

Fuzzy logic controller for cooperative mobile robotics implemented in leader-follower formation approach

Controlador de lógica difusa para robótica cooperativa móvil implementando el método líder-seguidor

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ABSTRACT: This paper presents the design of a fuzzy logic cooperative control by implementing the leader-follower approach that allows establishing and maintaining a specific geometric formation to a mobile robot group while they are moving along a predefined trajectory. As a result of the research, it was proved by simulation, a cooperative control system that permits a set of robots to keep a specific formation while the group performs a predetermined mission. This control system helps avoid obstacles by modifying the formation or by changing the leader inside the group.

RESUMEN: Este artículo presenta el diseño de un controlador de lógica difusa implementando el método líder-seguidor para un sistema de robótica cooperativa móvil, que permita a un grupo de robots establecer y mantener una formación geométrica específica mientras se desplazan siguiendo una trayectoria de referencia. Como resultado de la investigación, se probó mediante simulación un sistema de control cooperativo, que permite a un grupo de robots mantener una formación específica mientras desarrollan una misión determinada. Este controlador permite evadir obstáculos cambiando la formación o cambiando el líder del grupo en cualquier momento.

1. Introduction

Currently, the research in robotics has extended its interest to multi-robot systems trying to make easier the robots implementation in real applications that could help the society. Certainly, this kind of systems could develop several complex applications more economically and efficiently than a single-robot system. The construction of a multi-robot system has another advantage; the robots that are implemented are simpler, cheaper and more flexible than a single powerful robot developing a specific task [1].

The main idea of the cooperative mobile robotics is that one group of mobile robots can develop the same task better than a single robot, if they work coordinately. Controlling the position of each robot while they are moving in group, is the main problem of the formation control. However, if the group works cooperatively, each robot can take advantage sharing sensor signals; as a consequence, they save resources and have better fault-tolerance. This kind of robotics is introduced in applications such as

smart assistive environments or security; but its current main interest is to maintain a specific formation when the group is moving. Three main solutions are used to solve this problem, the leader-follower, virtual structure and behavior-based approaches [2], they are used for introducing the cooperative robotics in many applications for instance, search and rescue missions [3], automated highway systems [4], and robot soccer.

The virtual structure approach takes the total group formation as a single rigid structure, because this method is based on the arrangement around virtual points. In this approach, all robots work as a single complex robot that can move and rotate. This approach is used in applications where the trajectory and the formation are the same all time, but it is not appropriate if the application requires a decentralized system [5].

On the other hand, in behavior-based approach, each robot has a specific task but the interaction between them generates global desirable behaviors. Such specific task could be, for example, avoiding obstacles and collisions, seeking a goal or keep the formation. The task to be developed by each robot is determined, depending on the weighted sum of the basic behaviors that denotes the relative importance of each behavior. Then, the efficiency of this complex approach cannot be easily determined posing the main disadvantage of this method [5].

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In the leader-follower approach, the problem is divided into two different roles. One robot is denominated the leader of the group and others are identified as followers. In this method, the leader is the unique robot that knows the reference trajectory [6] and its responsibility is to guide the group to follow the reference, but the followers' responsibility is to maintain the formation respect to the leader [7]. This is the most common technique used in research, because the formation control practically is converted into two simple problems, a trajectory tracking by the leader and a control to keep the formation by the followers [8-10]. Furthermore, this method simplifies the programming and is more efficient computationally than the other two techniques, but its drawback is that the group must have a full-time communication, to send the leader's position to all the followers and if it does not exist a feedback from the leader, the formation could be broken [11, 12].

The main contribution of this paper is to develop a fuzzy logic control for a wheeled mobile robot group, which establishes and maintains a geometrical formation, during the route to the goal using the Leader-follower approach. Other contribution is the implementation of the fuzzy logic to design a control system that permits the group to change different aspects as the role, the pattern formation or the reference of each robot while the mission is being developed, giving different methods to avoid obstacles and resolve the noise problems.

The mobile robots present a lot of perturbations because they are in a really noisy environment, and all those disturbances are a big problem for the movement of the robots. An example of noise source to solve by the controller is the communication delay between the robots. The fuzzy logic control has had good results solving this kind of problem as in [3], and fuzzy logic is well implemented in this kind of robotics because it is the simplest way to develop it [13].

2. Formation control

In order to solve the formation control problem for a group of mobile robots, it is necessary to implement two independent controllers (see Figure 1). The objective of the first one is to maintain each robot inside the group formation. On the other hand, the second one is divided in two parts: an individual controller implemented in each robot and a trajectory tracking control that guides the robot to follow the instruction that the group controller sends. The last controller is developed depending on each mobile robot configuration. This article focuses primarily on the design of the trajectory generation control, based in the leader-follower approach using a fuzzy logic controller.

