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Path Tracking of Mobile Robot in Crops

Performance Evaluations of Position Control

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Abstract Evaluation of the performance of three controllers: adaptive PID, model reference adaptive controller, and fuzzy controller, is presented, applied to a mobile robot for autonomous path tracking in a crop. Different tests are run in a simulation environment in order to compare the same trajectory performed under each of those controllers. The tests are designed and implemented using Simulink® programming tools, making the robot follow a desired path across the crop. The results are compared considering the different error indices, curves and actuator requirements of each controller, in order to arrange them in different categories.

Keywords Mobile robot · Controllers · Trajectories · Evaluation

Mathematics Subject Classifications (2010)
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1 Introduction

The irruption of automatic or autonomous systems in different fields of human life has been a reality from many decades, understanding them as machines, computer programs and electronic devices that perform specific tasks in autonomous ways or under supervision in places like factories, hospitals, banks, shopping centers or homes, having the ability to interact with the environment and to manipulate objects to execute repetitive and/or specific tasks within the corresponding workspaces where they are incorporated.

For a long time, robotic systems have been an essential part of industrial production process where we can actually find controlled work environments, although there are some specific areas where robotics has not been integrated yet into everyday productive activities, as in the case of the agricultural sector [1].

Although many researchers have developed harvesting robots [2–5], able to detect and select fruits according to some specified criteria and then getting those fruits and putting them in containers, all the researchers had to deal with the lack of versatility of those devices to move across the crops or to work with different kinds of plantations with minimum configuration changes [6].

Mobile robots can be remotely operated or autonomous; the former are used to access hazardous or inaccessible places, hostile to people, allowing a human operator to determine and control the robot's movements.

Autonomous robots, not having the knowledge provided by an operator, must be able to self-locate and maneuver in an automatic way, if they are intended to perform their tasks effectively in accordance with previously defined control criteria. Therefore, they must have wide flexibility and adaptability to operate when faced with many situations and stochastic environments not previously considered in the design.

In this paper we address the concept of path tracking based on position and orientation control of a mobile robot able to move along the rows of a crop, so it can perform some tasks while moving along.

We introduce three different controllers for position control and path tracking: an adaptive PID controller, an adaptive control with reference model, and a fuzzy controller, in order to compare them and determine which one has the better performance. A similar comparison was made in [7], but for trajectory tracking of a SCARA robot.

Those controllers are evaluated considering –in order of priority– the different error rates, path tracking graphics, and torque requirements in the different wheels of the mobile robot. All the tests are carried out in simulation environments developed using Simulink® software.

Finally, we review and discuss the results with the aim to determine the best-evaluated controller, and describe the further activities that will continue this work.

1.1 Control of Mobile Robots

Position control and path tracking of mobile robots with nonholonomic restrictions have been remarkable and interesting issues for many authors [8, 9], and several methods are proposed in the corresponding literature, aimed at solving those problems.

An example of this can be seen in [10], where a discontinuous nonlinear control for a mobile robot is proposed, considering an external loop for position and an internal loop for motors, based on switching between status feedback and linearization for the external loop, and a PID controller for the internal loop. A similar solution is presented in [9].

An RBF adaptive neural compensation controller for path tracking of a mobile robot of the unicycle type is proposed in [11]. This compensator –along with the nonlinear controller– is able to generate the speed commands with a minimum error for the robot dynamics. It was shown that tracking control errors were bounded, and the limits were calculated in terms of the approximation error of the RBF neural net.

In the case of the AURORA robot [12], the control is mainly based on collision evasion for path tracking. In [13] we can see experimental results for the guidance of an autonomous mobile robot inside a greenhouse equipped with a distributed net of wireless sensors. A similar situation is discussed in [14, 15] where, starting from sensors placed in the front and sides of the robot, it is possible to adjust trajectories in correspondence with obstacles and movement restraints, and in [15] a pair of fixed sensors (*lidar*) avoid colliding with the obstacle and achieve boundary following.

In [16] the application of theories on Differential Flatness Systems for path tracking in mobile robots is discussed, parameterizing flat outputs using the point-to-point tracking method.

A solution of the localization problem is presented in [17] using as EKB plus sensors like encoders and lasers. Some artificial intelligence techniques are proposed in [18] where, starting from particle filters and bayesian nets, an algorithm is implemented allowing localization and decision-making for a mobile robot in controlled environments.

In [19] we can see the experimental results obtained with the development of a control and guidance system for a mobile agricultural machine by means of a vision system capable of detecting the natural limits between cut and uncut zones. Another associated work is presented in [20] showing the development of an autonomous guidance system for eventual assistance to an operator, based on *servoing*.

In [21] a series of control methods is detailed, and special mention can be made of the application of adaptive control for a mobile robot. Several authors propose control methods based on fuzzy logic, due to the intuitive advantages provided by this method through the use of knowledge rules and linguistic variables. An application based on an adaptive neuro-fuzzy inference system to a mobile robot navigation system is presented in [22], an implementation that allows the robot to perform different tasks in a partially unknown or unknown environment.

