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# Comparison of dynamic response and stability of PID, PI-D, PD2DOF and PD fuzzy controllers on a mechanical system

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## Abstract

Automation gains ground in the industrial sector day by day as a result of the new and more efficient control algorithms, in this context, the classical theory of control is a branch of knowledge established in the scientific community, but the most widely used in the industrial field, especially due to the ease of implementing a classic controller in industrial processes, even in those where the mathematical models of the systems are unknown, for example several heuristic methods for tuning PID controllers working as regulators is a widely known activity; the next step is the modern control, which is also quite developed but still has certain areas to study such as the development of optimal predictors or dealing with systems with communication delay. Finally, intelligent control is the branch of study that generates the most interest nowadays. It tries to combine artificial intelligence techniques with automatic control. One of the most popular intelligent control methods is fuzzy control or fuzzy logic control, in this work, different classical, modern and intelligent control techniques will be implemented to a line follower robot to evaluate the performance, stability and response of each one, as well as its implementation costs.

**Keywords:** Modified PID, 2-DOF Control, Fuzzy Control, Line Follower, Simulink, Compare.

## Resumen

La automática gana terreno en el entorno industrial día a día producto de los nuevos y más eficientes algoritmos de control, en este contexto la teoría clásica de control es una rama del conocimiento ya más que asentada en la comunidad científica pero la más utilizada en el ámbito industrial, más que nada por la facilidad que se tiene en la implementación de un controlador clásico en procesos industriales, incluso en procesos donde no se conocen los modelos matemáticos de los sistemas, por ejemplo, es una tarea bastante estudiada la sintonización de un regulador PID por métodos heurísticos; el siguiente escalón es el control moderno que también está bastante desarrollado pero que todavía presenta ciertas áreas de estudio como el desarrollo de predictores óptimos o el afrontar sistemas con retardos de comunicaciones, finalmente el control inteligente es la rama de estudio que más interés genera hoy en día y que intenta combinar técnicas de inteligencia artificial con el control automático, uno de los métodos de control inteligente más populares es el control borroso o control por lógica difusa. En este trabajo se implementarán distintas técnicas de control clásicas, modernas e inteligentes a un robot seguidor de línea para evaluar el rendimiento, la estabilidad y la respuesta de cada una, además de su coste de implementación.

**Palabras Clave:** PID modificado, control 2-DOF, control borroso, seguidor de línea, Simulink, comparación.

## 1. Introduction

Having a control algorithm easy to implement, with low computational cost and with good stability against operational disturbances, is the permanent challenge of automation, within the classical control theory there are more controllers than the famous PID, some of these controllers include prediction strategies that can be expensive in terms of processing, while others can be less pricey but more complex to implement in digital systems due to their continuous behavior.

In this work, the efficiency of a common PID controller will be compared with: a PI-D controller (a variation to the general PID model), a PID controller with two degrees of freedom (PID2DOF) and a fuzzy PD control, in order to identify the strengths and weaknesses of each control technique or algorithm.

PID is the most widely applicable, studied and documented controller in industrial control applications in the world, in[1]–[4]several works that include the implementation of a PID controller are presented, among which a thermal system, a level system and an electrical power system by frequency control can be observed, cited works do not present more than 5 years since their publication, which represents their validity even in the study of certain automatic systems, in addition the variety of systems demonstrates the versatility of a PID controller to be used in systems of a different nature, in[5] and [6] two most highly cited papers including comprehensive reviews of the emergence and development of PID controllers are presented.

As previously mentioned, within classical control theory, the PID controller is the most documented and well-known, but there are techniques with certain variations with respect to the PID, which are less known, such as the PI-D control; it is a variation to the classic PID configuration, this type of controller has certain advantages such as noise or alterations elimination in the measurements of the controlled variable and can even be applied successfully in various non-linear models and therefore in real systems with some uncertainty in their dynamic. In[7]–[10]the authors present several works using the PI-D control technique, also, in[11]An effective combination of PI-D control with robust control $H_2$ is presented; In general terms, the PID control combines the fundamentals of a common PID control, with an elimination of the existing impulse or "kick" product of the derivative action; in a real PID this impulse is eliminated with a limit saturator, directly affecting the original response of the control action, a more efficient and testable way to eliminate the initial kick, without the control action being clipped, is to use a control PI-D.

