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An Artificial Protection Field Approach For Reactive Obstacle Avoidance in Mobile Robots

Victor Ayala-Ramirez, Jose A. Gasca-Martinez,
Rigoberto Lopez-Padilla and Raul E. Sanchez-Yanez
*Universidad de Guanajuato DICIS
Mexico*

1. Introduction

Mobile robots using topological navigation require of being able to react to dynamical obstacles in their environment. Reactive obstacle avoidance is also an essential capability needed by a mobile robot evolving in a cluttered dynamic environment. Scenarios like offices where people and robots share a common workspace are difficult to be modeled by static maps. In such scenarios, robots need to avoid people and obstacles when executing any other task involving its motion.

Another application for reactive obstacle avoidance arises when the robot is building a map of an unknown environment. The robot will need to react to different events during its exploring task. For example, the robot needs to be able to avoid a wall not previously known or to evade another moving object in its neighborhood.

In the past, several researchers have proposed reactive navigation methods. Some examples of these methods are: The artificial potential field (Khatib, 1986) and the elastic band approach (Quinlan & Khatib, 1993; Lamiraux & Laumond, 2004) proposed originally both by Khatib; the vector field histogram (Borenstein & Koren, 1990), the dynamic window approach proposed by (Fox et al., 1997) and the nearness diagram, recently proposed by (Minguez & Montano, 2004).

Our approach is to build an artificial protection field around the robot and to survey it by fusing laser range finder and odometry measurements. In this work, an approach to reactive obstacle avoidance for service robots is proposed. We use the concept of an artificial protection field along a robot pre-planned path. The artificial protection field is a dynamic geometrical neighborhood of the robot and a set of situation assessment rules that determine if the robot needs to evade an object not present in its map when its path was planned. This combination results in a safety zone where no other object can be present when the robot is executing a motion primitive; a zone where the robot needs to recalculate its path; and some other zones where the object can perform successfully its navigation task, even if obstacles are detected near the robot path. During the execution of a motion primitive, dynamical

obstacles are detected by using a laser range finder. If the obstacles detected in the neighborhood of the robot path enter the artificial protection field of the robot, reactive behaviours are launched to recalculate the path online in order to avoid collisions with them. Our method has been tested in an experimental setup both in a simulation platform and in the real robot in a qualitative manner. The robot has demonstrated successful evolution on these tests for static and dynamic scenarios.

The structure of the chapter will be as follows: Firstly, we are going to review recent approaches in reactive navigation for robots. We will also review their usefulness in topological navigation approaches. A second section will describe in detail what are the specific features of the proposed artificial protection field approach and a critical comparison of its characteristics against some other algorithms for obstacle evasion in the recent literature. Test protocols used to validate our approach will be inspected in detail in a subsequent section. We will show results in a custom-developed robotic simulation platform for our robot. We will also show experimental tests that have been implemented on a Pioneer P3-AT mobile robot named XidooBot under several scenarios. Our main findings will then be discussed and we finish our proposal with a section giving our conclusions and perspectives of future work.

2. Reactive Navigation Methods

Robot navigation using reactive methods has been studied extensively. Here we present main approaches and recent methods proposed in literature.

One of the first approaches used for reactive navigation is the potential field (PF) approach. (Khatib, 1986) proposed the generation of an artificial potential field that repels the robot from the obstacles and that attracts it toward its goal. Main problem of this method is the emergence of isopotential regions because of the potential selection for the environment elements; that traps the robot in local minima regions, impeding it to attain its goal. This drawback limits the applicability of the method in complex environments. Recently (Antich & Ortiz, 2005) have proposed to define a behaviour based navigation function that combined with the PF approach can partially overcome main drawbacks of the PF approach. PF methods are global planning methods so they can be used also for motion planning.