A predictive fuzzy controller is proposed in [23] that, starting from the future estimation of a variable, allows an improvement of the controller's performance. In [24, 25] a control system based on fuzzy logic is used for a mobile robot's navigation. A set of fuzzy rules and Petri nets allow the mobile robot to avoid obstacles and collisions with other mobile robots in unknown environments. A new evolutionary algorithm is proposed in [24] to deal with changes in the dynamic environment, a fuzzy-set-based multi-objective fitness evaluation function is adopted in the evolutionary algorithm, allowing the incorporation of complex linguistic features that a human observer would consider desirable in the behavior of a nonholonomic mobile robot.

For the total control of the robot it is necessary to perform two independent control loops [10], one of low level to control the speed of the wheels, and another of high level for position control. In this case, the evaluation is focused on those more complex controllers that offer better robot performance.

Trajectory tracking problems of mobile robots in agricultural environments have been the subject of study for many authors, since autonomous systems usually must perform in unknown environments which require a high level of adaptation and efficiency [26–28].

Having in mind the different existing possibilities for solving the control problem, it is necessary to design, evaluate and compare different methods, in order to find a proper controller that can adjust to the specific needs of the proposed robot, therefore in this work we will make a comparison and evaluation that allows us to find the most adequate one.

The main goal of this work is to define a robust and easy-to-implement path tracking controller that has enough flexibility to work in unknown and changing environments, and is the main component of a hybrid control system that will use –in a secondary way– a reactive or behavior-based control for a mobile robot performing crop-harvesting tasks.

2 Modeling and Description of a Differential Mobile Robot

In order to carry out the evaluation of the different controllers and their responses to tracking a reference path, we considered a differential kinematic model for the studied mobile robot, as shown schematically in Fig. 1. This robot can be represented by:

$$q = \begin{bmatrix} x & y & \theta \end{bmatrix}^T \tag{1}$$

where x and y are the coordinates of the center C and θ is the orientation angle of the mobile robot, taken counterclockwise from the X-axis. The angle θ is restricted within the range $[-\pi, \pi]$. This model is presented in [26, 29–31].

Using the kinematic relationship (2) it is possible to determine the position and orientation of the mobile robot in the global reference system.

$$\dot{q} = S(q) \cdot V \tag{2}$$

where $V = \begin{bmatrix} v\ \omega \end{bmatrix}^T$, and **v** with ω denote respectively the linear and angular velocity of the center point C along the robot's axis. With this model we

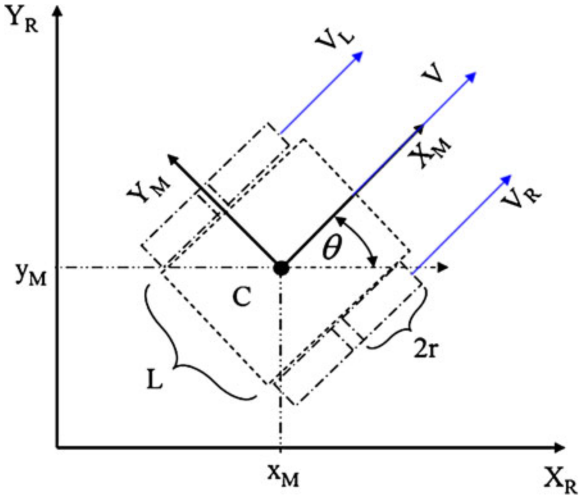


Fig. 1 Representation of the mobile robot considering speeds in local and global reference systems

can perform simulations and tests for the different controllers regarding path tracking.

Besides, the matrix S(q) is given by:

$$S(q) = \begin{bmatrix} \cos\theta & 0 \\ \sin\theta & 0 \\ 0 & 1 \end{bmatrix} \quad (3)$$

The model of the mobile robot has three output variables that represent Cartesian position and orientation of the device with respect to a reference system, and two inputs corresponding to linear and angular speeds of the mobile robot.

However, these inputs can be transformed into the angular speeds of their wheels by means of relationship (4). Since the DC motors are the real actuators of the mobile robot, if we want to achieve path tracking control we must act on the wheels of the mobile robot.

$$V = \begin{bmatrix} \frac{r}{2} & \frac{r}{2} \\ \frac{r}{L} & -\frac{r}{L} \end{bmatrix} \cdot \begin{bmatrix} w_R & w_L \end{bmatrix}^T \quad (4)$$

where $[w_L, w_R, r, L]$, respectively, represent the angular speed of the left wheel, the angular speed of the right wheel, the radius of the mobile robot's wheels, and the distance between wheels.

In order to produce the movement in the wheel axes of the robot, we used direct current motors, so besides the kinematic model we also considered modeling the actuators of each wheel –a simplified dynamic model for the actuators that provide the movement of the wheels– which corresponds to a transference function of Eq. 5 that relates the voltage with the speed or position of the axis,

$$\frac{\psi(s)}{U(s)} = \frac{a}{s \cdot (s+b)} \quad (5)$$

where ψ is the position of the motor axis, U is the motor input voltage, and a, b represent the parameters of the motor's transfer function.

