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Abstract

This work studies and proposes a remote control architecture for a set of nonholonomic robotic vehicles. We used a new decentralized control strategy based on the Leader-Follower principle, the GPS information, and signal level of the wireless communication to generate an optimal path for each nonholonomic robot. We incorporate a reactive term in the optimization process based on the Deformable Virtual Zones (DVZ) that modifies the path of each robot for a given ultrasound sensor information of each robot in order to get away from obstacles.

1 Introduction

The multi robots systems is an important robotics research field. Such systems are of interest for many reasons: Tasks could be too complex for a single robot to accomplish; using several simple robots can be easier, cheaper and more flexible than a single powerful robot

The study of multi robots systems naturally extends on single robots systems but it could be considered a discipline unto itself. There are two main approaches for controlling a set of cooperative robots: systems theoretic and behaviour based, the behaviour based methods use any algorithmic behaviour structures without an explicit mathematical model of the subsystems or environment. (Arkin, 1998), on the other hand, the system theoretic approach relies strongly on use of the system dynamics and models of the interaction between the robots (Das *et al*, 2002), (Fredslund & Maratic, 2002). Most of the control theoretic methods for cooperative robots formation use a decentralized control (Feddema *et al*, 2002). These systems use local feedback controller based on the local measurements.

This research work is focused on new control strategy for multiple vehicles, based on GPS position and wireless communication. The control objective is consisted of generating a specific geometric formation based on the location of the nearest neighbour.

The wireless communication based on Wifi technology between each vehicle allows a geometric formation to be spread over a large spatial terrain (100 to 200m between each vehicle). The vehicles formation will be remote operated within the Wifi communication area. The first objective is to analyse and perform a new control algorithm to coordinate robotic vehicles. This algorithm is based on centralized control laws. The control variables are the position vector obtained by a GPS sensor fitted on each vehicle and the signal level of wireless communication. The wireless communications are used to share information except if the GPS sensor information is not available or the received signal level tends to zero. In that case, the communication device becomes a sensor and the signal stemming from the neighbour vehicle allows the vehicle which lost GPS data for instance, to stay in communication zone. This control method secures the transmission links.

In many real applications in cooperative robotics we have limited or no information of the environment characteristics, e.g. rescue mission in disasters areas. In this kind of mission the robot formation should be able to avoid any obstacle while they continue any formation task.

There exist several methods for moving in formation, and for obstacle avoidance described in the literature while the combinations of these two techniques are less studied.

For the obstacle avoidance problem there are several approaches, like the artificial potential field method (Khatib, 1986), in which the idea is to fill the workspace of the robot with an artificial potential field in which the vehicle is attracted to its goal and is repulsed away from the obstacles; one of the inherent problems of this method is the existence of local minima which are undesirable equilibrium points of a gradient system. They appear when the sum of the attractive and repulsive forces induced by the potential vanishes before its goal. Other method for obstacles avoidance is the Deformed Virtual Zone (DVZ) method (Zapata, 2004). The DVZ method is a reactive control pour the obstacles avoidance. This is a reactive method for the obstacles avoidance; it correlates the deformations of a virtual zone (called DVZ) produced by external stimulus (obstacles), and the best control action to get back to the original geometrical form to minimize the external interactions. For the generation of the reflex action in the DVZ method, we need only measure an intrusion in the defined zone virtual that is, no information over the nature of obstacle is needed but only the measures of distances around the robot (Albaric, 2002).

In this research work we include the reactive properties of the DVZ method in a decentralized control strategy for the formation, by means of the inclusion of a DVZ term in the optimal trajectory generation process. The inclusion of this term in the generation trajectory process enables to obtain a control strategy that achieves the characteristics of the planning based in the known environment information, for the mission accomplishment and also reactive properties to deal with the unknown information (obstacles), that is for any given cooperative group task the robot will keep his position in the formation except if any obstacle is detected by the robot ultrasound sensor, in this case the DVZ term will modify the trajectory to minimize the interaction of the obstacle detected.

