (2)$$

where B and K are positive constants representing the damping and spring effect of the interaction robot-obstacle in the repulsion zone, respectively. The impedance error x_a is calculated using the component F_t (Fig. 2), as

$$x_a = Z(s)^{-1} F_t, \qquad (3)$$

while the angle φ that causes a rotation in the target position x_d is given by

$$\varphi = x_a sign(F_r). \qquad (4)$$

Thus, the real target position x_d is rotated to a temporary position x_r given by

$$x_r = \begin{bmatrix} \cos\varphi & \sin\varphi & 0 \\ -\sin\varphi & \cos\varphi & 0 \\ 0 & 0 & 1 \end{bmatrix} x_d, \qquad (5)$$

which becomes the new reference to the *final pose controller* (a control loop responsible for taking the robot to the goal), as shown in Fig. 3. There the control signals u and ω represent the robot linear and angular velocities, respectively, while the current pose of the robot, in cartesian coordinates, is characterized by $\mathbf{x_c'} = [x_c \; y_c \; \phi_c]$.

Whenever an obstacle is detected in the repulsion zone, a fictitious force F is generated, which generates a non-zero rotation angle φ, causing the robot to avoid the obstacle (the external loop, relative to the

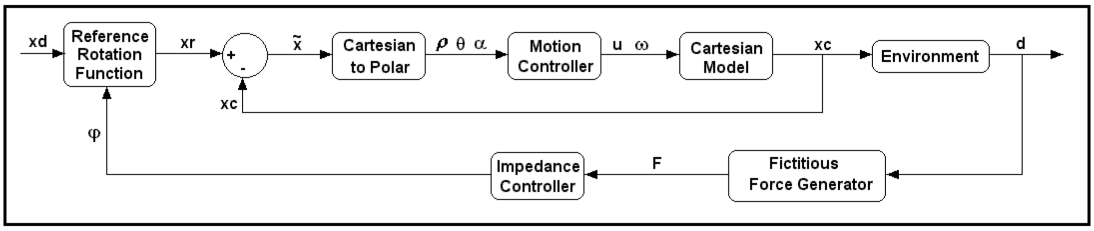

Figure 3: Block diagram corresponding to the Impedance Based Control System.

impedance controller (Hogan, 1985)). The rotation (avoidance) angle is inversely proportional to the distance robot-obstacle and to the angle β. In this strategy the path the robot takes to escape from an obstacle is not taken into account. The vehicle is supposed to get close to the real target position while maneuvering to avoid any obstacle. After passing the obstacle, the angle φ becomes zero and the rotation matrix becomes an identity one, thus causing x_d not to change.

Finally, it is worthy to emphasize that this control system is stable in the Lyapunov sense (Secchi et al., 2001). This means that the robot will always reach the goal (if the goal is reachable), independently of the obstacles in its path.

2.2 A Simulated Example

An example is here simulated, in which the robot should reach the point (9000 *mm*, 5000 *mm*), avoiding any obstacle in its path. Fig. 4 shows the path followed by the robot from the starting point (0 *mm*, 0 *mm*, 0) to the destination point (the orientation of the robot when reaching the goal is not taken into account). When an obstacle is detected, a fictitious force is generated and the robot makes a turn. The value of d_{max} was chosen to be 70 *cm*. Fig. 5 shows the control signal u generated by the final pose controller. From such figure one can notice meaningful variations in the robot linear velocity. They mean great acceleration and deceleration of the robot motors.

3 THE NEW CONTROL SYSTEM

A new control system is here proposed, which is based in escape paths that are tangent to the obstacle detected. Such a control system uses just part of the Impedance Based Control system, namely the inner loop in Fig. 3 (see Fig. 6). The difference is that the rotation angle φ is not calculated using the repulsive force F anymore, but using the angular position of the obstacle relative to the robot. The rotation angle is now determined to make the vehicle to turn around until getting aligned to the tangent to the obstacle contour. One advantage of this method is that the robot contours the obstacle, thus describing excellent trajectories when navigating (Maravall and de Lope, 2002), as it is shown in the sequence.