The robot parameters correspond to the distance between wheels and the radius of the wheels, and the values used in the performed simulations, listed in Table 1, that correspond to actual values, as shown in Fig. 12 and point 6.

Table 1 Parameters of the mobile robot

Parameters	Values	Units
r	0.0 5	[m]
L	0.12	[m]

3 Implemented Controllers and Control Law

Here we will detail how we implemented each of the controllers proposed for path tracking. Although there are many kinds of controllers and methods suitable for achieving this task, in this work we decided to use adaptive controllers, since they are easy to implement. Control adaptation and path tracking are essential issues for moving along a crop in an autonomous way, due to the stochastic conditions inherent to crop environments. The implementation of controllers does not demand a high level of processing, so this is a key factor that allows the robot to perform other tasks in the field in an effective manner.

If we want to control a mobile robot, it is necessary to know its location at any moment, that is, its position and orientation with respect to the global reference system. For this purpose, we need to establish a relation between the local and global reference systems of the mobile robot.

If we consider point P as a desired position for the mobile robot (see Fig. 2), we will have that the robot, represented by the center of mass C, and displayed in Fig. 2, is at a distance d and with a deviation angle ϕ from this point. For the robot

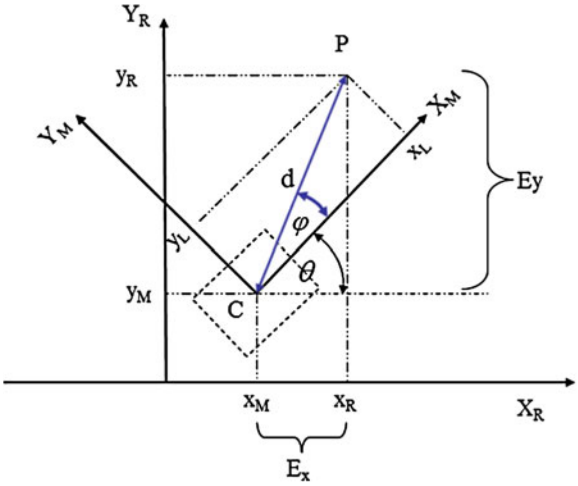


Fig. 2 Distance and deviation angle from the target point

to reach the desired point, we must reduce the distance and the deviation angle to zero.

Considering the schematic representation shown in Fig. 2, we can see point C, that represents the gravity center, and the M-axis and R-axis systems that correspond to the robot's local and global reference systems, respectively.

Finally, we can establish a series of relationships allowing to represent a point P, which corresponds to the mobile robot's future or desired position in terms of the local system, starting from the global system.

The relationships finally obtained are:

$$\begin{bmatrix} X_L & Y_L \end{bmatrix}^T = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \cdot \begin{bmatrix} E_x & E_y \end{bmatrix}^T \tag{6}$$

where $\begin{bmatrix} X_L \; Y_L \end{bmatrix}$ are the respective positions on the X and Y axes of point P within the local system, and $\begin{bmatrix} E_x \; E_y \end{bmatrix}$ are the differences in the X and Y axes between point P and the center of mass C of the robot in the global system, all measurements in [m].

From Eq. 6 we get a relation between any point of the local system or the mobile robot's reference system, starting from the global system, depending on the position of the mobile unit or of point C within the latter. Besides, E_x and E_y represent the mobile robot's error on each axis of the global reference system, produced during the process of tracking a path represented by a series of coordinates for point P.

The problem of control, given a desired reference position, is reduced to getting the distance and deviation angle equal to zero, to achieve the objective of position control. From Fig. 3 we can get the relations for those variables.

$$\varphi = \tan^{-1}\left(\frac{Y_L}{X_L}\right) \tag{7}$$

$$d = \frac{X_L}{\cos(\varphi)} \tag{8}$$

If we want to achieve control and path tracking, we must obtain the position control of the mobile robot, starting from the desired references, considering their values in the global reference system. In this way, we establish a control loop that provides as outputs the angular speed that each wheel has to acquire in order to get the desired position.

Although the required control output corresponds to the speeds of both wheels, the implemented control is actually carried out by means of the linear speed $V$and the angular speed $w$of the mobile robot. With Eq. 4 we can get the values for the speed of each wheel in terms of the control outputs.

The angular speeds are also references for the second control loop (internal loop) that, depending on the manipulation of the input voltage of the actuators (motors), allows the speeds required for each wheel to be obtained.