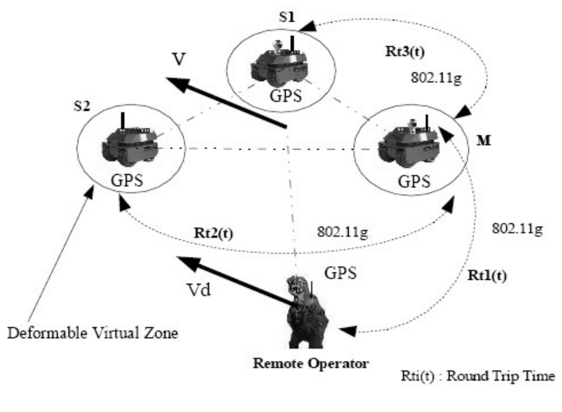

Figure 1: Cooperative Robotic Vehicles

2 Decentralized Control Algorithm

The decentralized control law is based on a Leader-Follower method (Desai *et al*, 1997), (Zarrad, 2004).

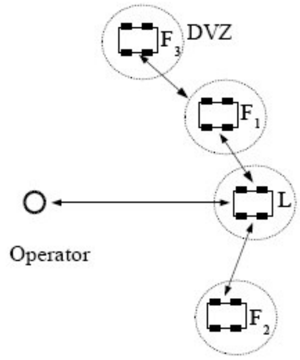

Fig. 2 Decentralized Control Strategy

At the beginning of experimentation, one of the robots which is in the communication area of the operator is arbitrary chosen as the Leader, the other are Followers (Fig. 2). The desired position of the Leader is defined by the operator. The follower desired position are defined by the position of his nearest neighbor rose by a distance d_{lf}. Thus if the operator modify the trajectory of the Leader, the formation will automatically follows the Leader. In that strategy case, each Follower could be also a Leader for any of his neighbors.

2.1 Follower Leader Positioning

Under decentralized control strategy, the set of coordinated mobile robots follows a Leader-Follower model. Each Follower deduces his position vector by using both GPS sensor and the angular position of the Wifi sector antenna.

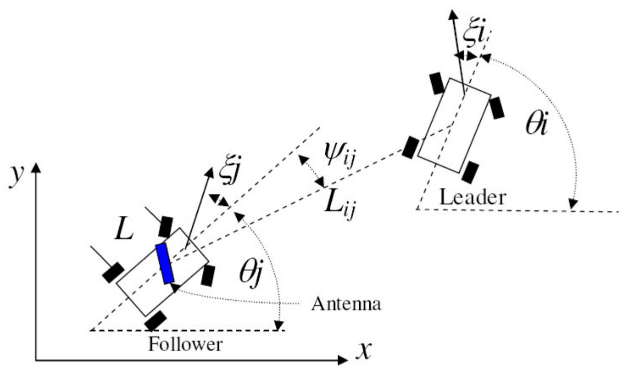

Figure 3: Leader-Follower Positioning

The Wifi motorized sector antenna gives the steering angle of the best receiving level from the Leader. Using this information and the absolute position given by the GPS sensor, we can define the expression of the desired position vector of the vehicle *j* as:

$$
\begin{aligned}
x_j^{\ d} &= x_i - L_{ij}^{\ d}\cos\left(\theta_j - \psi_{ij}^{\ d}\right)\\
y_j^{\ d} &= y_i - L_{ij}^{\ d}\cos\left(\theta_j - \psi_{ij}^{\ d}\right)\\
\theta_j^{\ d} &= \operatorname{atan}\left(\frac{y_j^{\ d} - y_j}{x_j^{\ d} - x_j}\right)\\
\xi_i^{\ d} &= \theta_j^{\ d} - \theta_j
\end{aligned} \qquad (1)
$$

Where $L_{ij}^{\ d}$ is the desired length between the vehicles i and j, ψ the angular position between the two vehicles and θ the relative orientation of vehicle. The position of the First Leader is defined by the human operator.

2.2 Leader Follower Without GPS

If there is any fail in the GPS sensor system, the Follower Leader positioning is performed by means of the received signal level (RSL) and the directional antenna angle.