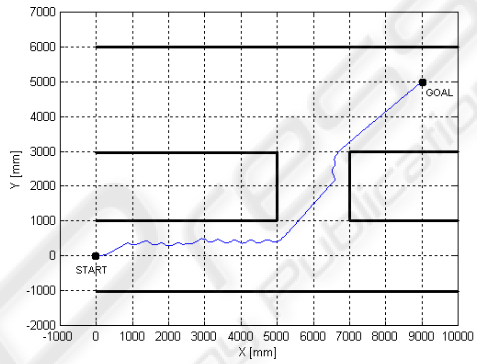

Figure 4: The path followed by the robot (Impedance).

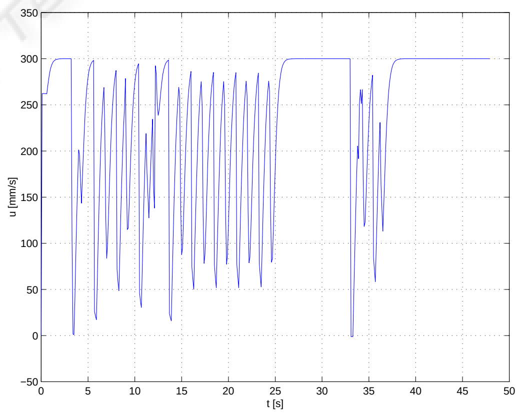

Figure 5: The linear velocity of the robot (Impedance).

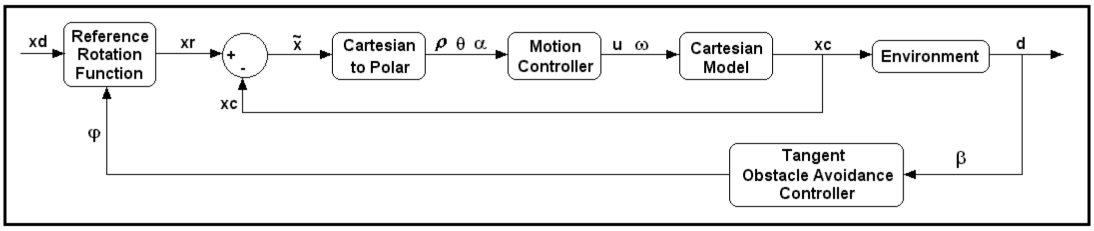

Figure 6: Block diagram corresponding to the new control system.

3.1 Describing the New Control System

When the robot gets into the repulsion zone (Fig. 7), the angle β is determined (it is the angle between the axis of movement of the robot and the radius corresponding to the sensor measuring the least distance from the robot to the obstacle detected). Knowing the robot orientation relative to the real target (the angle α) and the positions of the ultrasonic sensors around the robot platform, the angle φ that allows a tangential deviation is obtained as

$$\varphi = \left(\frac{\pi}{2} - |\beta|\right) reverseSign(\beta) - \alpha, \qquad (6)$$

where $reverseSign(\beta)$ corresponds to $-Sign(\beta)$.

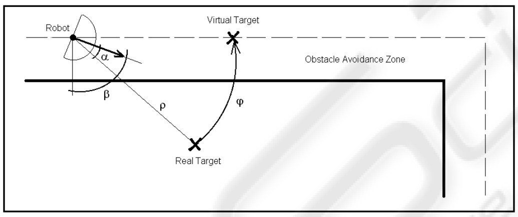

Figure 7: Obtaining the angle φ.

The angle φ is then used in the rotation matrix in (5) and the real target is rotated to a new position (the *virtual target*). The final pose controller, which calculates the new robot orientation to reach the target, uses the coordinates of the virtual target, causing the robot to take the tangent to the obstacle border. Notice that in the absence of obstacles the change in the position of the real target is null, and the robot continues seeking for the real target. This algorithm is represented in Fig. 6, where u, ω and the vector $\mathbf{x_c}$ have the same meaning as in Section 2.

