Analysis of
Mobile-Robot/Environment Interaction

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1. Introduction

Real-time obstacle avoidance is one of the key issues to successful applications of mobile robot (MR) systems. All MRs feature some kind of **collision avoidance**, mechanisms that detect an obstacle and stop the robot in order to avoid a collision. These include bumpers with microswitches or simple ultrasonic range sensors. **Obstacle avoidance** represents a much higher level of sophistication, where the robot is able to detect and detour obstacles. This task is much more complex, since it involves not only the detection of an obstacle, but also some kind of quantitative measurements concerning the obstacle's dimensions. Once these have been determined, the robot has to steer around the obstacle and resume motion toward the original target. **Autonomous navigation** represents the highest level of MR performance. Autonomous navigation, in general, assumes an environment with known and unknown obstacles, and it includes **global path planning** algorithms (Borenstein and Koren, 1986a) to plan the robot's path among the known obstacles, as well as local path planning for real-time obstacle avoidance.

Based on our previous mobile robot experience with the "Nursing Robot" (Borenstein and Koren, 1985; 1986a, 1986b, 1987a, 1987b), we developed a new and powerful algorithm, entitled the Virtual Force Field (VFF), that allows real-time obstacle avoidance at high speed. In this algorithm, obstacles are represented as occupied cells in a grid. Each cell's count represented as a certainty value C(i,j), which indicates the measure of confidence that an obstacle exists within the cell area (a concept introduced by Moravec, 1986). In our algorithm, each occupied cell exerts virtual repulsive forces onto the mobile robot, and the target location generates an attractive virtual force. The vectorial sum of all virtual forces provides the instantaneous steering command tp the robot. The idea of obstacles applying repulsive forces is known as the Potential Field concept (Khatib, 1985). The novelty of our VFF method lies in the combination of Certainty Grids for obstacle representation and Potential Fields for steering command generation (Borenstein and Koren, 1988b) as well as the implementation of the combined real-time application in a dynamic system. The VFF method has been found to be especially effective in compensating for the shortcomings of ultrasonic sensors (Borenstein and Koren, 1988a). In addition, the VFF method also compensates for the dynamics of a fast running robot as we have demonstrated on a real mobile robot running at 0.78 m/sec (Borenstein and Koren, 1988c).

We have implemented the VFF algorithm on a commercially available CYBERMATION K2A mobile platform. The CYBERMATION has a maximum travel speed of V_{max}=0.78 m/sec and weights (in its current configuration) about W=125 kg. This platform has a unique 3-wheel drive (synchro-drive) that permits omnidirectional steering.

We have equipped this mobile platform with a ring of 24 ultrasonic sensors and an additional computer (a PC-compatible single board computer, running at 7.16 MHz), to control the sensors. Similar sensor configurations have been designed for other mobile robots, such as (Denning, 1985).

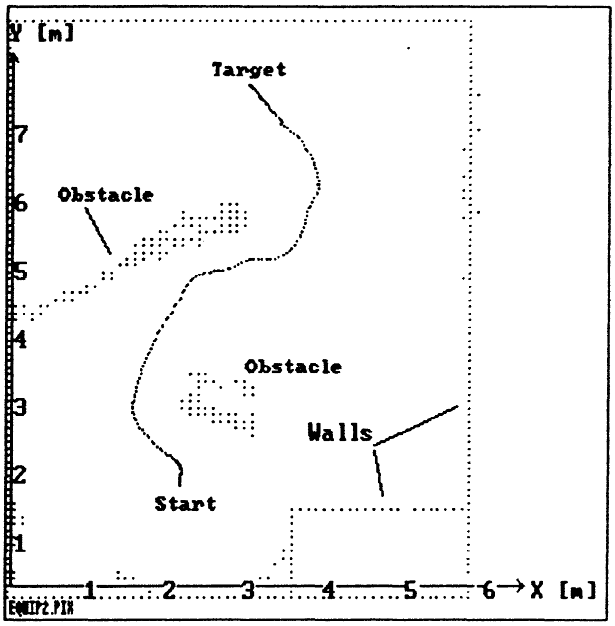

Fig. 1:
Robot run with actual ultrasonic data obtained in real-time during the robot's motion. Maximum speed = 0.78 m/sec and average speed = 0.53 m/sec.