A variation of the PF methods is known as the elastic band (EB) approach. EB methods propose to deform an a-priori computed path when obstacles not considered at planning time are detected during the execution of a give trajectory. Some examples of this approach are the works by (Quinlan & Khatib, 1993) for manipulator robots and (Lamiroux & Laumond, 2004; Lamiroux et al., 2004) for mobile robots. As said before, EB methods require a pre-planned path, so they can not be used for exploration tasks.

The vector field histogram (VFH) is a reactive navigation method proposed by (Borenstein & Koren, 1991). The main idea is to represent the free space surrounding the current position of a robot using an occupancy grid. A polar histogram is created and the robot selects the direction with the maximal cell count of free space as a preferential orientation for its motion. This method is essentially a local navigation method to avoid obstacles.

(Fox et al., 1997) have originally proposed the dynamic window (DW) approach to avoid collision with obstacles in a reactive way. In this method, the dynamic restrictions of differential and synchro-drive steered robots are taken into account to generate arc motion primitives that avoid intruding elements. The optimization of the motion primitives find the optimal values for the translational and rotational velocities with respect to the current target heading, robot velocity and clearance.

A more recent approach is presented by (Minguez & Montano, 2004; Minguez, 2005; Vikenmark & Minguez, 2006) as the nearness diagram (ND) approach. This method models objects and free space in the proximity of the robot. The robot recognizes its situation with respect to the task to be done. The robot takes then consequent actions (motion laws) according to the assessment. Recently, (Li et al., 2006) have proposed the hybridization of this technique with the DW approach. Main contribution of this improvement is to increase the speed of the mobile robot even in troublesome scenarios.

Some other methods have also been proposed recently for reactive navigation. Some of them use fuzzy logic to control the reactive motion of the robot. Some examples of this approach are the works by (Mester, 2008) and (Larson et al., 2005). Some other consider also the identification of the behaviours associated to dynamic obstacles by using Bayesian approaches, as for example, (Lopez-Martinez & Fraichard, 2008) and (Laugier et al., 2008). However, they are not very related with our approach even if they are alternatives for reactive robot motion.

3. The Artificial Protection Field Approach

Our approach is based in the concurrent execution of two tasks: the execution of a navigation command and the obstacle detection task. The navigation commands implement the planned path in a static and known environment configuration. We define the robot pose by using the (x, y, θ) coordinates. The motion primitives link two poses by using advance and rotate primitives. Nevertheless, each time an obstacle is detected the motion command is stopped and a re-planning process is spawned. In the following, we give the details of the above procedure implemented in a mobile robot platform.

3.1 Obstacle Detection

In any reactive navigation method, the robot needs to acquire information about its surroundings in order to detect obstacles. In our robot, obstacles are detected by using the laser range finder (LRF) sensor. The LRF measures acquired by the mobile robot are classified to determine a safety condition for it. In particular, they are classified according to its closeness to a protection zone around the robot. We call such safety zone an artificial protection field (APF).

3.2 Artificial Protection Field

The APF is defined in terms of three restrictions:

Firstly, we consider a region where the robot can freely execute the motion commands without re-planning its path, namely the minimal obstacle free space E . The shape of the

boundary of this region can be arbitrarily defined by using a polar defined function $r(\theta)$. The value of this function r_θ is taken as the maximal distance being free of obstacles at an orientation θ with respect to a robot-centered coordinate system. That is,

$$E = \left\{ \theta, r \mid 0 \leq r \leq r_\theta, r_\theta = r(\theta), \theta \in \left[-\frac{\pi}{2}, \frac{\pi}{2} \right] \right\} \quad (1)$$

In our particular application, we have used a half-ellipse boundary referenced in the robot as shown in Figure 1.