To develop the group controller, the leader-follower approach is the best solution, considering that it generates

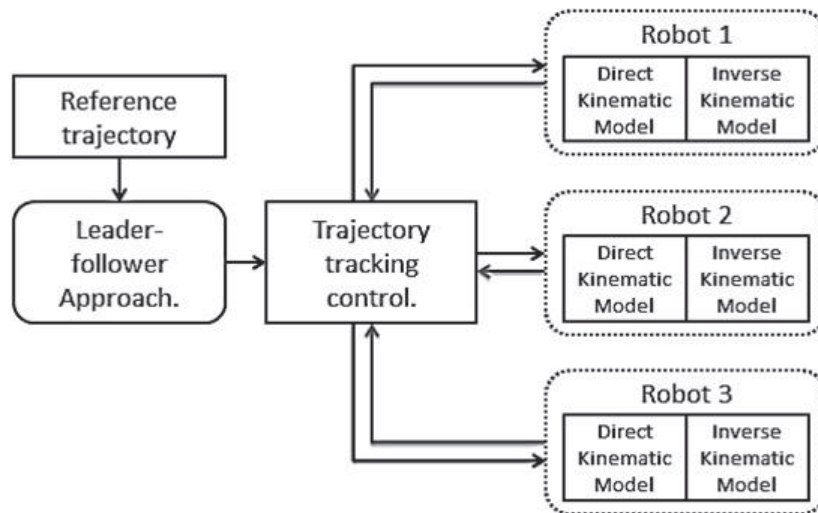


Figure 1 Control strategy block diagram

all trajectories that each robot has to follow. This controller must guide each robot to converge into a desired geometrical formation and maintain it while the group is moving along a trajectory. To achieve this goal, the controller receives the reference trajectory and its responsibility is to generate the linear velocities that each mobile robot should have to maintain the formation [14]. The reference trajectory is associated to inertial coordinate system and it can be implemented in any robot that moves on the plane (X, Y), and is defined as follows in the Eq. (1), where Tx and Ty represent the axes position respectively:

$$T_R = [T_x \quad T_y]^T \tag{1}$$

3. Mobile robot modeling

To develop a group controller that can be used in any type of mobile robot, the system is modeled as a simple particle

that moves in the plane (X, Y) [15, 16]. The differential equations that describe the kinematic behavior of robot motion are the Eq. (2), where x and v are the particle position and velocity respectively [17].

$$\begin{aligned} \dot{x} &= v \\ \dot{v} &= f(t, x, v) \end{aligned} \quad (2)$$

The kinematic behavior of the mobile robot is defined by the following state vector in the Eq. (3) [15, 16]. Also, the following space state equations represent the movement of each robot inside the plane, as the Eqs. (4) and (5) describe them, where u_k is the vector that contains the system reference and the system outputs are the positions (X, Y) of each robot [18, 19].

$$x_k = [X_k \quad \dot{X}_k \quad Y_k \quad \dot{Y}_k] \quad (3)$$

$$\dot{x}_k(t) = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix} x_k(t) + \begin{bmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix} u_k(t) \quad (4)$$

$$y_k(t) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} x_k(t) \quad (5)$$

4. Leader-follower approach

In the leader-follower approach, one robot is assigned as the leader of the group and the rest of the robots are the followers. The main function of the leader is to guide the group formation to follow the trajectory reference [1]. Also, each follower must establish and maintain its position inside the formation in reference to the leader's movement. The followers only know the relative displacement of the other robots but just the leader knows the trajectory reference (see Figure 2).

To determine the error e_k , the position of each robot x_k is compared with the global position h_k in the Eq. (6). After that, the errors of the adjacent robots are averaged in E_k , as the Eq. (7). Also, the relative position error z_k of each robot is calculated with the difference between the

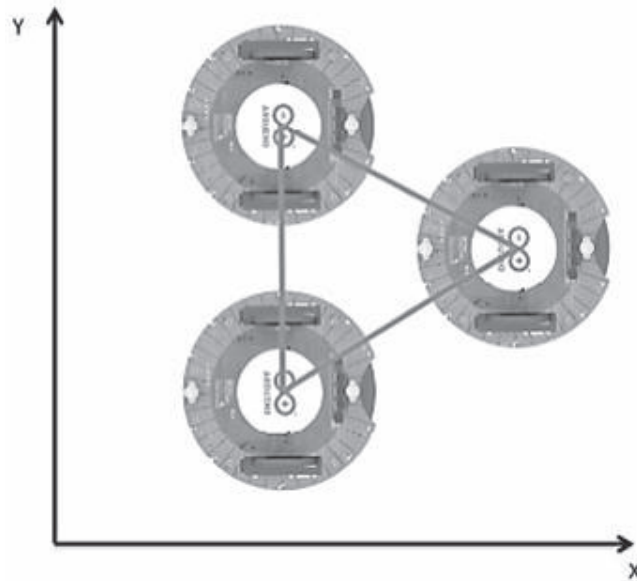


Figure 2 Representation of a triangle formation of three mobile robots

error e_k and the average error E_k , proved in the Eq. (8). The objective of the control system is to reduce this relative error to 0, which means that the robots are in formation [20].

$$e_k = x_k - h_k \quad (6)$$

$$E_k = \frac{1}{n} \sum e_k \quad (7)$$

$$z_k = e_k - E_k \quad (8)$$

The equations that describe the robot movement have linearly independent variables, for this reason the system can be separated in two subsystems. Each one, describe the movement in one axis (X or Y) and is represented by the following space state Eqs. (9) and (10) and the transfer function Eqs. (11) and (12).