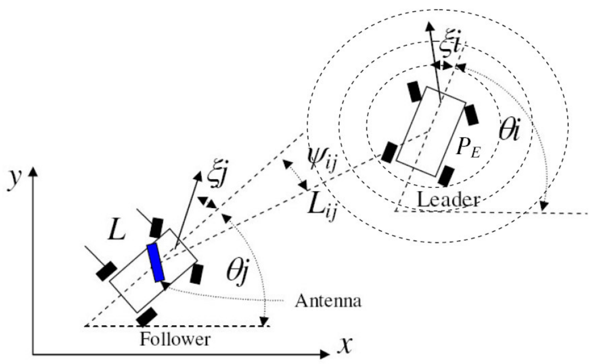

Figure 4: Leader-Follower without GPS

The RSL for the robot follower j is:

$$P_{jdBm} = 10\log\left(\frac{P_j}{10^{-3}}\right)$$

$$P_j = \frac{P_E}{4\pi L_{ij}^{\ 2}}$$

or:

$$L_{ij} = \sqrt{\frac{P_E}{4\pi P_j}}$$

2.3 Trajectory Planning Algorithm

To control multiple robots, compatible trajectories for each robot are essential. This is especially critical for nonholonomic robots performing collaborative tasks. The core idea is to build a feasible optimal trajectory between the current robots state and the desired one. The desired one is computed by means of the Leader-Follower approach.

In the trajectory planning algorithm we first makes use of the differential flatness property to find a new set of outputs in a lower dimensional space, and then we parameterize the outputs by the B-spline basis representation. The coefficients of the B-splines are solved by a sequential quadratic programming solver to satisfy the optimization objectives and constraints. Finally, the trajectories for the vehicle controller are represented by the B-spline curves with these coefficients. In the following, we summarize the constructing techniques of the TPA for the vehicle dynamics.

2.3.1 Flat Outputs

The robot dynamic model is:

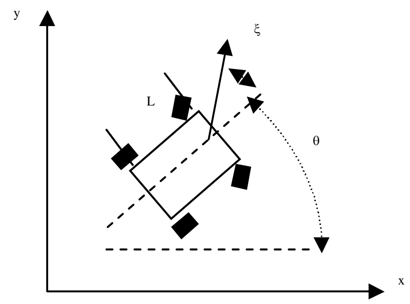

Figure 5: Vehicle Model

$$
\dot{\mathbf{x}}(t) = \begin{pmatrix} \dot{x}(t)\\ \dot{y}(t)\\ \dot{\theta}(t)\\ \dot{\xi}(t)\\ \dot{v}(t)\\ \dot{\omega}(t)\end{pmatrix} = \begin{pmatrix} v\cos(\theta)\\ v\sin(\theta)\\ \frac{v}{L}\tan(\xi)\\ \omega\\ -\frac{v}{\tau_v}\\ -\frac{\omega}{\tau_\omega}\end{pmatrix} + \begin{pmatrix} 0 & 0\\ 0 & 0\\ 0 & 0\\ 0 & 0\\ \frac{1}{\tau_v R} & 0\\ 0 & \frac{1}{\tau_\omega}\end{pmatrix}\begin{pmatrix} Uv\\ U\omega\end{pmatrix}
$$

or:

$$\dot{\mathbf{x}}(t) = f\left(x, U\right) \qquad (2)$$

Where v and ω are: The linear and the direction angular speeds respectively; τ_v and τ_ω the time constants of motors and **U** the control vector, and R the wheels radius of the vehicle.

For the output set, $z = \{x, y\}$, and its derivatives we obtain:

$$\theta = \tan^{-1}\left[\frac{y'}{x'}\right] \qquad (3)$$

$$v = \sqrt{(x')^2 + (y')^2} \qquad (4)$$

$$\xi = \tan^{-1}\left[L \frac{(x' y'' - x'' y')}{\left((x')^2 + (y')^2\right)^{3/2}} \right] \quad (5)$$

$$\omega = \frac{\left[-3(x' y'' - x'' y')(x' y'' + x'' y') + \left((x')^2 + (y')^2\right)(x' y^{(3)} - x^{(3)} y')\right]\left[\sqrt{(x')^2 + (y')^2}\right] L}{\left((x')^2 + (y')^2\right)^3 + (x' y'' - x'' y')^2 L^2} \quad (6)$$

$$Uv = \frac{\tau_v 2(x' x'' + y' y'') + (x')^2 + (y')^2}{R\sqrt{(x')^2 + (y')^2}} \quad (7)$$

$$U\omega = (\tau_\omega \omega' + \omega) = \left(\tau_\omega f\omega'(x', y', x'', y'', x^{(3)}, y^{(3)}) + \omega\right) \quad (8)$$

where $y^{(n)}$ is the n time derivative of the variable $y(t)$.