Similarly, two-degrees-of-freedom controllers are modifications that can be made to a classic, modern, or even some intelligent controls; that is, it is not a unique modification of a PID controller but a modification for any single-variable control in which a second control technique is added, a PID control with two degrees of freedom can be built from a PID-PID combination with all its variations, that is, any of the two controllers can be P, PI, PD or PID, depending on the response expected to be obtained from the system. In[12] and [13]the authors present various approaches for tuning this type of controller, while in[14]– [16] several works are observed, where controllers with two degrees of freedom have been implemented, some PID 2DOF and others Fuzzy 2DOF.

The last control technique that will be used in this work will be fuzzy control of a proportionalderivative nature by the model presented by the system, which will be observed later. A fuzzy control is distinguished by the absence of a mathematical model for its design implementation, and analysis, they are controllers that seek to integrate the expert knowledge of an operator into a mathematical method of fuzzy or blurred variables. The main benefit is that their tuning is not based on the mathematical model of the system to be controlled. Since it does not have an established mathematical model, its stability and robustness cannot be demonstrated either. Which becomes its main weakness. Despite this, fuzzy controllers have been used in a wide range of jobs and applications, as shown in [17]– [22], where fuzzy or blurred controllers first appeared more than 20 years ago. [23]– [26] contain information on the evolution of these systems and their application methods.

In general, line follower robots are an experimental platform widely used in the learning of automatic control systems. in general, they are usually implemented with a PID controller. In the present work, the four control strategies mentioned previously have been tuned and implemented to evaluate their performance. Stability in a disturbed operating mode. For this reason, they will first be evaluated in a simulated way using a dynamic model presented in this same work.

Once the systems have been evaluated in the simulations, real tests will be carried out to verify the analytical results of the simulations. In order to carry out an effective evaluation of each controller, certain design and operation limits will be defined, such as the tuning time for each controller, recognizing that, in addition to obtaining the analytical parameters, a fine tuning will be sought. Another limit of operation will be the forward speed of the robot and the angle of closure of curves.

After the experimentation, it is intended to know in a solid way, the viability of implementation, of each of the aforementioned controllers, in this type of dynamic systems.

## 2. Materials and methods

### 2.1. System Model

In general, a line follower robot is a system with two inputs and one or two outputs depending on its complexity. In this case study, only the position of the robot on a navigation line or mark will be analyzed, so the system is considered with a single output. Figure 1 shows the free body diagram of the system, where and are the inputs, which, in turn, are the propulsive forces that the tires exert on the robot, a product of the friction they have with the ground.$F_I F_D$

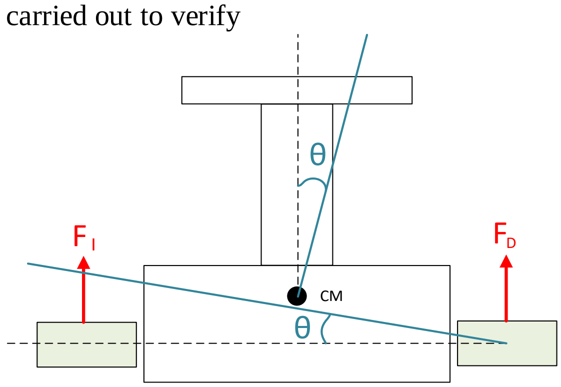


Figure1. Line follower robot free body diagram.

If a rotational analysis is performed with respect to a rotation axis perpendicular to the screen, which passes through the center of one of the tires (right tire in the image), it can be seen that the angular displacement of the robot is the output variable, with which the position of the robot can be determined with respect to the navigation mark. Since it is a rigid solid, the angular displacement at all points of the robot is the same. This angular displacement will be identical if the rotation of the robot is carried out with respect to an axis passing through the center of mass of the robot, that is:

$$\sum \tau_{CM} = I\theta'' \tag{1}$$

Where $I$ is the robot's moment of inertia with respect to its center of mass. If a coefficient B of viscous friction between the robot and the ground is considered, the differential equation of the robot is obtained:

$$xF_D - xF_I - B\theta' = I\theta'' \tag{2}$$

Where $x$ is half the total width of the robot, Equation 2 shows that the position of the robot depends on two inputs, namely, the force of the right tire and the force of the left tire. The transfer function matrix of the system, in relation to its two outputs, results in:

$$\theta(s) = \begin{bmatrix} \frac{x}{Is^2 + Bs} & -\frac{x}{Is^2 + Bs} \end{bmatrix} \begin{bmatrix} F_D \\ F_I \end{bmatrix} \tag{3}$$

As can be seen in equation 3, the transfer functions with respect to both left and right forces only differ by one sign, showing that one force will counteract the movement of the other in a symmetrical way; To obtain the model that relates the voltage applied to each motor and the output angle, only one transfer function will be used, and in the simulated model, the complete system will be implemented with two identical functions of different signs.