It is important to notice that the control loop corresponding to the proposed controller is slower than the control loop corresponding to the final pose controller. Then, the robot is able to follow the variation imposed to the target position. Notice also that the same idea applies to the impedance based control. Knowing this, the asymptotic stability of the impedance based control system is demonstrated in (Secchi et al., 2001). Now, if one compares the block diagrams corresponding to both impedance based and tangential deviation control systems, it is possible to realize that the proposed control system is also asymptotically stable, once the inner loop of both systems is the same. This means that the strategy here proposed for obstacle deviation always takes the robot to the target (if the target is reachable), thanks to its asymptotic stability.

3.2 A Simulated Example

The objective in this simulation is to take the robot from the starting point ($0\ mm,\ 0\ mm,\ 0$) to the goal point ($9000\ mm,\ 5000\ mm$) once more, avoiding any obstacle in its path. Fig. 8 shows the path the robot followed until reaching the goal. As the obstacles (the walls of the corridors the robot enters in) are detected, the robot turns around in order to follow a line parallel to the walls. The repulsion zone was defined as $70\ cm$ once more. Fig. 9 shows the linear velocity developed by the robot. An important remark about this method is that while avoiding obstacles, approximately between 4s and 17s in Fig. 9, the robot keeps navigating with constant linear velocity (the values of the angular velocity and the orientation, in such time interval, are very close to zero).

3.3 Comparing the Results

After analyzing the graphics related to the impedance based control system and the proposed control system, it is possible to figure out some strong differences between both approaches. The first one is that while avoiding obstacles the strategy here proposed assures constant linear velocity to the robot, thus avoiding unnecessary acceleration and deceleration, reducing the energy consumption and saving batteries.

In addition, the tangential obstacle avoidance allows reaching the target point in less time than the

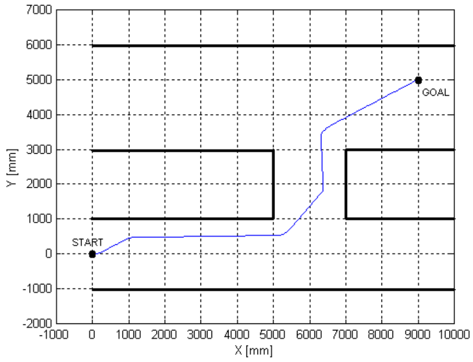

Figure 8: The path followed by the robot (Proposed Method).

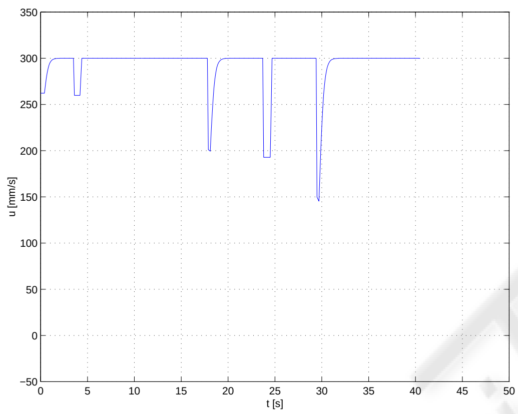

Figure 9: The linear velocity of the robot (Proposed Method).

impedance based strategy. This is a consequence of the facts that the path the robot follows is closer to the optimum one, as one can see in Fig. 8, and the robot linear velocity is not decreased during the obstacle avoidance, which occurs when using the impedance based strategy. Therefore, the strategy here proposed for obstacle avoidance is extremely attractive.

In addition, the simulated example itself shows that the tangential strategy for obstacle avoidance gives the robot the capability of following walls or corridors with no additional computation.