The complete mobile system, including the VFF algorithm, is denoted as CARMEL (*C*omputer-*A*ided *R*obotics for *M*aintenance, *E*mergency, and *L*ife support).

Fig. 1 shows a typical run of the robot with actual ultrasonic data, obtained in real-time during the robot's motion. The robot ran at a maximum speed of 0.78 m/sec and achieved an average speed of 0.53 m/sec.

The maximal range for the sensors was set to 2 m, which is why only part of the rightmost wall is shown, whereas the rear wall and most of the leftmost wall remained undetected. Note that the objects gradually emerge on the computer screen, as the robot moves. Each dot in Fig. 1 represents one cell with a Certainty Value (CV) unequal to zero. CVs are color-coded on the computer screen, but this can not be reproduced here.

2. The Need for Adaptive Control

As was mentioned before, the VFF algorithm is based on the balance between a virtual attractive force $\underline{F}_t$ pulling the MR to the target and a repulsive virtual force $\underline{F}_r$ generated by the obstacles. The equation of the repulsive force is given by

$$\underline{F}_r = \sum_{i,j} \frac{\hat{r}_{i,j} F_0}{d^n_{,j}} \qquad (1)$$

where F_0 and n are constants (currently, we use n=2), $\hat{r}_{i,j}$ is a unity vector directed from cell (i,j) to the robot, and $d_{i,j}$ is the distance between the MR and cell (i,j) on the grid.

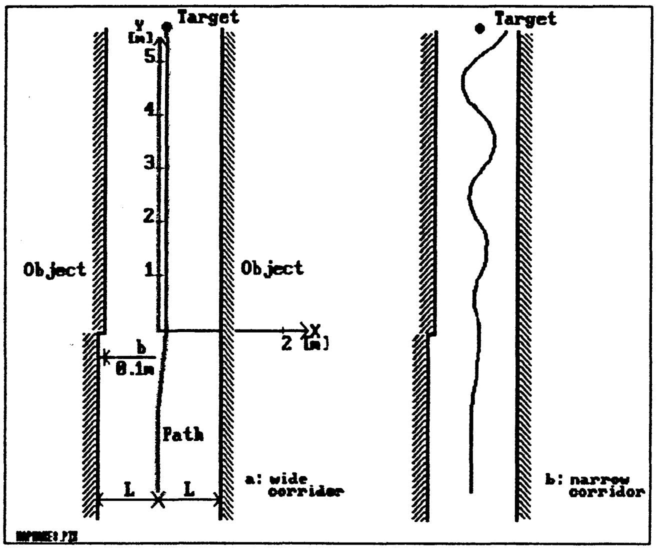

Fig. 2:
Simulation results with our mobile robot travelling in: a. a wide corridor b. a narrow corridor

The distance by which the MR travels alongside an obstacle is determined by the resultant $\underline{F}_r$ as well as the (constant) attraction force $\underline{F}_t$. Thus, the parameters n, F_0, and $\underline{F}_t$ affect the distance between the MR and the scanned object as well as the smoothness of the MR motion.

One problem associated with the VFF algorithm occurs when the MR has to pass between closely spaced objects or through a narrow passage or corridor. In our experiments we observed a tendency of the robot to oscillate in such cases.

The situation illustrated in Fig. 2 shows simulation results of our mobile robot traveling in a wide (case a) and a narrow (case b) corridor. In the wide corridor, a sudden change in the width causes the robot to smoothly adjust its path. In the narrow corridor, however, the sudden change excites the robot into unstable oscillations. This example shows that with the VFF method the mobile robot and the environment are becoming one close system, and therefore changes in the environment might change the stability of this system. In order to guarantee stability, parameters in the VFF algorithm must be self-tuned to the environment's level of clutter.

The objective of this Technical note is to formulate the differential equation that describes the interaction between the mobile robot and the environment. This equation will be needed as the model for adaptive control algorithm that will become part of the extended VFF method.