The second restriction considers the distance of the current position of the robot with respect to the goal of the motion primitive, named d_g . That is, we do not want to react to an obstacle in E which is farther than the goal. The zone satisfying this restriction is represented by G in Figure 1, and it is shown in yellow. Given that we take a Euclidean distance metric, the shape of E is a half circle centred on the robot reference point, that is

$$G = \left\{ \theta, r \mid 0 \leq r \leq d_g, \theta \in \left[-\frac{\pi}{2}, \frac{\pi}{2} \right] \right\} \quad (2)$$

Finally, the critical space C (see Figure 1) is a safety zone to avoid collisions of the robot with obstacles. If we take a critical distance d_c , region C is defined as follows:

$$C = \left\{ \theta, r \mid 0 \leq r \leq d_c, \theta \in \left[-\frac{\pi}{2}, \frac{\pi}{2} \right] \right\} \quad (3)$$

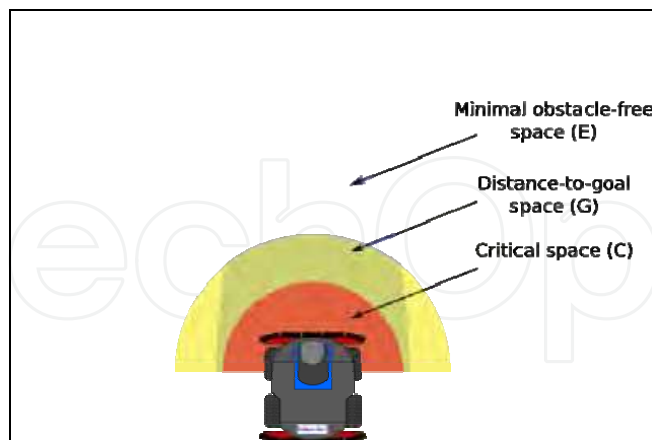


Fig. 1. Description of the interest regions around a mobile robot.

3.3. Situation Assessment

Reactive behaviours of the robot are launched after recognizing a danger context. To recognize which behaviour has to be taken by the robot, we use the LRF measures as input information. As usual, the sensor provides us with a range distance to the next obstacle at a

pre-defined set of orientations. We process this set of measurements to infer the free zone L in front of the current position of the mobile robot. We assess then the situation that the robot is facing. Our goal is to classify the situational context of the robot as a class of the following list of exhaustive states: Obstacle free situation (labelled as O_f), a low risk situation (labelled as O_l), a medium risk situation (O_m) and a high risk situation (O_h).

Obstacle Free Situation O_f

This is the ideal situation for the robot because it has not detected an obstacle in E . That situation lets the robot to continue with the execution of the current motion primitive. Formally this is represented by:

$$\bar{L} \cap E = \emptyset \rightarrow O_f. \quad (4)$$

Low Risk Situation O_l

When an object invades the minimal free space of the robot, we consider the event as a low risk situation if the obstacle is farther than the goal position, i.e.,

$$\bar{L} \cap E \cap \bar{G} \neq \emptyset \rightarrow O_l. \quad (5)$$

Medium Risk Situation O_m

The robot is facing a medium risk situation if the following three conditions are fulfilled:

- There is an object invading the minimal free space.
- The target position for the motion primitive is closer than the current position of the robot.
- The obstacle does not enter into the critical space C .

Formally, that implies,

$$\bar{L} \cap E \cap G \cap \bar{C} \neq \emptyset \rightarrow O_m. \quad (6)$$

High Risk Situation O_h

A high risk situation is the event where the robot has detected an object invading its critical space. In a formal way,

$$\bar{L} \cap C \neq \emptyset \rightarrow O_h. \quad (7)$$

Figure 2 shows how obstacles are detected and used to assess the robot situation.