4 EXPERIMENTAL RESULTS

In order to validate the control system here proposed, it was programmed in the computer onboard the Pioneer 2-DX mobile robot and was tested in various experiments. One of these experiments corresponds to the trajectory in Fig. 10, and confirms the effectiveness of the tangential obstacle avoidance approach. The robot is supposed to reach the point $(9000\ mm,\ 5000\ mm)$, starting navigating in the point $(0\ mm,\ 0\ mm,\ 0)$. This experiment confirms the simulated results, as one can see by comparing the graphics corresponding to the real experiment and to the simulation in Section 3.

The second experiment corresponds to a very important situation (see Fig. 11): due to the position of of the starting point and the goal, as well as the configuration of the walls, the robot is supposed to describe an U path. In this situation it is forced to overlap the goal position, because of the wall at its left side, thus going too far from the goal before restarting seeking for it again. This point represents a local minimum and the proposed method allows escaping from situations like that, as shown in the experiment. As one can see, it does not gets stuck in a local minimum, like it happens in connection to the Potential Field method (and those that are derived from it). The same figure also shows how the robot performs when there are obstacles in a corridor: the tangential escape approach makes it to contour the obstacle, like one can see in Fig. 11.

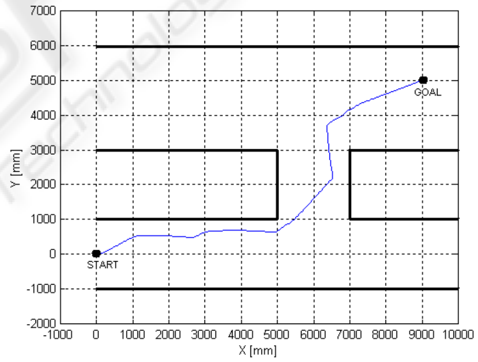

Figure 10: The path followed by the robot (Proposed Method).

As one can also see from Fig. 11, the approach proposed to avoid obstacles has been successful in guiding the robot through narrow passages. The two obstacles in the first horizontal and in the vertical corridors create narrow passages through which the proposed control system guides the robot.

To close the experimentation, the same experiments were also run using the Impedance Based Control system. In the first one the robot reached the goal without major problems, but in the second one it did not manage to go beyond the obstacle in the horizontal corridor. Then, one gets the conclusion that the proposed approach is effectively much better in terms of avoiding obstacles, energy consumption, time to get the goal and motor wearing.

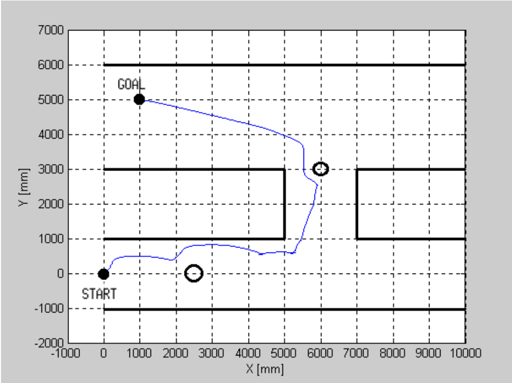

Figure 11: Experiment in a U-path with two obstacles (Proposed Method).

5 CONCLUSION

A new method is proposed in this paper to control a mobile robot when avoiding obstacles along its path from a starting point to a target point. Such method is a modification of the well known Impedance Based Control System, in which the target point has its real position temporarily redefined, thus causing a change in the robot path in order to deviate from any obstacle. The same strategy is here adopted, but the idea is to redefine the temporary position of the target point according to a new paradigm: the robot should keep aligned to the tangent to the obstacle border.

The control system thus implemented is shown to be stable in the Lyapunov sense, as well as the impedance based one, and many experiments have shown its efficiency in guiding the robot. The whole path followed by the robot is quite close to the optimal one, the maneuvers performed are softer, the navigation time is lower and the motors of the mobile robot are less demanded, for the lower variations imposed to the angular and linear velocities, as it can be checked in the experiments presented.

Finally, besides its simplicity and effectiveness, it should be emphasized that the proposed control system also allows implementing the behaviors *Wall Following* and *Corridor Following* with no additional computation.

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