$$\dot{x}(t) = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} x(t) + \begin{bmatrix} 0 \\ 1 \end{bmatrix} u(t) \quad (9)$$

$$y(t) = [1 \quad 0]x(t) \quad (10)$$

$$\frac{x(t)}{T_x(t)} = \frac{1}{s^2} \quad (11)$$

$$\frac{y(t)}{T_y(t)} = \frac{1}{s^2} \quad (12)$$

$$M_{Formation} = \begin{bmatrix} x_1 & y_1 \\ x_2 & y_2 \\ x_3 & y_3 \end{bmatrix} \quad (13)$$

$$R_f = M_{Reference} - M_{Formation} \quad (14)$$

To develop an effective and computationally less expensive controller, triangular inputs and outputs were used since these are adequate for the requirements of the system. This formation fuzzy logic controller was developed with four inputs and a double output (see Figure 3). The inputs are the position errors and the actual lineal velocities for each axis, as the Eq. (15) describes (see Figure 4). On the other hand, the outputs of the controller are the lineal accelerations that the robot must have in each axis to reduce the error (see Figure 5). When the error of the position equates to zero, the robot is in the correct position inside the formation.

$$\begin{aligned} E_x &= R_x - X_k \\ E_y &= R_y - Y_k \\ v_x &= \dot{X} \\ v_y &= \dot{Y} \end{aligned} \quad (15)$$

5. Fuzzy logic controller

The formation controller was designed to create any formation pattern using the leader-follower approach, where the leader has to follow the trajectory reference, and the followers have to maintain a specific position in relation to the leader. Robots can form various shapes in formation, the most common geometrical shapes are line and triangle, and both were tested in this article. The formation trajectory control is responsible to generate the linear velocities that each mobile robot must have to precisely follow the formation trajectory.

To control the group, the specific position of each robot inside the formation is necessary; each position is contained in the M formation, the Eq. (13) describes the matrix. With the reference trajectory and the formation position, the leader calculates and sends the specific global position that each robot must maintain; the result of the Eq. (14) is sent to each robot. It is important to note that any robot can be leader or follower, depending on the mode of operation assigned to each one.

After analyzing the particle's movement inside the space, it was determined to control the position of each robot is necessary to know two specific things: the position error that each robot has and the way in which each one is moving (velocity). Consequently, the model does not consider external forces that perturb the movement. The fuzzy controller for evaluating the desired acceleration calculates the output depending if the robot has to slow down or accelerate in each axis. For example, if the robot

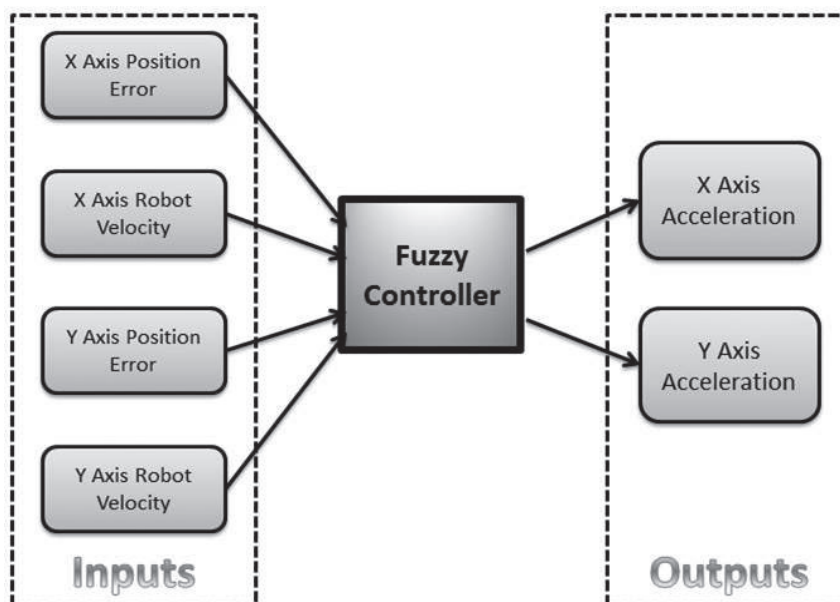


Figure 3 Logic Fuzzy Controller

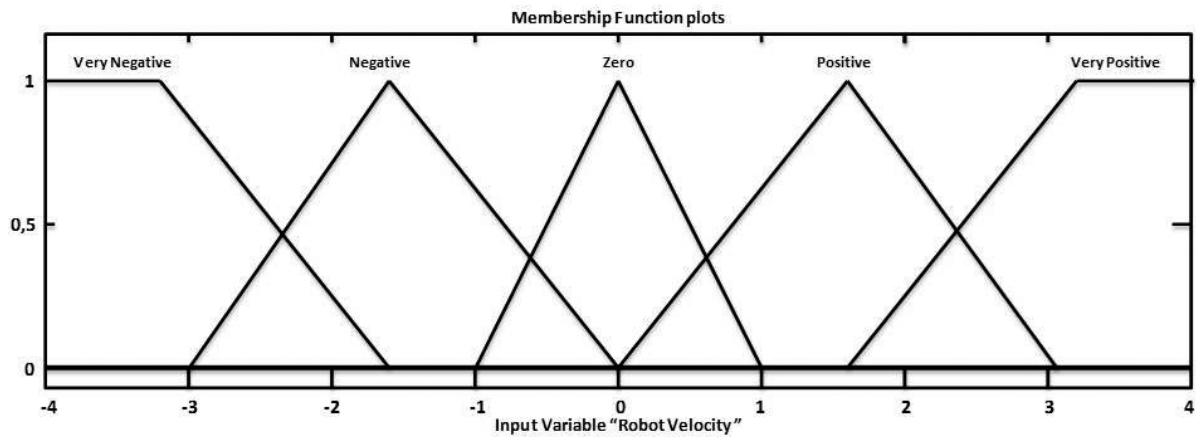
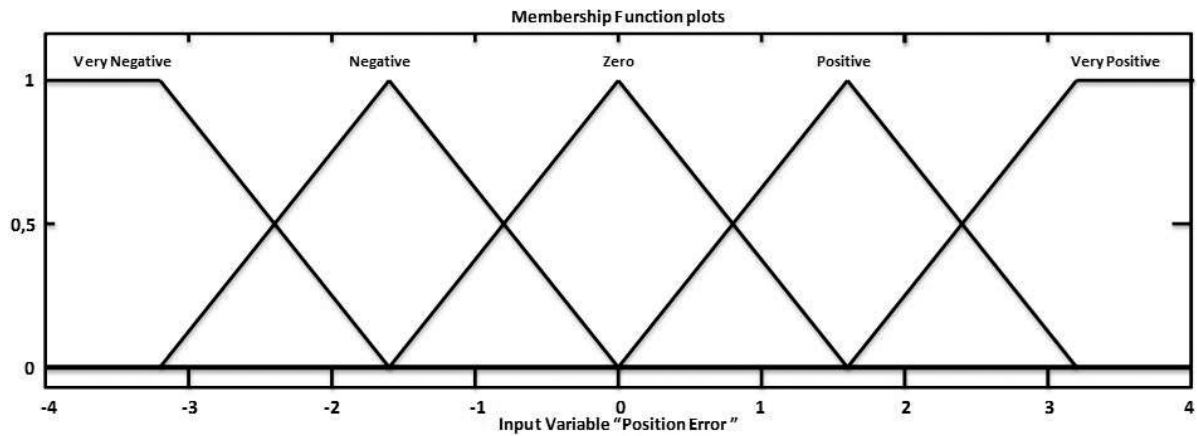