As mentioned above, to simulate the control of the mobile robot we modeled the motors acting on the wheels, so we can represent the dynamics associated with the control of the system and at

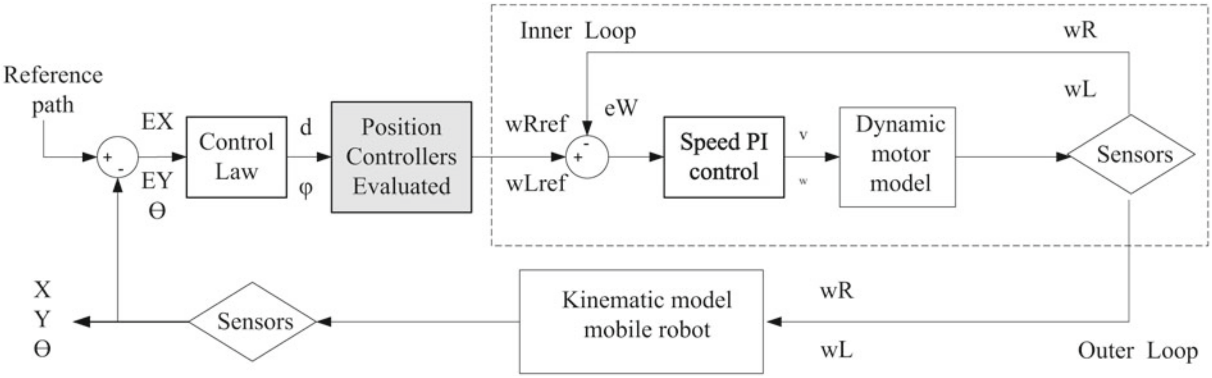


Fig. 3 Control scheme for the mobile robot

the same time we can get more acute simulation results, allowing adjustments to be minimized at the time of implementing a real system.

In order to carry out the proper tests on the trajectory controllers, we must consider in the general test scheme the errors produced in the sensors that measure position and orientation of the mobile unit (X, Y, θ), as well as the errors in the speed of the wheels and the mobile robot (w_R, w_L, V), since those errors produce effects on the robot's localization that must be considered [32].

In Fig. 3 we can see the scheme used for the application of path tracking control to the mobile robot. This scheme was implemented in Simulink® starting from blocks and functions, switching between the different controllers proposed for the reference path. A sampling time of 0.02 seconds was defined, using random Gaussian errors to represent inaccuracies in the sensors, and considering as maximum the percentage values stated in the data sheets of the commercial devices. We also considered, depending on the model of the motor, the real admissible voltage limits for those actuators.

To obtain speed control of the actuators (inner loop) we used a classic PID controller, the same as in [8], without considering testing other kinds of controllers, since the main purpose of this work is to achieve the control of position and path tracking. Then we implemented and simulated three different controllers:

- Model Reference Adaptive Control (MRAC).
- PID Control with Parameter Adaptation (PID ADA).
- *Fuzzy* Controller.

The robot is subjected to a trajectory that emulates the displacement in a real plantation, where the device has to move through different rows, executing some tasks, and then reaching the final point. The proposed trajectory is displayed in Fig. 4.

Next we describe the process with each of the controllers proposed for path tracking of the described mobile robot in crops.

3.1 Model Reference Adaptive Control

For the implementation of position control using the Model Reference Adaptive Control (MRAC) [21], in the scheme shown in Fig. 3 we used a controller like the one shown in Fig. 5, considering as inputs the displacement error and the distance from the target point that are detailed in Eqs. 7 and 8. The controller outputs correspond to the angular speeds of each wheel, which represent the speed control references of the motor, in the inner loop. However, the references for this controller correspond to the value zero "0" since the goal is for the control to lead to zero the distance and deviation differences between the target point and the mobile robot.

For the implementation of the MRAC, we considered a damped second order as the reference model, which was represented by means of its transference equation.

In this way, the kinematic model for the mobile robot with MRAC control is transformed into:

$$\dot{q} = S(q) \cdot \left[a_0 \cdot d + a_1 \cdot d_{\text{ref}} \quad a_0 \cdot \varphi + a_1 \cdot \varphi_{\text{ref}} \right]^T \tag{9}$$

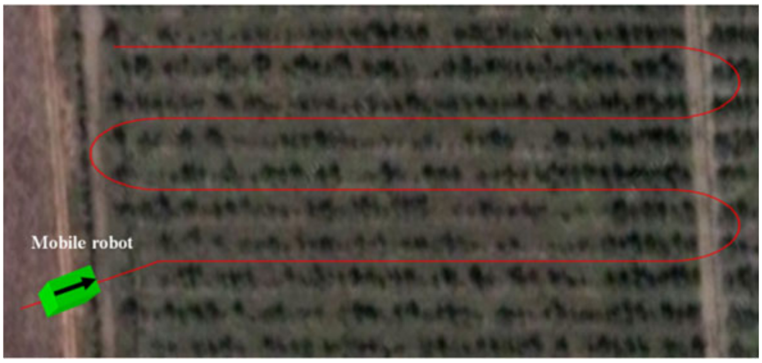


Fig. 4 Trajectory proposed for tracking in a plantation for the mobile robot (*Google Earth*-2013)