Equations 4 and 5 represent the electrical and mechanical behavior of a DC motor, respectively.

$$R_a i_a + L_a i_a' + k\emptyset' = v(t) \tag{4}$$

Where $k$ is the numerical constant of the motor, and are the armature resistance and inductance and $\emptyset'$ is the angular speed in $rad/s$. The input voltage of the motor will be the manipulated variable of the model, which is later regulated with the duty ratio of a PWM signal. The mechanical components of the engine are those that relate its rotational movement with the thrust force of the prototype, the characteristic equation is:

$$ki_a - B_m\emptyset' - xF_D = I_m\emptyset'' \tag{5}$$

Where $I_m$ y $B_m$ are the motor's inertia and rotational viscous friction constants. The angular displacement of the robot coincides with the length of the arc described by the tires, that is:

$$\theta L = \emptyset r \tag{6}$$

Where L is the length of the robot and r is the radius of the tires, to reduce the number of variables, the lengths are associated as $n = \frac{L}{r}$, with this expression, the model of the system due to a single motor is:

$$\frac{\theta(s)}{V(s)} = \frac{k}{as^3 + bs^2 + cs} \tag{7}$$

Where:

$$\begin{gathered} a = IL_a + I_m nL_a \\ b = BL_a + IR_a + (B_m nL_a + I_m nR_a) \\ c = BR_a + (k^2 n + B_m nR_a) \end{gathered} \tag{8}$$

Equation 7 is the transfer function that relates the angular position of the robot and the supply voltage of one of the motors, as can be seen the system has a pole at zero, for which the system will be unstable in open loop, this coincides with the logic that a motor is turned on and the robot will be freely rotating on an axis, as long as the motor does not stop. Figure 2 shows the response curves of the system to an impulse in open and closed loops with respect to the operation of a single motor.

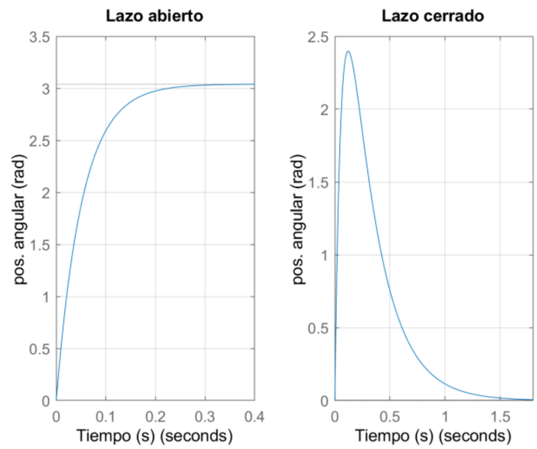


Figure 2. System responses in degrees vs. seconds

The curves shown in Figure 2 represent the impulse response of the system. It can be seen that the system is unstable in open loop, where the system stops approximately 3 radians from its initial angular position, while due to the effect of the pole at the origin, the system becomes stable in closed loop, also presenting a zero error in steady state.

The prototype that was used as an experimental platform is the one shown in Figure 3. Its most important parts are built around a lightweight black acrylic chassis, two 6V micromotors each, non-slip tires, and a 2-cell LIPO battery. The robot processor is an Arduino nano. A TB6612FNG controller was used to control the motors and a QRT-8RC infrared sensor array.

## 2.2. Actual model

Figure 3. Experimental prototype.

Table 1 shows the physical characteristics of the experimental robot.