Thus the set of outputs z are flat outputs (Martin, 1992) of system the system (1).

2.3.2 *Parameterization*

The flat outputs are parameterized in terms of the B-splines basis

$$x(t) = z_1(t) = \sum_{i=1}^{pj} B_{i,kj}(t) C_i^x \quad (9)$$

$$y(t) = z_2(t) = \sum_{i=1}^{pj} B_{i,kj}(t) C_i^y \quad (10)$$

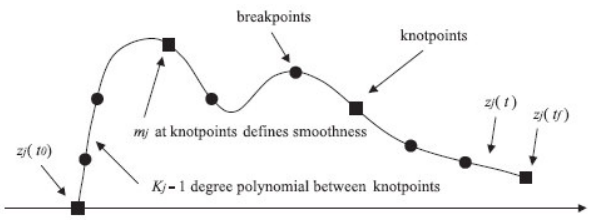

Figure 6: B-Spline curve

where $B_{i,kj}$ are the ith B-spline basis function for the output $z_j(t)$ with polynomial order kj , C_i^j are the coefficients of the B-splines

2.3.3 *Time Optimal Trajectories*

The time optimal problem could be formulated for each robot as finding trajectories and controls which minimize the following functional:

$$J = \int_{to}^{tf} dt \quad (11)$$

where t_o is the initial or current time, the unknown final time is t_f. The trajectories must join the terminal states $x(t_o)$ and $x(t_f)$, and have to satisfy the following constrains.

The control bounds

$$U_{\min} \leq U \leq U_{\max} \quad (12)$$

The steering angle bounds

$$\xi_{\min} \leq \xi \leq \xi_{\max} \quad (13)$$

For the parameterized system the equation (11) is

$$\min_{C_i^j} \int_{to}^{tf} dt \quad (14)$$

under the following constraints

$$U_{\min} \leq f_U\left(x(t), x'(t), \ldots x^{(q)}(t), y(t), y'(t), \ldots y^{(p)}(t)\right) \leq U_{\max} \quad (15)$$

$$\xi_{\min} \leq f_\xi\left(x(t), x'(t), \ldots x^{(q)}(t), y(t), y'(t), \ldots y^{(p)}(t)\right) \leq \xi_{\max} \quad (16)$$

This optimal problem is modified into a nonlinear programming problem, and solved by gradient descent using the quasi Newton method (Milan, 2003).

2.3.4 *Control Configuration*

We include the optimal trajectory generation step, into a two degree of freedom configuration (Milam, 2003).

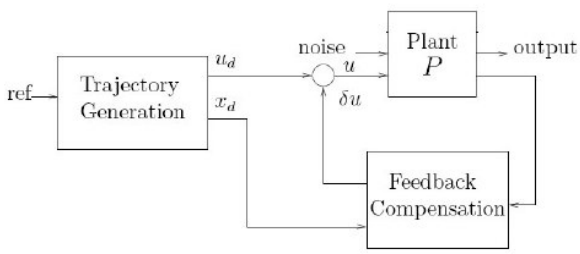

Figure 7: Two Degree of Freedom configuration

Under this configuration, each robot builds his optimal trajectory from his current state to the desired one. And by means of the flat outputs they obtain both the control and state desired vectors. A linear feedback (proportional) block is added to compensate any noise or modelling errors in the system (Van Nieuwstadt *et al*, 2003).

2.4 Reactive Method for Obstacle Avoidance

In this section we add the reactive propertie to the Trajectory Planning Algorithm. To do this, we use the concepts of the Deformable Virtual Zones. The core idea is to include a DVZ term into the cost function which should be minimized to obtain a free collision and faisable trajectory for each robot. In the next section we briefly explain how to build the Deformable Virtual Zone then we show how to include it into the Reactive Trajectory Planning Method.