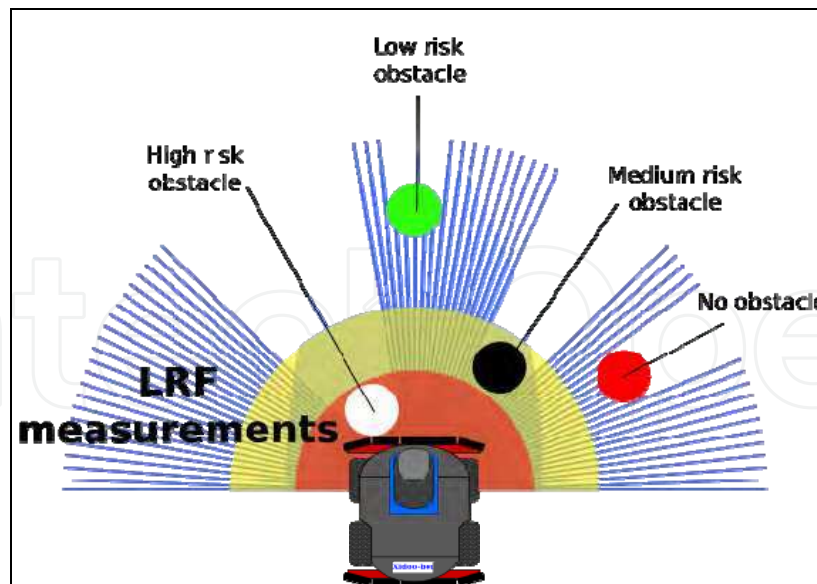


Fig. 2. Situation assessment in a service robot using the APF.

3.4. Reactive Behaviour

During the execution of a motion command, the robot is polling its sensors in order to assess the navigation situation. When a no risk (O_f) or low risk (O_l) situation is detected, the motion primitive continues its execution. A medium risk situation O_m causes the robot to execute the following actions: 1) Stop motion execution, 2) Re-plan its path to get an obstacle free trajectory, and 3) Execute the modified path. If a high risk situation O_h is recognized, the service robot interrupts immediately its motion to avoid collision with the intruding object. An activity diagram of the actions taken as a reaction to the situation assessment is shown in Figure 3.

3.5 Path Re-Planning

If the robot recognizes a medium risk situation, it stops execution of the current motion primitive. It also launches a path re-planning process that uses LRF measurements as input information. The purpose of this process is to find an intermediate goal s_g^* in the free space perceived by the robot and that minimizes some metric related to the path.

To do so, we analyse some points in the free-space L (see Section 3.3) detected by the LRF. The feasible intermediate target goal S_g consists of all the points in a given set of radial distances from the current position of the robots that belong also to L . Another characteristic that all points in S_g have is that an inspection window W centered on them presents no collision with any obstacle. The inspection window extends from an angle $\theta - \Delta\theta$ to an angle $\theta + \Delta\theta$, where θ is the angular coordinate of the point in S_g being tested with respect to the robot-centered coordinate system, and $\Delta\theta$ is the width of the inspection window.

All target goals in S_g are then attainable. We carry out an optimization process over all these points and we choose the optimal one according to the objective function being optimized.