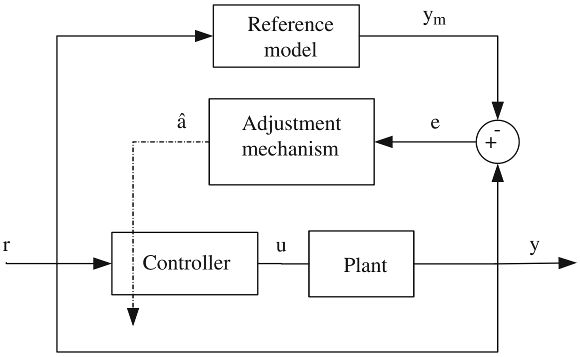


Fig. 5 Scheme used for the MRAC controller

where a_0 and a_1 represent the adaptive parameters of the controller, that were calculated from the following adaptation law:

$$\begin{bmatrix} \dot{a}_{0d} \\ \dot{a}_{1d} \end{bmatrix} = \begin{bmatrix} -\alpha_d \cdot e_{MRACd} \cdot d & -\alpha_d \cdot e_{MRACd} \cdot d \end{bmatrix}^T \tag{10}$$

$$\begin{bmatrix} \dot{a}_{0\varphi} \\ \dot{a}_{1\varphi} \end{bmatrix} = \begin{bmatrix} -\alpha_\varphi \cdot e_{MRAC\varphi} \cdot \varphi & -\alpha_\varphi \cdot e_{MRAC\varphi} \cdot \varphi \end{bmatrix}^T \tag{11}$$

where the controller parameters α_{ik} correspond to an adaptation or learning constant i of variable k, and e_{MRACk} is the error of variable k, between the reference model and the controlled "plant".

After that, the controller outputs are converted into reference signals for both wheels of the mobile robot, starting from Eq. 4, so we can get the desired path tracking once the internal control loop is executed.

The selection of controller parameters is made from different tests with trajectories similar to the one proposed in Fig. 4, finally choosing the parameters that showed the best performance in those tests.

3.2 Adaptive PID Controller

For the implementation of control using an adaptive PID controller, we used a dynamic adaptation of parameters and gains of a classic PID controller. The adaptation of parameters is carried out considering the following adaptation law:

$$\frac{da}{dt} = -k \cdot e \cdot \frac{\partial m_{\text{ref}}}{da} \tag{12}$$

where a are the controller parameters, corresponding to K_{cV}, T_{dV}, T_{iV}, K_{cW}, T_{dW} and T_{iW} parameters of the PID controller, k is the learning adaptation constant, m_{ref} is the reference value to be reached by the controller, in this case equivalent to zero "0", to cancel the distance and deviation of the mobile robot, and e is the error between the output and the reference value.

In this way, the kinematic model for the mobile robot using the adaptive PID controller is transformed into

$$\begin{aligned} \dot{q} = S(q) \cdot \big[&(k_{cV} + T_{iV} + T_{dV}) \cdot d_{\text{ref}} \\ &\times (k_{cw} + T_{iw} + T_{dw}) \cdot \varphi_{\text{ref}}^T\big] \end{aligned} \tag{13}$$

Like as in the previous case, here we also considered as inputs the displacement error and the distance from the target point for the external control loop, and as outputs the speed references for both wheels in the internal loop.

Similarly, the selection of controller parameters is made from different tests carried on trajectories similar to the one proposed in Fig. 4, and also choosing the parameters with the best performance.

3.3 Fuzzy Controller

For the implementation of a Mamdami-type fuzzy controller for path tracking of the studied robot, we proposed a control similar to the one described in [23–25, 33]. We considered two inputs, corresponding to the distance error E_d and the deviation angle E_ϕ between the mobile robot and the target point, and two outputs, corresponding to the linear speed **V** and the angular speed **w** of the mobile robot. The basic scheme of the controller used in Fig. 3 is shown in Fig. 6.

In general terms, the fuzzy controller works in the following way: when the distance between the mobile robot and the target is too long, it is necessary to increase the linear speed; on the other hand, if the distance is short, the speed must

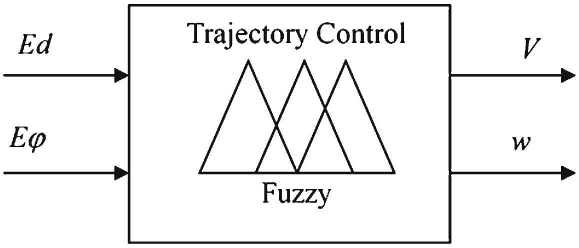


Fig. 6 Scheme used for the fuzzy controller

be reduced. There is a high dependence between the linear speed and the distance to be covered, but the adjustment of deviations of the mobile robot is mainly related to variations in the angular speed. The modification of those speeds by the controller allows to give the internal control loop the adequate references for path tracking.

We designed triangular and trapezoidal membership functions for each variable, considering different ranges for each of them, according to the analysis of the behavior of each variable of the mobile robot.

The kinematic model for the mobile robot with the fuzzy controller can be written in a synthetic way

$$\dot{q} = S(q) \cdot \left[V_{FUZZY} \quad w_{FUZZY} \right]^T \tag{14}$$

We considered that the distance from the target point is always positive, and is within the range $E_d \in [-20, 20]$ meters if $E_\varphi \in [-\pi, \pi]$. The membership functions, the fuzzy sets and the rules designed for the control of the mobile robot are described in a previous study, but is similar to work presented in [25], in which the authors analyze the path tracking of a mobile robot and evaluate the performance of five position controllers, including this fuzzy controller.