Figure 4 Formation Controller Fuzzy Input Sets

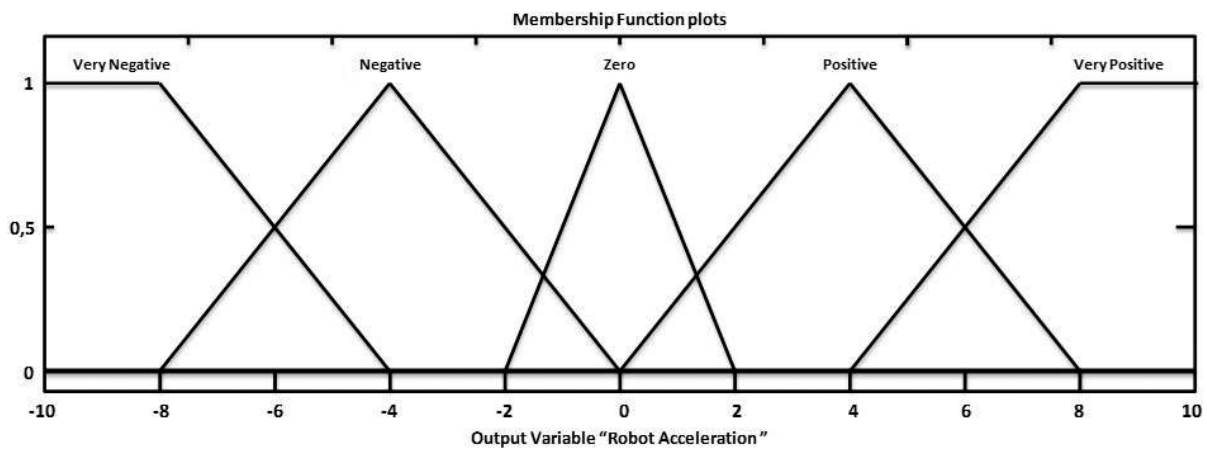


Figure 5 Formation Controller Fuzzy Output Sets

presents a position error and does not have velocity, the controller should accelerate the robot, causing it to move toward the target. The situation would be different if the robot has the same position error but this time it has a positive velocity, in this case the controller should slow down the robot, causing it to stop into the target. Finally, if the robot is in the

target, the controller should keep the robot in the same place without any velocity.

A total of 19 rules for each axis were used for the formation controller and they are presented in the Table 1, and the Figure 6 depicts the fuzzy action surface for each axis system under the fuzzy rules. The control surface shows that there are not strong changes, which generate extreme

control actions, and permits to conclude that the system does not present abrupt actions as high accelerations or strong changes in the position of the wheels.

Since the X axis motion is not directly related to the movement of the Y one, it is possible to conclude that the variables are linearly independent, and for that reason, one fuzzy logic controller was implemented in each axis

separately. To control all group formation each robot that forms part of the group must have the same fuzzy logic controller, and the interaction between all the robots makes the formation (see Figure 7).