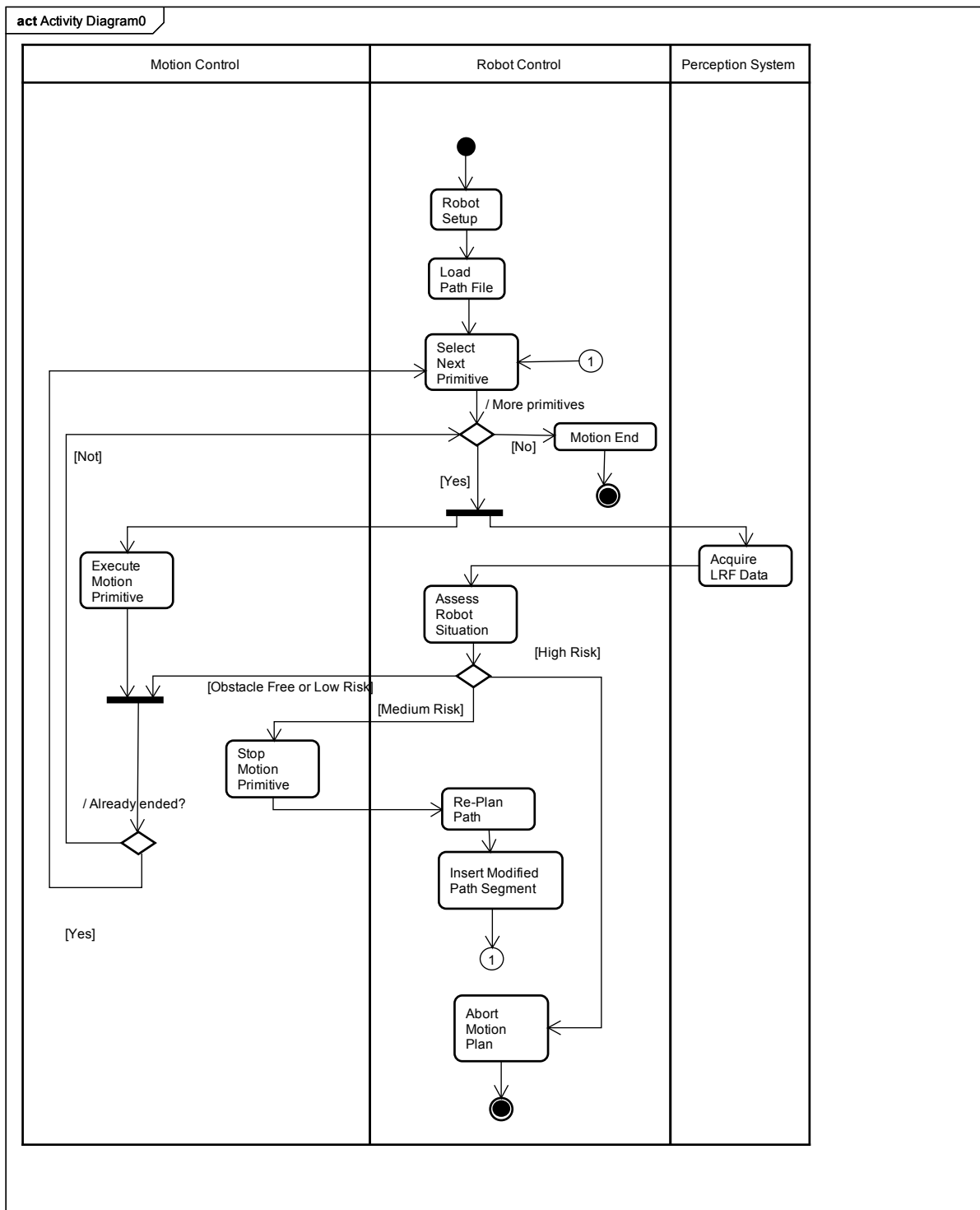


Fig. 3. Activity diagram for the reactive behaviour of the service robot.

Let us consider, for example that our objective is to minimize closeness to the target position s_t in the interrupted motion command. Then, for all s_k in S_g :

$$f(s_k) = \|s_t - s_k\|. \quad (8)$$

and then

$$s_g^* = s_k \Leftrightarrow f(s_k) = \min_{s_k \in S_g} \|s_t - s_k\|. \quad (9)$$

where for example, $\|\bullet\|$ could be an Euclidean norm.

4. Test and Results

We have run tests firstly in a custom-developed simulation platform. The goal of these experiments was to define the best parameters for the implementation on a real P3-AT robotics platform named XidooBot. We have then executed motion scripts that tested exhaustively all the contexts that could arise in the reactive navigation task.

The first set of tests has been performed in a custom-developed simulation environment. A scenario with multiple objects is shown in Figure 4. Here, we can observe the re-planning of a new trajectory once the robot finds an obstacle in its APF. After that, an obstacle-free trajectory is executed until it reaches its goal. The half-elliptical safety zone at the end of the trajectory is specifically indicated in the Figure.