4 Computer Simulations and Synthesis of Results

The simulations were made using the trajectory shown in Fig. 4, and including the controllers and considerations described in the previous point. The trajectory is entered in the control scheme as a vector in the time domain. Using different of Simulink® tools it is possible to get the results and graphics for each of the stages shown in the scheme of Fig. 3.

4.1 Error Indices

In order to make the quantitative comparison of the controllers, we used different error indices which allow quantifying the ability of each controller to fulfill the requirements of the imposed references. Those indices are

- Agreement Index:

$$IA = 1 - \frac{\sum_{i=1}^{n} (o_i - p_i)^2}{\sum_{i=1}^{n} (|o_i - o_m| + |p_i - p_m|)^2} \tag{15}$$

- Residual Mean Square:

$$RMS = \sqrt{\frac{\sum_{i=1}^{n} (o_i - p_i)^2}{\sum_{i=1}^{n} o_i^2}} \tag{16}$$

- Residual Standard Deviation:

$$RSD = \sqrt{\frac{\sum_{i=1}^{n} (o_i - p_i)^2}{n}} \tag{17}$$

with p_i as output value of the controlled system, o_i as reference or expected value, o_m as mean value of the expected values, and n as the total number of data. We considered that for RMS and RSD the values under 0.1 were acceptable, and for the case of IA the acceptable values were over 0.9.

Each of those indices allow to evaluate in a different way the robot's behavior with regard to path tracking on each Cartesian axis, comparing the reference values for each axis with the values obtained after applying the proposed control method. The use of three different indices allows, when making a joint comparison, to eliminate statistical bias and local errors that could lead to the generation of erroneous conclusions that could not be identified when using only a single index. A method of comparison of performance evaluation for the path tracking is presented in [31], but in this case they only use the error sum of squares, which mean the sum of the squared differences between each observation and its group's mean.

4.2 Synthesis of Results

The results obtained with each controller, considering the previously described indices, the graphics of trajectories, and the torques required for each controller proposed for the robot's path tracking process shown in Fig. 4 are commented next.

In Table 2 we present the performance indices obtained by the robot in each of the test cases, considering the different controllers.

From the error indices listed in Table 2 for each axis, we can see that the controllers show a very similar response, and all of them are within acceptable ranges. Based on these results, we can state that the adjustment and selection of parameters for the controllers was adequate. However, it is difficult to make a classification of the controllers, since the results do not present sufficient differences to make such a distinction. Because of this, we can only conclude that the tuning of the controllers was properly done.

Table 2 Error indices for the proposed controllers

Index	MRAC		Adaptive PID		Fuzzy	
	Ex	Ey	Ex	Ey	Ex	Ey
IA	0.9996	0.9996	0.9994	0.9998	0.9994	0.9989
RMS	0.0010	0.0080	0.0133	0.0058	0.0126	0.0132
RSD	0.1161	0.0563	0.1545	0.0412	0.1466	0.0928

Beside the indices, it is necessary to review the graphics for the desired and actually performed trajectories of the controlled robot. Those graphics are obtained through Simulink® and are displayed in a single chart for better visualization.

The results obtained after executing the trajectory control described in Fig. 3, when subjecting the robot to path tracking with the MRAC control method are shown in Fig. 7.

The results obtained using the adaptive PID controller, proposed in the simulation of path tracking for the mobile robot, are shown in Fig. 8.

Finally, the results obtained applying the proposed fuzzy controller to the mobile robot under the requirement of moving along a path between rows of a plantation, are shown in Fig. 9.

As in the case of the error indices, from the graphics it is not possible to obtain enough data to make a significant differentiation of the controllers, because the graphics only allow to conclude that the controllers are properly implemented.

Finally, we must consider the motor torque, which is linearly related to the armature voltage i, by a factor K; therefore, starting from the motor's input voltage we can obtain the torque for each motor.

Figures 10 and 11 show the graphics of the torques required for the motors of each wheel, in order to achieve the mobile robot's path tracking

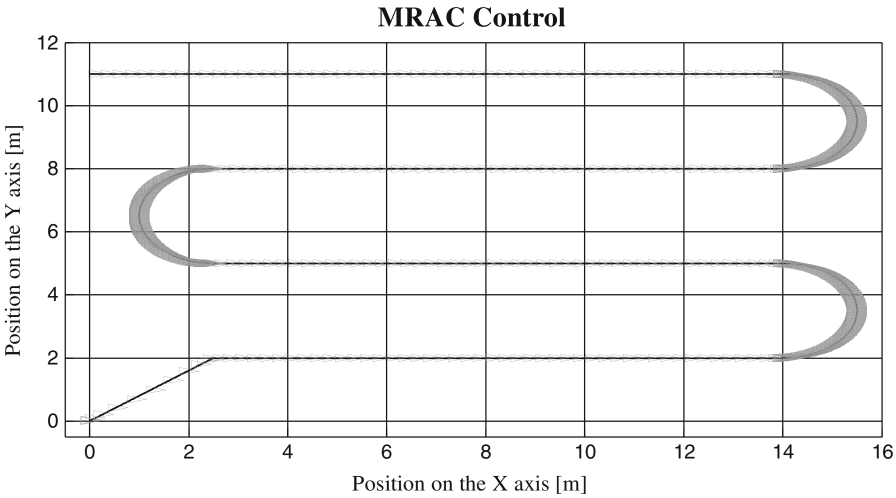


Fig. 7 Path tracking by the MRAC method. The desired path is shown in *black*; the position and orientation of the mobile robot are represented by *gray triangles*