Table 1: Characteristics of the line follower robot.

| **Characteristic** | **Unit value)** |
|---|---|
| Mass (m) | 186 $g$ |

| | |
|---|---|
| Inertia (I) | $4.86x10^{-5}\ Kgm^2$ |
| cte viscose (B) | $1.8x10^{-5}\ Kg/s$ |
| Length(L) | $13\ cm$ |
| Tire radius (r) | $2.2\ cm$ |
| Width ()$\boldsymbol{2x}$ | $15\ cm$ |

With the data in Table 1, it is possible to obtain the general model of the system based on the propulsive forces, and as mentioned, to determine the model based on the voltage applied to the motors, the parameters of these are needed, which are those shown in Table 2.

Table 2: Micromotor characteristics.

| **Characteristic** | **Unit value)** |
|---|---|
| Voltage | $6\ V$ |
| Speed ()$\emptyset'$ | $3300\ RPM$ |
| Pair | $0.17\ Kg * cm$ |
| $\boldsymbol{R_a}$ | $5.1\ \Omega$ |
| $\boldsymbol{L_a}$ | $0.6\ mH$ |
| motor inertia | $3.44x10^{-5}\ Kgm^2$ |

With the data from Tables 1 and 2, the model has been built in Simulink to obtain the first comparison responses. Figure 4 shows the model that corresponds to the movement of the robot with the two operating tires. Figure 5 shows the response to an ON-OFF controller that has been implemented solely to validate the system model, which will later serve as the basis for the implementation of the different controllers to be evaluated.

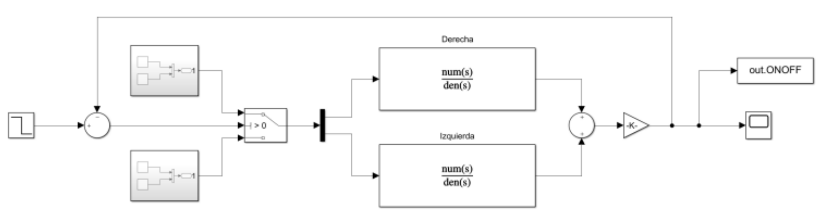


Figure 4. Line follower robot model, ON-OFF control.

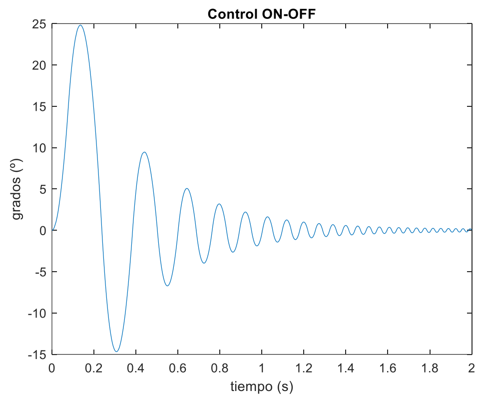


Figure 5. System response with an ON-OFF control.

In Figure 5, the system could stabilize with a ripple around the set point with the usual oscillation of an ON-OFF control. This in reality could only occur at low speeds. If the speed is high, the measurement of the angle The robot's position cannot be measured beyond 18° in each direction of rotation (maximum range of the sensor). That is, if an angle exceeds this value, the robot will automatically become unstable.

## 23. PD control

As both the open-loop and closed-loop system models have a pole at zero, the integral component would not be needed to control the system. The value of the PD control gains was obtained first with the Ziegler-Nichols for underdamped systems. Finer tuning was done later. As the system is digital, it is convenient to adjust a discrete controller in the form:

$$U(z) = \frac{(k_p + k_d)z - kd}{z} E(z) \tag{9}$$

Where the gains that yielded the best results in the simulation were $k_p = 0.016$ and $k_d = 0.0014$, these values will be verified later with the experimental test.

The PD control is tuned for a single motor and combined in the complete model, i.e., the same PD control will operate for both tires of the robot with no signs changed. To combine the control of both tires in the system, it is operated in a similar way as ON-OFF control. That is, when the robot moves to the left, the right wheel must increase its speed to compensate for the error and the left wheel reduces its speed. Both effects are carried out depending on the control action provided by the controller. When the movement of the robot is generated for the right side, the operation will be inverse. This principle will be used for all the controllers to be compared. The model implemented with the PD control results as shown in Figure 6.

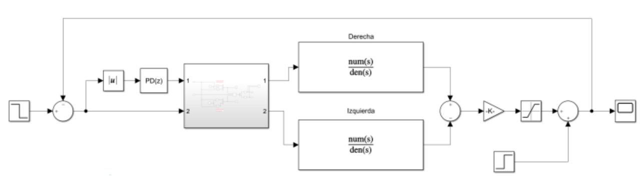


Figure 6. PD control applied to the two-wheel system.