To evaluate the fuzzy logic controller, its performance was compared with the PID controller developed in [14]. For each controller, the response produced by a step input was

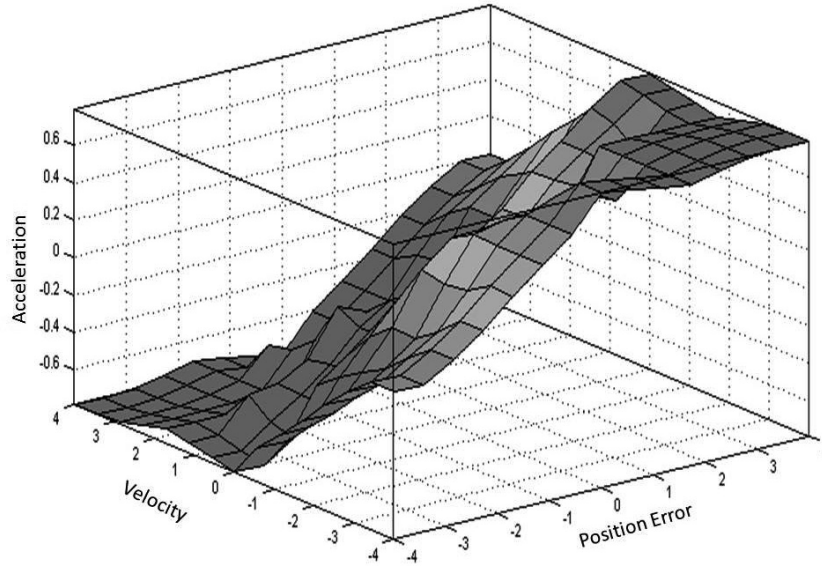


Figure 6 Fuzzy action surface for each axis system

Table 1 Rules required for each axis Formation controller

Inputs		Output
Position Error	Velocity	Acceleration
Very Positive	Very Positive	Positive
Very Positive	Positive	Positive
Very Positive	Zero	Very Positive
Very Positive	Very Negative	Very Positive
Positive	Very Positive	Negative
Positive	Positive	Negative
Positive	Zero	Positive
Zero	Very Positive	Very Negative
Zero	Positive	Negative
Zero	Zero	Zero
Zero	Negative	Positive
Zero	Very Negative	Very Positive
Negative	Zero	Negative
Negative	Negative	Positive
Negative	Very Negative	Positive
Very Negative	Very Positive	Very Negative
Very Negative	Zero	Very Negative
Very Negative	Negative	Negative
Very Negative	Very Negative	Negative

evaluated and the controllers were adjusted to produce the same over peak, with the objective to make a valid comparison. In the Table 2 the characteristic parameters calculated for each set of controllers are summarized.

What is more, the Figure 8 shows the approximation curves to the final set point trajectory (Step), for each controller with same criteria.

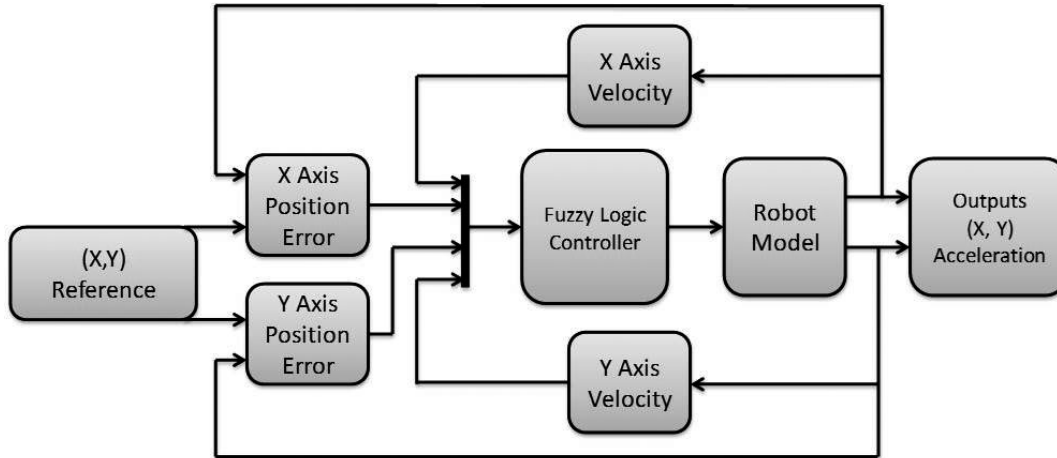


Figure 7 Formation Controller Structure

Table 2 and Figure 8 shows the PID controller presents an over peak and content of ripple greater than its fuzzy counterpart, requiring almost the same time establishment. Although the PID controller acts at a higher speed, the fuzzy controller improve the values of some of the most important performance rates, such as the overshoot, oscillations and ripple factor.

Table 2 Comparing parameters of the controllers

Controller Type	Fuzzy Logic	PID
Settling Time	6s	5.7s
Over peak	3%	5%
Ripple	0.26%	0.44%