Fig. 8 Path tracking by PID ADA. The desired path is shown in *black*; the position and orientation of the mobile robot are represented by *gray triangles*

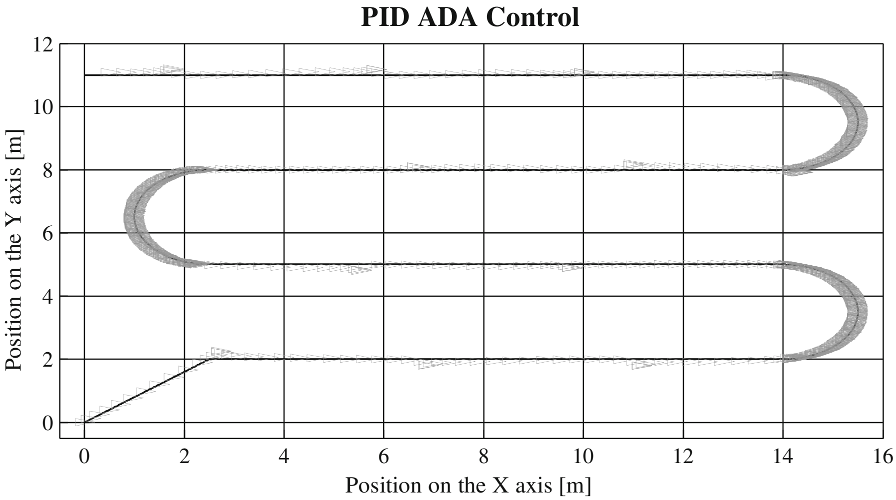


Fig. 9 Path Fuzzy Control. The desired trajectory is shown in *black*; the position and orientation of the mobile robot is represented by *gray triangles*

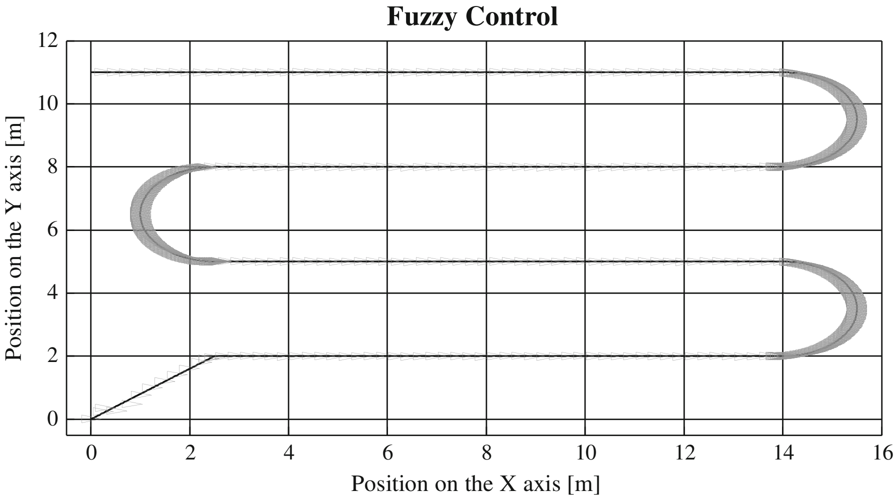
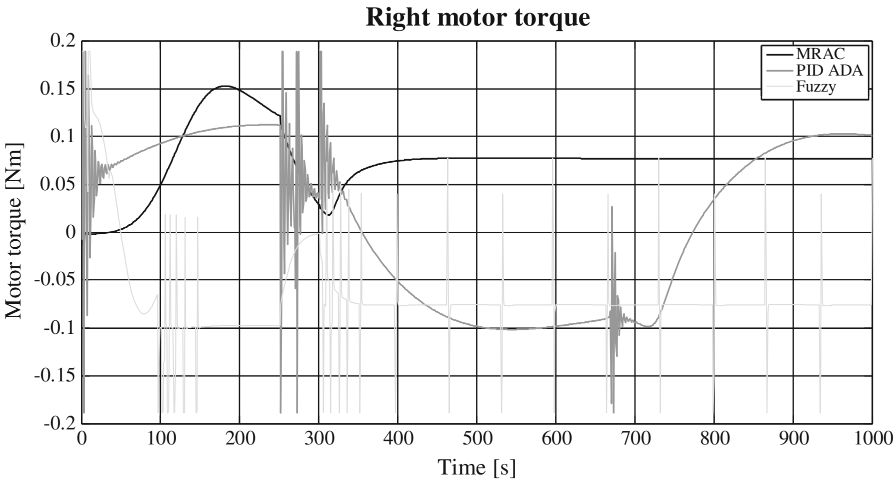