3. The Differential Equation for the MR/Environment

For the analysis of the MR/Environment interaction we assume that the robot moves at the middle of a long passage. At point Y=0 a pertubation takes the MR to the right by a small distance x. The VFF pushes the MR back to the left. We want to explore the behavior of the MR/environment interaction system.

The simplest model for the MR steering motor is a first-order differential equation

$$\tau \dot{\omega} + \omega = \Omega \qquad (2)$$

where ω is the actual steering-rate and Ω is the corresponding command. (The actual relationship is more complicated than the one represented in Eq. 2, since it also includes a corrective network in the steering controller). The steering-rate command is calculated in our system by

$$\Omega = K\ (\delta - \theta) \qquad (3)$$

where δ is the required steering angle and θ is the actual steering angle, both measured from the Y-axis. Again, the calculation of Ω in our system is more complex, but in principle Eq. 3 is correct. Substituting Eq. 3 and $\mathring{\theta} = \omega$ into Eq. 2 yields the steering equation

$$\tau\ddot{\theta} + \dot{\theta} + K\theta = K\delta \qquad (4)$$

We designate the magnitude of the lateral repulsive force acting on the MR at Y > 0 as F'_{rx}. We define a lateral constant $F_{rx}=\Sigma C(i,j)F_0$, which is equal for the left and right wall, assuming constant C(i,j) for all obstacle-filled cells. The total repulsive force on the MR consists of two components, one generated by the left wall (at an average distance L+x) and the other by the right wall (at an average distance L-x), since we assumed that the MR moved accidentaly to the right).

$$F'_{rx} = \frac{F_{rx}}{(L+x)^n} - \frac{F_{rx}}{(L-x)^n} \qquad (5)$$

where F_{rx} and n are constants (currently we use n=2).

Assuming that L >> X, Eq. 5 yields

$$F'_{rx} = -\frac{nF_{rx}}{L^{n+1}}\,x \qquad (6)$$

which means that the MR is pushed back to the left. The required steering angle is calculated by

$$\tan\delta = \frac{F'_{rx}}{F_t} = -Nx \qquad (7)$$

where F_t is the target directed attractive force (in the Y-direction) and

$$N = \frac{F_{rx}n}{F_tL^{n+1}} = f\frac{n}{L^{n+1}} \qquad (8)$$

with

$$f = \frac{F_{rx}}{F_t} \qquad (9)$$

Since motion is almost parallel to the Y-axis, the angle δ is small, and Eq. 7 yields

$$\delta = -Nx \qquad (10)$$

The velocity component of the MR in the X-direction is given by

$$\dot{x} = V\sin\theta \simeq V\theta \qquad (11)$$

combining Eqs. 10 and 11 yields

$$\dot{\delta} \doteq -NV\theta \qquad (12)$$

By differentiating Eq. 4 and substituting Eq. 12 into the resultant equation the interaction model MR/environment for long passages is obtained:

$$\tau\bar{\theta} + \ddot{\theta} + K\dot{\theta} + NV\theta = 0 \qquad (13)$$

The characteristic equation of the Laplace transform of Eq. 13 might be written in the following format:

$$(s+a)(s^2 + 2\xi\omega_n s + \omega_n^2) = 0 \qquad (14)$$

The damping factor ξ at the natural fequency ω_n in Eq. 14 depend on the term N in Eq. 8, which, in turn, depends on L — the distance between the MR and the scanned object (i.e., the environment).

The damping of this differential equation is smaller when the distance L to the obstacles is smaller. Therefore, the narrower the passage becomes, the more jerky and oscillatory the MR motion will become. This is a dangerous situation in a a cluttered environment, and it can be remedied by applying adaptive control.

4. Conclusions

It was shown that the MR and the environment are behaving as a complete system for navigation with the VFF algorithm. When the level of obstacle clutterness increases, the damping of this system decreases, and the MR might oscillate and collide with obstacles.

To remedy this situation, an environment-adaptive control method is needed for the VFF algorithm. With this adaptive concept, the parameters K (Eq. 13) and f (Eq. 9) will be self-tuned according to the MR/object distance L, with the goal to maintain a constant damping factor.

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