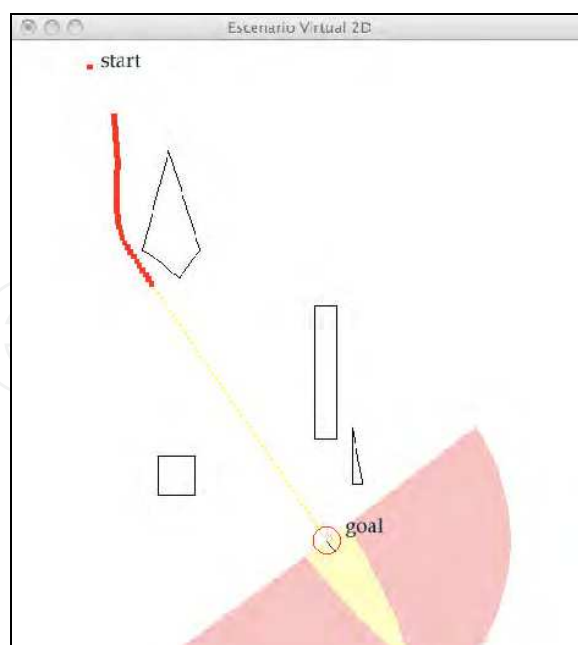


Fig. 4. Simulation of a script composed of a single straight-line segment.

In Figure 5, the simulation of a more complex trajectory is given. Here, point A is an intermediate goal and the final one is point B. We observe a reactive behaviour zone in the

trajectory between the start point and point A. From A to B, it's necessary beginning with a continuous re-planning of the trajectory until the goal is attained executing a straight trajectory.

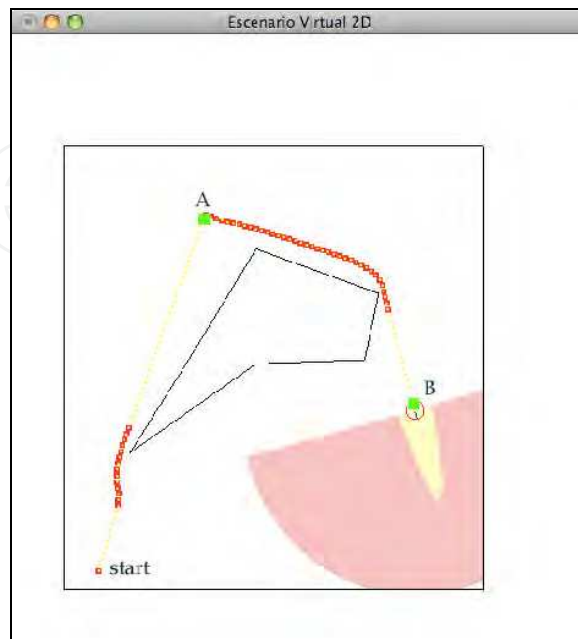


Fig. 5. Execution of a script composed of multiple straight-line segments.

A second phase of tests was run in the real platform for robotics experiments. We have also setup scenario configurations that cover all the cases foreseen in the APF approach. The reactive navigation system has been tested qualitatively. The test procedure includes the execution of a set of paths in an environment where obstacles were added dynamically during the motion commands execution. Figure 6 shows a successful motion command execution because no obstacle was detected along the execution of the motion primitives. Even if an obstacle is near the target position of the robot, path is not re-planned because the object does not interfere the robot motion.



Fig. 6. A reactive navigation scenario (case I) for a Pioneer P3-AT.

A second example is shown in Figure 7. When the motion execution is launched, the robot detects a medium risk situation, so it re-plans its trajectory. We can see in Figure 7 what are the sub-goals chosen by the robot in order to reach the originally planned target position.

A more complex environment is shown in Figure 8. We have several obstacles near the planned path (shown in blue). In the figure, we can see the executed path (shown in red) after reacting to the presence of obstacles.

A closed path execution is shown in Figure 9. Our reactive strategy is applied when during the execution of a path segment an obstacle appears. We show the planned path in blue and the modified executed path in red. As we can see, the robot passes by the control points of the motion primitive sequences without problems.