When simulating the system, there are no inconveniences when combining the continuous model with the discrete control, because the controller output becomes continuous with a zero-order retainer. In the real model, the control is implemented on a microprocessor, so it must necessarily be in its discrete form. The sampling time for all controllers will be set to maintain consistency in the comparison.

To test the stability and dynamics of each controller, the response of a single motor to a non-null input will be verified first, and second, the two-wheel system will be tested with a null set point, which is what is intended in the line follower robot. Additionally, disturbances will be added to both sides of the system, simulating curves, to observe the response of the control systems and their output actions.

The response curves are shown later in Figures 14 and 15.

### 2.4. PI-D control

As mentioned, the PI-D control tries to eliminate the initial "kick" of the regular PID controller. As in the previous case, the integral stage will not be considered, so the controller will be P-D. In general, it is a poorly documented configuration because lower performance is expected, at least in response time, than that obtained with PID control.

Figure 7 shows the implementation of the PD controller for the operation of a single motor, the difference is that the derivative gain acts on the variation of the controllable variable but not on the error value. This prevents the error from being generated. The initial impulse in the controller is due to a transient of the reference point or setpoint.

The value of the gains is tuned using the gains of the PD controller as a starting point, then a fine adjustment is made through simulation to try to obtain the best possible result. The gains that gave the best result are: $k_p = 0.016$ and $k_d = 0.0021$.

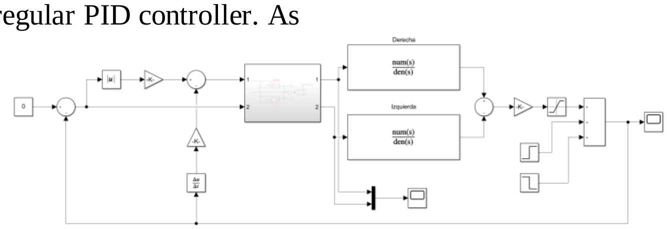


Figure 7. PD control applied to the two-wheel system.

The discrete model of the controller is:

$$U(z) = k_p E(z) - k_d (1 - z^{-1}) Y(z) \qquad (10)$$

If equation 10 is reduced, it can be shown that P-D control (in this case) is equivalent in closed loop to PD control, but with the removal of the initial impulse, which in turn generates saturation problems in the actuators.

In Figures 14 and 15, the response curves of the system can be observed, first when using the model of a single motor and second, the response curve of the complete system before certain test disturbances.

### 2.5. 2DOG PD Control

The control with two degrees of freedom was developed with the intention of generating a better response of a system before ramp and parabola inputs of the setpoint. It has also been shown that it is more robust against disturbances than a regular PID control; the output of the system with closed-loop control in the event of any disturbance has the form:

$$Y(s) = \frac{k_p s A(s)}{sB(s) + k_p(\alpha s^2 + \beta s + \gamma)} D(s) \qquad (11)$$

Where: $A(s)$ and $B(s)$ represent the numerator and denominator of the system model, respectively, $\alpha,\ \beta$ and $\gamma$ represent the combined gains of the two controllers, which form the two-degree-of-freedom control. This characteristic form shows that, because of zero at the origin, the system will always approach zero as time approaches infinity.

For the tuning of the PD 2DOF regulator, two analytical steps are carried out and subsequently a fine adjustment is made; in the first place, it seeks to satisfy the need to eliminate the error in the stable state for disturbances or variable inputs, for which the reference value is assumed to be zero and the combined controller is assumed to have the form of a regular PID. Under the established assumptions and with the form of the first controller, the zeros that manage to eliminate the error in the stable state of the system are sought under design considerations such as the stabilization time and the maximum over peak. Once the constants of the desired poles have been identified, these become the coefficients of the numerator polynomial of the general controller, whereupon the second tuning step is to obtain the gains of each controller individually. Figure 8 shows the architecture of the PD2DOF controller.

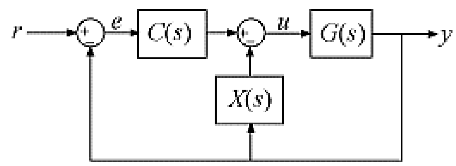


Figure 8. Feedback architecture of a 2DOF PID controller.