Fig. 10 Torque requirements of the right motor for each controller



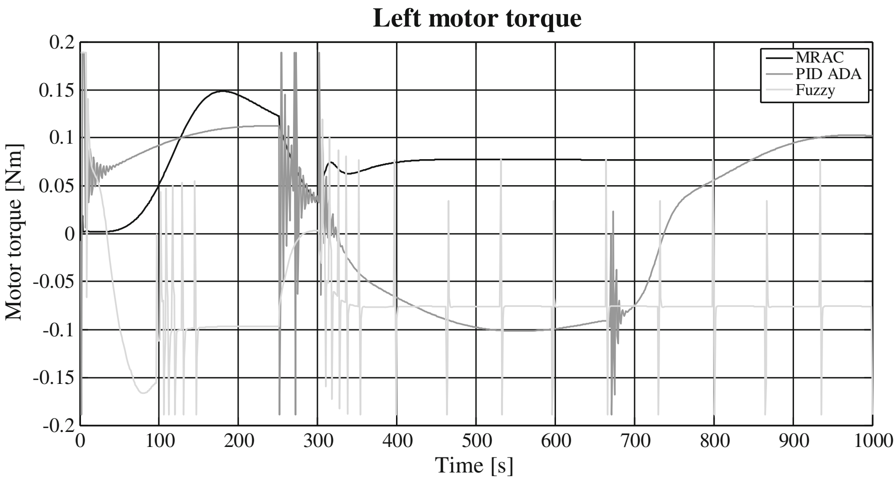


Fig. 11 Torque requirements of the left motor for each controller

process with each of the proposed controllers, considering the movements along a single row and back, since the behavior for the following rows must be the same.

This time, it is actually possible to get some conclusions from the graphics, since actuator requirements are quite different in each case. For example, we can see the high demands posed by the adaptive PID and fuzzy controllers, due to the efforts made by those controllers in the turns that the robot must make at the end of each row, turns that the MRAC controller addresses in a smooth and steady way, making it the best choice in this relation.

5 Conclusions and Future Development

Considering the quantitative results shown by the different indices, we can see that the better results were provided by the MRAC controller, although the difference with respect to the other controllers is not so significant as to discard them offhand. After reviewing the qualitative results of each controller, graphically displayed in Figs. 7, 8, and 9, we can confirm at a glance the conclusions obtained with the quantitative data. Again, however, it is not possible to define clearly which is the best option for the robot.

Nevertheless, there is an interesting point to be considered about the controllers, that is, the problem of the torques required for each motor. As we can see, the torques required for tracking the path shown in Fig. 4 are too high and demanding when using some of the controllers, as seen in Figs. 10 and 11.

Having in mind the results and the priority defined for the different evaluation methods, the best evaluated controller is the MRAC, since it shows better error indices while having tracking graphics similar to those of the other controllers. Besides, its torque requirements show smooth curves, therefore extending the life of the motors, since they work most of the time at a more stable regime.

In this work we present an evaluation of the dynamic performance of three controllers, namely adaptive PID, model reference adaptive control, and fuzzy controller, applied to a mobile robot for autonomous path tracking between rows in a plantation, starting from position control of the robot. Several tests were carried out in a simulation environment, although here we presented only the desired trajectory for path tracking in crops, which was designed and implemented using MatLab/Simulink programming tools, driving the robot to follow a desired trajectory.

As a final conclusion, we can state that the MRAC controller appeared to be the best solution for path tracking of the mobile robot, mainly thanks to the good performance it showed under similar conditions as those of the other controllers, and also because of its inherent adjustment abilities when faced with changes and

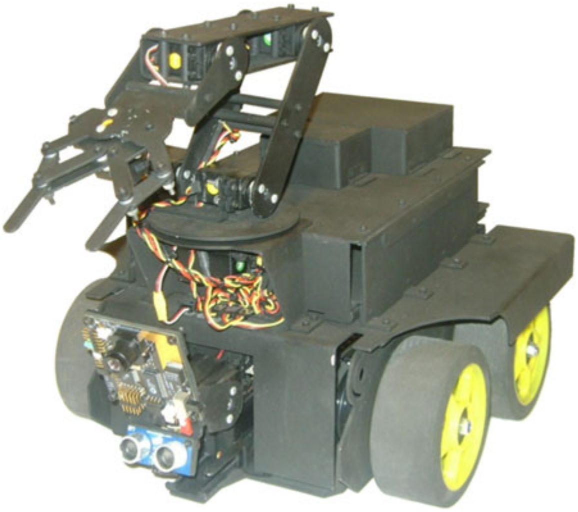


Fig. 12 DIE-USACH Mobile Robot

external influences, a very important feature when dealing with non-deterministic environments like crops.

According to the results obtained after the simulation tests, we started a stage leading to the practical implementation of the MRAC controller in an already existing, actual robot shown in Fig. 12. Currently, this mobile robot is being modified to equip it with more proprioceptive sensors that allow it to execute the control and path tracking tasks that it is expected to perform in a crop environment.

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