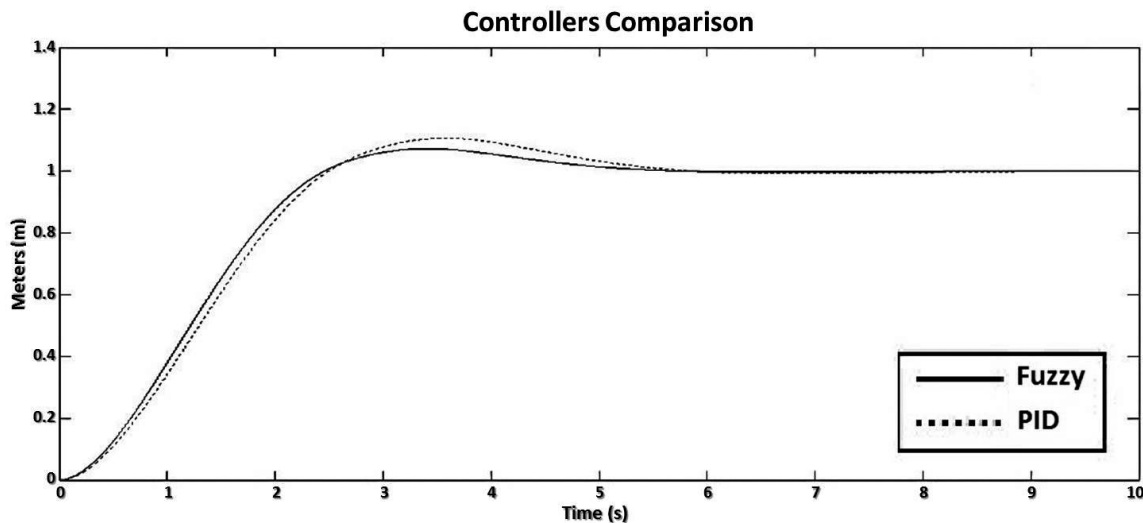


Figure 8 Response curves for controllers

6. Results

To test the control system developed in this article, several proofs of different type were developed by changing leader, reference and formation, looking to prove if the control works in a positive way. The first test was developed

by simulating a group of three robots that maintains a triangular formation and follows a constant reference trajectory, with the robot R2 selected as a leader. The control response analysis allows concluding that the formation control system generates the right trajectories. These paths permit the group to follow the reference and maintain the desired pattern formation (see Figure 9).

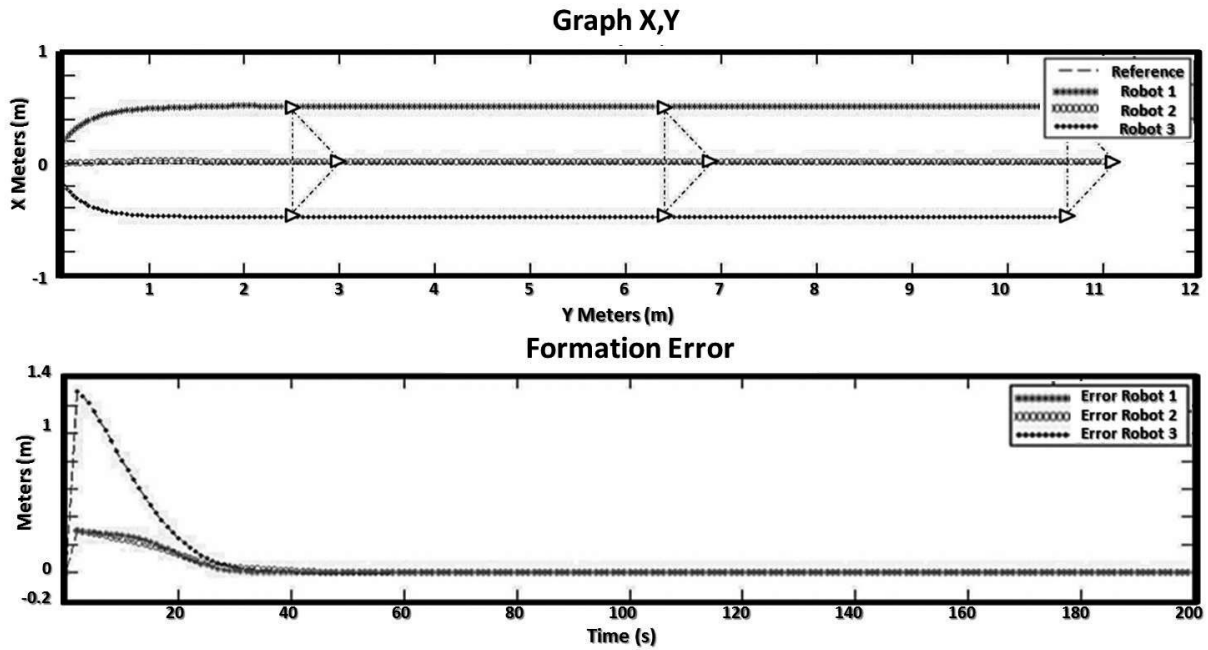


Figure 9 Constant reference for triangular formation trajectories

After checking the leader robot, it successfully follows the reference trajectory and the follower robots are able to establish and maintain its position in the formation, the next test was developed by changing the reference each

30 seconds. This is the first method to avoid obstacles, since these can be avoided by changing the reference with the help of a vision system, implemented on an external computer that monitors the obstacles (see Figure 10).