2.4.1 Deformable Virtual Zone Definition

The DVZ approach is supposed to be surrounded by a Deformable Virtual Zone whose the geometry depends on the robot kinematics and deformation are due to the intrusion of proximity information in the robot space. The DVZ method consists in minimizing these deformations by locally modifying the control vector (acceleration, orientation, etc.). This algorithm is like a two player game, the first one e.g. the environment, induces the undesired deformations and the second one, e.g. the robot controller, tries to rebuild the DVZ.

In this work we define an ellipse as DVZ parameterized by the linear velocity of the vehicle v and the orientation angle of vehicle θ.

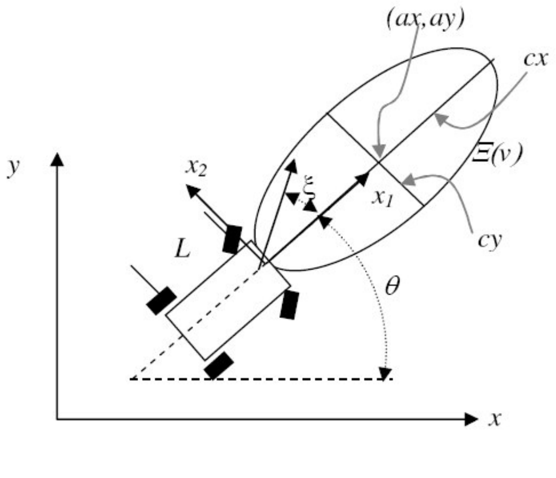

Figure 8: DVZ definition

the ellipse equation is:

$$\sum\left(\frac{x_i + a_i}{c_i}\right) = 1 \;,\; a = \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \text{ and } c = \begin{bmatrix} c_1 \\ c_2 \end{bmatrix} \qquad (17)$$

with

$$\bar{c}_1 = c_2 \,,\; \bar{c}_2 = c_1 \;\; \bar{c} = c_1 c_2 \;;$$

and

$$A = \sum v_i^2 \bar{c}_i^2 \;;\; B = \sum 2 v_i a_i \bar{c}_i^2 \;;\; C = \sum a_i^2 \bar{c}_i^2 - \bar{c}^2$$

$$A\Xi^2 + B\Xi + C = 0 \;\Rightarrow \Xi = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \qquad (18)$$

Where Ξ the norm of the DVZ in the unitary direction $v = v_i e_i$, and the point correspondent is

$$P = \Xi\begin{bmatrix} v_1 & v_2 \end{bmatrix}$$

The undeformed DVZ depends on a vector π characterizing the motion capabilities of the robot:

$$\Xi_h = \rho_\pi(\pi) \text{ where } \pi = \begin{bmatrix} V & \theta \end{bmatrix} \qquad (19)$$

The deformation depends on the intrusion of proximity I information and the undeformed DVZ:

$$\Delta = \alpha(\Xi_h, I) \qquad (20)$$

2.4.2 Reactive Trajectory Planning Method

To modify the trajectory of each robot for the obstacle avoidance, we propose to include the following DVZ term as the performance index (11) of the Trajectory Planning algorithm.

Any detected obstacle will produce a deformation Δ over the DVZ

$$\Delta = \Xi_h I \cos(\gamma) \qquad (21)$$

where, I is the intrusion over the ultrasound sensor rang, and γ is the angle of the sensor robot (figure 8).

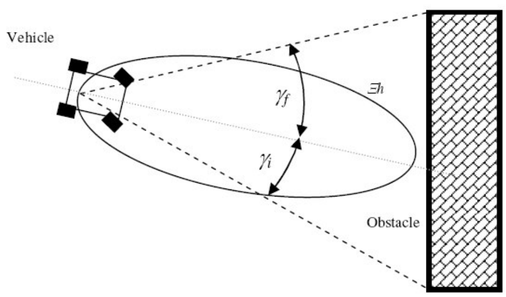

Figure 9: DVZ deformation

the total deformation over the DVZ region is

$$\Psi(t) = \int_{\gamma_i}^{\gamma_f} \Xi_h(\upsilon,t) I(\upsilon,t) \cos(\upsilon) d\upsilon \qquad (22)$$

if we use the flat outputs we obtain:

$$\Xi_h(\gamma,t)I(\gamma,t)\cos(\gamma) = K\left(x(t), x'(t), \ldots x^{(q)}(t), y(t), y'(t), \ldots y^{(p)}(t)\right)$$