The discrete-time architecture is maintained and the expression of each controller is:

$$C(z) = bk_p + \frac{k_i}{(1 - z^{-1})} + ck_d(1 - z^{-1})$$
$$X(z) = (1 - b)k_p + (1 - c)k_d(1 - z^{-1}) \quad (12)$$

It is worth noting that the controller $X(z)$ has a PD configuration, this is true for most systems with one pole at the origin, it can also be represented in a two degrees of freedom controller in a single expression as:

$$U(z) = k_p(br - y) + \frac{k_i(r - y)}{(1 - z^{-1})} + (cr - 1)k_d(1 - z^{-1}) \quad (13)$$

More detailed information on expressions 12 and 13 can be found in[27].

The adjusted gains for the PD2DOF controller are $k_p = 0.017, k_d = 0.00235$while the compensation constants are $b = 1$ and $c = 0.808$. According to the fine adjustment, these constants are the ones that gave the best results, something important to note is that the gains of the PD controller coincide quite a lot with the gains of the PD-2DOF controller, varying the compensation constants, another important fact to highlight is that Due to the value of the offset constant $b$, the controller $X(z)$has a purely derivative architecture. The model implemented for checking the controller is shown in Figure 9.

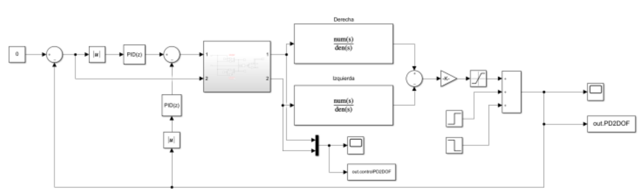


Figure 9. 2DOF PID control applied to the two-wheel system.

The response curves are shown in Figures 14 and 15.

### 2.6. PD Blur Control

As mentioned in the introduction, fuzzy control does not use the system model nor does it have a formal mathematical representation that seeks to satisfy tuning. Its implementation arises from interpreting human knowledge through linguistic labels and membership functions. To generate a PD control using fuzzy rules, the same variables that a PD regulator needs should have been used, that is, the error and the derivative of the error. A monovariable controller was built to maintain the same line of analysis and interpretation. Subsequently, it was adapted to the two-wheel system as explained in section 2.3.

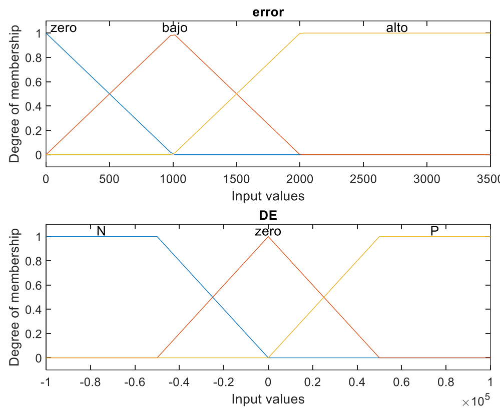


Figure 10. Fuzzy sets and linguistic labels of the variables: error and error derivative.

For the exposed controller, three input sets were generated, with their respective linguistic labels, for each input variable $e(t)$ and $\frac{de(t)}{dt}$, as can be seen in Figure 10.

From Figure 10, it should be mentioned that the error is only considered positive. To set the control to the two-wheel model, the operation of each tire is considered independently. The derivative of the error is if it has negative values, since the change if could give in a negative way, even if the error is only positive.

Furthermore, the output sets were defined as shown in Figure 11.

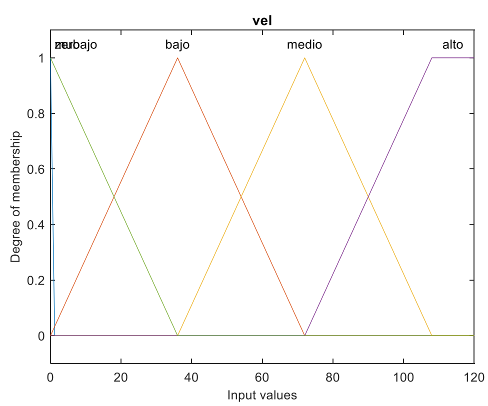


Figure 11. Fuzzy sets and linguistic labels of the output variable. (Control Action).$u(t)$

In Figure 11 it cannot be seen clearly, so the existence of a "singleton" set of value 0 must be pointed out, which is necessary so that the control action is annulled when there is no error. The fuzzy controller is by far the most complicated to tune. When you do not have the necessary experience, because there is no mathematical formulation or standardized procedure for its optimization, the only way to interpret a correct tuning is with the heuristic method of try and failure.