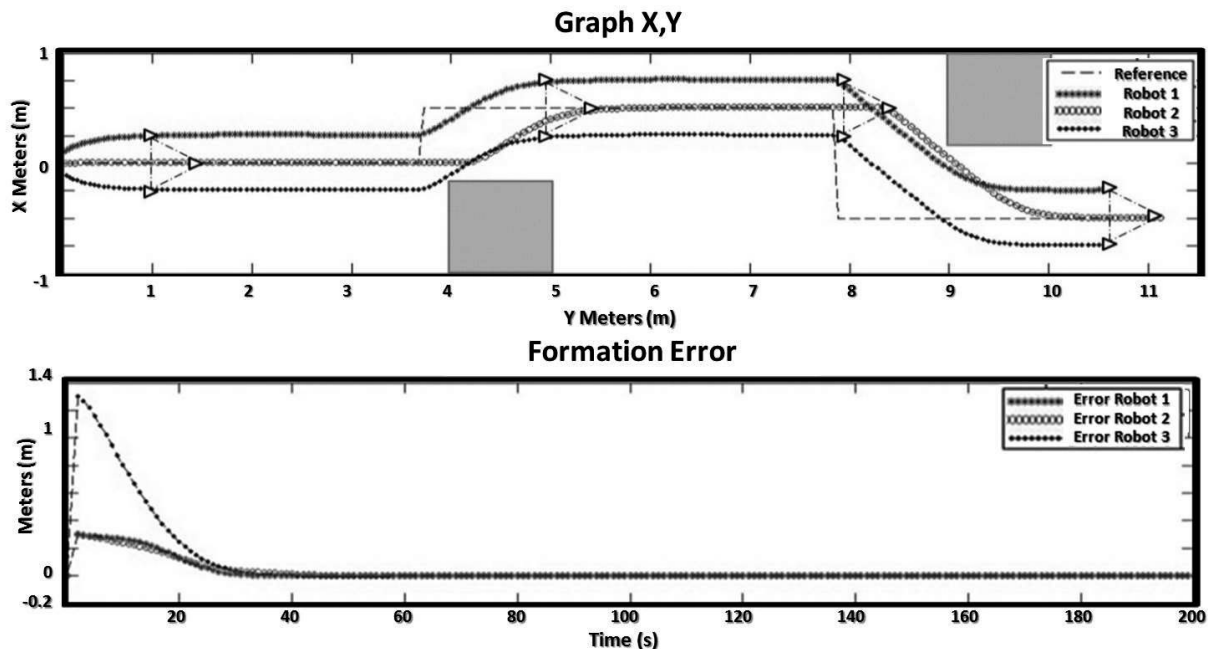


Figure 10 Obstacles avoided by changing the reference trajectory

The following test was changing the group's leader with a constant reference. The group of robot must change the group leader in two cases. The first one is, if the actual leader presents a fault or it is lost; the second one, if a robot

detects an obstacle in front of it, the leader of the group changes searching to avoid the obstacle (see Figure 11). This method presents an advantage since it does not need an external computer to work appropriately.

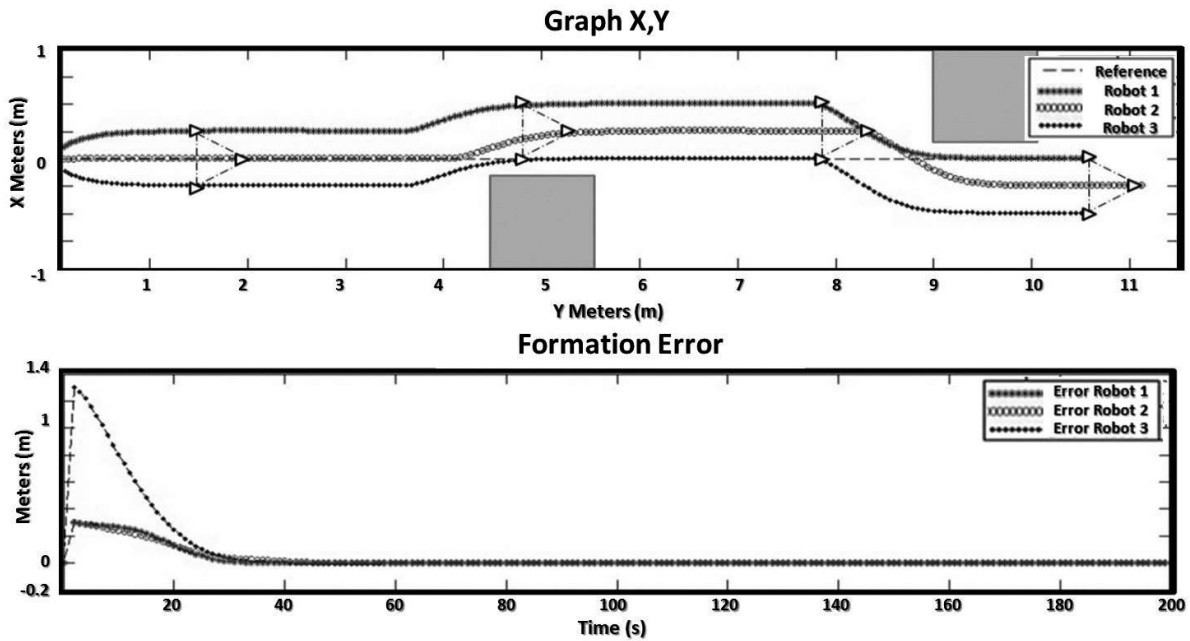


Figure 11 Constant reference changing the group leader to avoid obstacles

The next test was developed by changing the formation pattern, verifying if the control system allows the group to change it at any time. This is a useful tool in several situations, for example, it is a solution to move the group inside the restricted spaces or carry objects with different

geometries. In this paper the change of formation was tested as a solution to avoid obstacles (see Figure 12).