or

$$\Xi_h(\gamma,t)I(\gamma,t)\cos(\gamma) = K(Z,\gamma) \qquad (23)$$

for

$$Z = \left\{x(t), x'(t), \ldots x^{(q)}(t), y(t), y'(t), \ldots y^{(p)}(t)\right\} \qquad (24)$$

for any instant t_o, we could build the parameterized trajectory to reach the desired state within *tf*, and if we also know any obstacle information, i.e. any ultrasound sensor active, then we could predict the total deformation that will be produced in the DVZ over the hold trajectory. That is:

$$\Psi s = \int_s \int_{\gamma_i}^{\gamma_f} K(Z,\upsilon)\, d\upsilon\, ds \qquad (25)$$

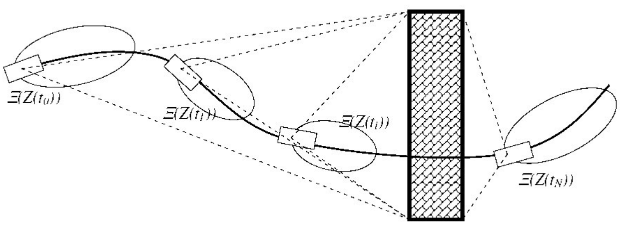

Figure 10: Parameterized DVZ deformation

We propose to find the trajectory s for a single robot that minimizes the deformation of the DVZ. We modify the performance index (11) by adding the term Ψs.

The main idea of this method is that for any time, each robot will find a time optimal trajectory that joins the current state and the desired one and minimizes the DVZ deformation. The trajectory will be modified to minimize this deformation, and different information over the obstacle will be obtained, and other trajectory will be built. This interaction process allows to obtain a free collision trajectory.

3 Simulation Results

3.1 Experimental Setup

As part of a project that congregates three laboratories and the French Army Research Office, we have developed a first experimental setup. That consists of three mobile robots. The robot is a four wheels drive vehicle. The vehicle has two motors, one to drive the wheels, and other one to change the direction of steering front wheels.

The robot (figure 10) is equipped with: one GPS sensor, four ultrasound sensors for the obstacles detection, one bidirectional antenna which is oriented by an electric motor. To transmit his GPS information each robot has an omnidirectional antenna (Wifi devices).

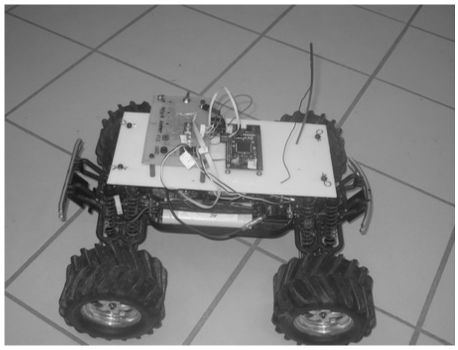

Figure 11: 4WD robot

3.2 Simulation Results

We have developed a Simulink Model for each robot with this model we could include up to three robots. We identified all parameters of the robot model (2) for the experimental vehicle. Based on these parameters, and using the mathematical model developed in this article, we obtain the following results. These results will be validated later in the experimental platform (three robots similar to this one presented in this section), that our laboratory is going to build.

3.2.1 Validation of the Reactive Planning Algorithm

In this first simulation we use two robots. The robot Leader follows a predetermined trajectory, and the follower has to perform a diagonal formation (figure 11).