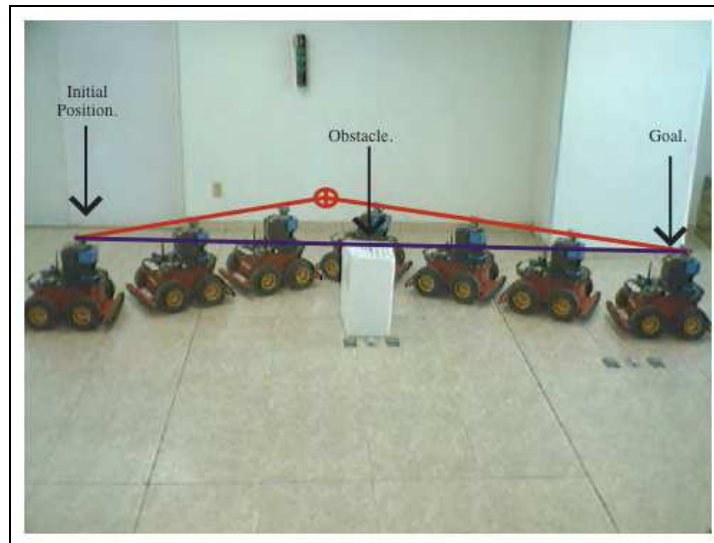


Fig. 7. A reactive navigation scenario (case II) for a Pioneer P3-AT.



Fig. 8. A reactive navigation scenario (case III) for a Pioneer P3-AT.

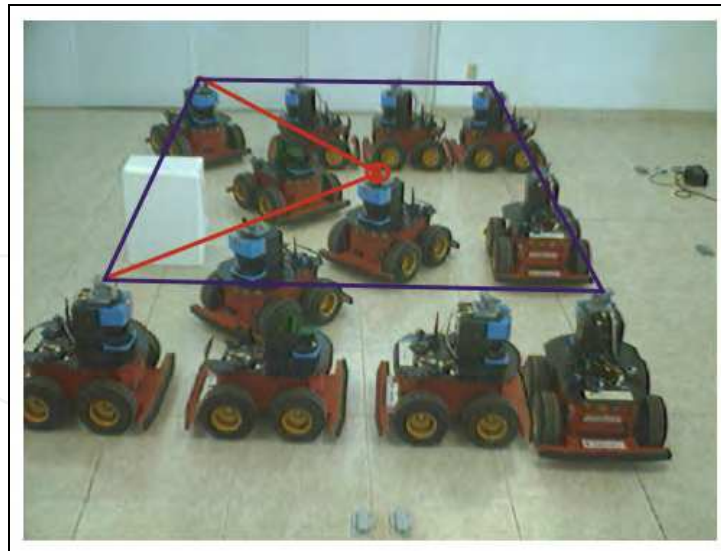


Fig. 9. A reactive navigation scenario (case IV) for a Pioneer P3-AT.

5. Conclusion and Perspectives

In this work, we have presented a reactive obstacle avoidance approach based on a situated-activity paradigm. Our system has demonstrated to be robust in qualitative tests developed on a dynamically changing environment. We have shown tests in a custom-developed simulation platform and in the real robot. Our approach is based in the risk assessment made by the robot by using an artificial protection field to avoid moving obstacles.

In the near future, we will evaluate quantitative performance of the method by analyzing pose errors after the re-planning step both in simulation and in the real robotic platform XidooBot. Fusion of several sensors information will be done in order to improve the robustness of this approach. This method will be integrated with a topological navigation system.

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Mobile robots navigation includes different interrelated activities: (i) perception, as obtaining and interpreting sensory information; (ii) exploration, as the strategy that guides the robot to select the next direction to go; (iii) mapping, involving the construction of a spatial representation by using the sensory information perceived; (iv) localization, as the strategy to estimate the robot position within the spatial map; (v) path planning, as the strategy to find a path towards a goal location being optimal or not; and (vi) path execution, where motor actions are determined and adapted to environmental changes. The book addresses those activities by integrating results from the research work of several authors all over the world. Research cases are documented in 32 chapters organized within 7 categories next described.

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Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
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Unit 405, Office Block, Hotel Equatorial Shanghai
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中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821

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