Finally, several changes that the control system allows were tested. At 10 seconds, the formation was changed;

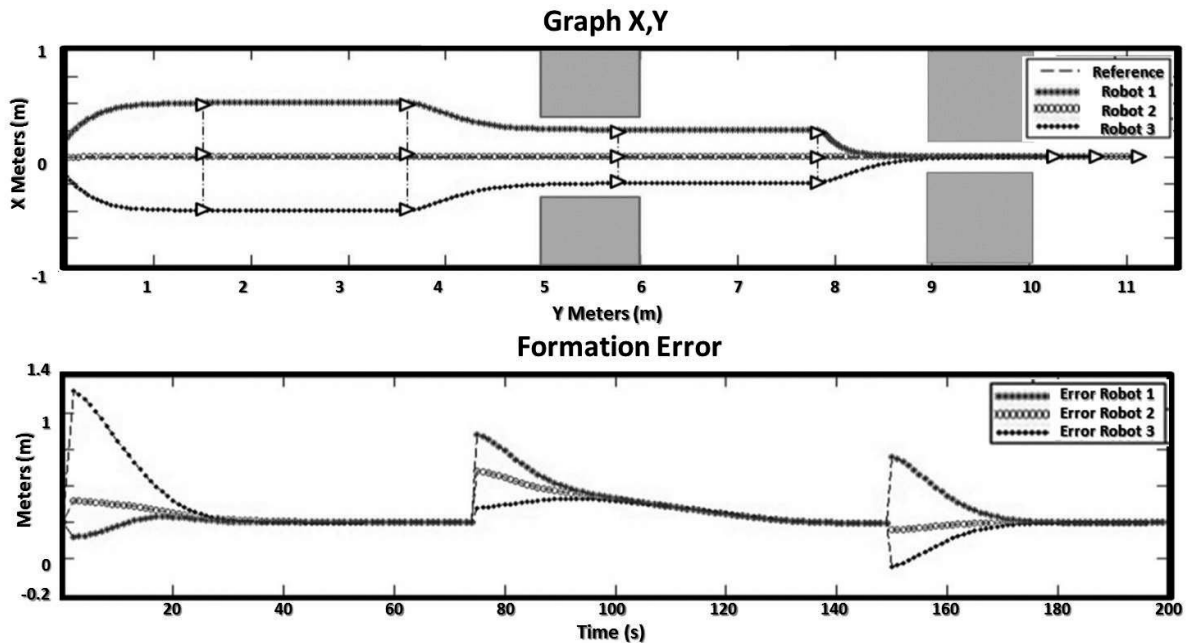


Figure 12 Obstacle avoided by changing the formation geometry

then, after 20 seconds, the reference and leader will change (see Figure 13). With this last test is established that the control system generates the references to maintain a

formation while a target is followed, in addition to allowing the formation or leader to be changed at any time.

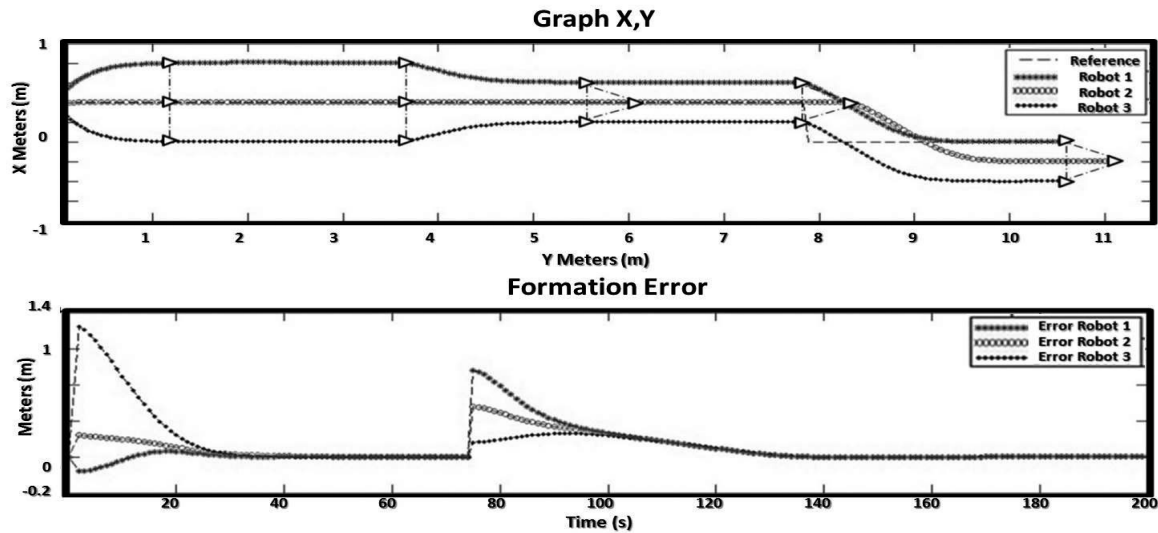


Figure 13 Reference by changing the formation, leader and reference

7. Conclusions

The first remarkable conclusion is that fuzzy controllers do not require a precise knowledge of the process, neither the exact model to perform its control; this was confirmed in the experimentation. Considering the quantitative information contained in Table 2, it was determined that the traditional control (PID), responds faster but with a bigger over peak that generates more ripples percentage than the fuzzy logic controller. Although, according to the settling time parameter the PID controller is 10% faster, it is possible to conclude that the Fuzzy logic controller is highly desirable in this control process, because it has fewer oscillations that improving the robot formations.

This work demonstrates that fuzzy logic can be used to solve the formation problem control, position control and avoid obstacles, and collisions control. The controller developed consists in a fuzzy logic formation controller, which is suitable for changing the desired formation and the leader of the group at any time. Also, the controller variability allows avoiding obstacles encountered on the group of robots way by changing the leader, the reference or the formation.

It was shown by means of simulation, that the control strategy has a good performance by generating the formation trajectories, because the leader robot leads the group to follow the reference trajectory, and followers' robots achieve to establish and maintain its position in the formation successfully. The formation trajectories generated by this controller can be used as a reference for tracking control system of any mobile robot moving in the plane (X, Y).

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