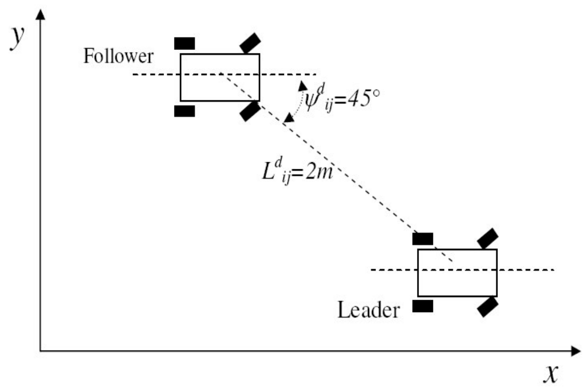

Figure 12: Diagonal formation

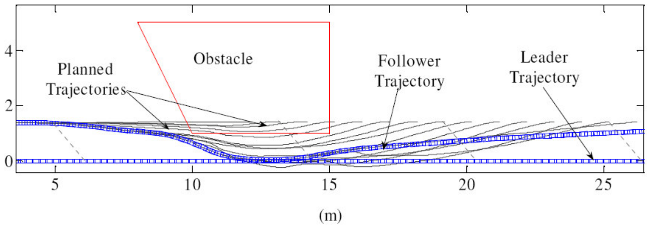

Figure 13: Follower Trajectories

in the figure 12, we see the follower trajectory as he perform an obstacle avoidance and follows his target position (Leader-Follower Positioning). We also see the optimal trajectories for different states of the robot follower.

In the next simulation (figure 13) the follower robot has to track the leader position ($L^{d}_{ij}=0$), for the following initial condition:

Leader:	Follower:
$x_l(0)=0$	$x_f(0)=-5m$
$y_l(0)=0$	$y_f(0)=-5m$
$\theta_l(0)=0$	$\theta_f(0)=\pi$
$\xi_l(0)=0$	$\xi_f(0)=0$
$v_l(0)=0$	$v_f(0)=5m/s$
$\omega_l(0)=0$	$\omega_f(0)=0$

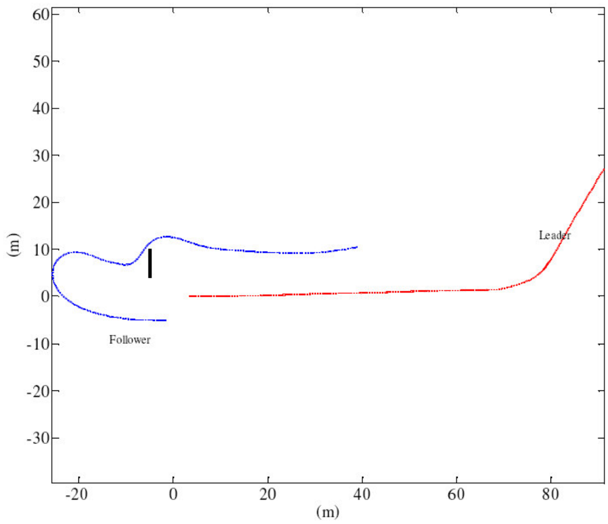

Figure 14: Leader Follower Trajectories

for these condition we could see (figure 13) how the robot follower avoid the obstacle, and follows the leader trajectory.

The figure 14, shows the modification of the trajectory by the obstacle presence, and how the robot search a collision free trajectory.

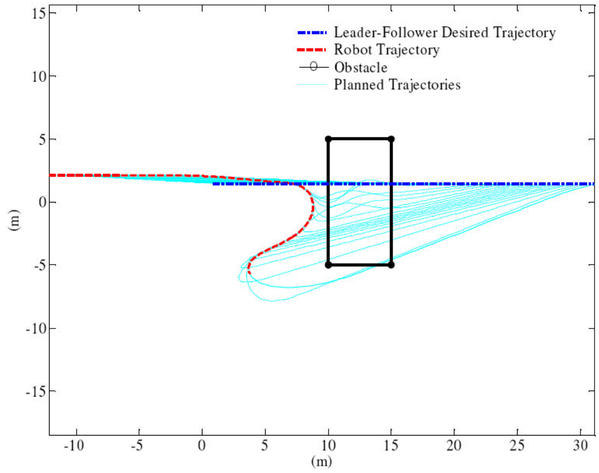

Figure 15 : Obstacle Avoidance

4 Conclusions

We propose a new reactive planning method based on the Deformable Virtual Zones, and optimal trajectories generation as control strategy, based on: GPS, signal level and ultrasound sensors for cooperative nonholonomic vehicles in unknown environments. We use the Leader-Follower strategy and a decentralized trajectory planning in order to control the geometric formation. The robot's ultrasound sensor information is used to compute a DVZ deformation for a planned trajectory we deform this trajectory to minimize that deformation. That allows to each robot avoid any obstacle while he follows his position in the robot formation.

The decentralized characteristic of the proposed method allows to apply this strategy to control of large robots formation.

We hope to validate this method on the experimental setup of our laboratory, in order to know the highlights of this strategy.

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