The definition of rules for the sets shown in Figures 10 and 11 that yielded the best results generates the control surface shown in Figure 12.

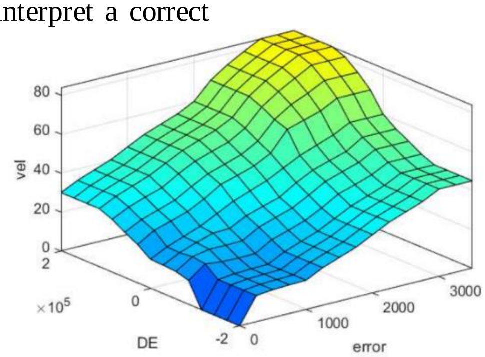


Figure 12. Blurred PD controller control surface.

It can be seen in Figure 12, that the control surface is non-linear at certain operating points, but in general it maintains a symmetry as linear as possible in response to changes in the input variables. The control results were not the best, as will be seen in Figures 14 and 15.

The test pattern for the fuzzy PD controller is shown in Figure 13.

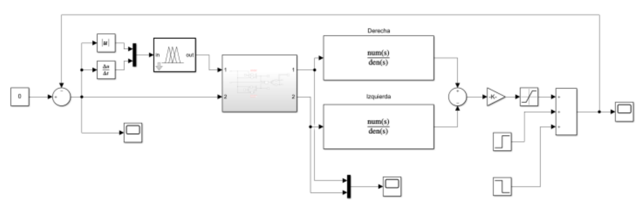


Figure 13. Fuzzy PD control applied to the two-wheel system.

## 3. Analysis and Results

### 3.1. Analytical Results

Once the different control techniques have been tuned, the responses they generate from the system will be observed, to examine the differences, benefits and limitations of each one, in Figure 14 the response curves of the loop closed system can be seen, applying PD, P-D y PD 2DOF controllers, fuzzy control PD is not included because it would require a re-tune of the system including a single motor.

As mentioned, the measurement range of the sensor is 18º for each side of the sensor, that is, 36º of overall angular deviation. The infrared sensor, for its part, generates values between 0 (black line under the left end of the sensor) and 7000 (black line under the right end of the sensor), that is, if the sensor returns a value of 0, the angular position of the sensor will be -18º, if the sensor returns a value of 3500, the robot will be in an angular position of 0º, that is, it is perfectly aligned with the navigation route.

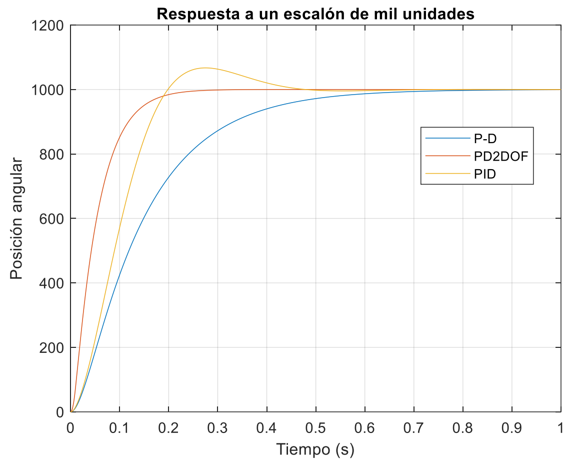


Figure 14. Response curves of the different control techniques.

Figure 14 shows the responses of the system to a step of 1000 units (5.14º approx.) under the action of the aforementioned controllers. It can be seen that the PD2DOF controller generates the best response curve in all aspects; it presents a time of lower establishment than the other techniques and does not have an overshoot, reasons that lead us to think that in practice it will be a fairly robust control. For its part, the classic PD control has a response with the largest overshoot of the three techniques under analysis, which would cause oscillation in the experimental model. Finally, the P-D control presents the slowest curve and also has a small overshoot.

The manipulable variable of the system is precisely the supply voltage that is delivered to the motors. This voltage is regulated by means of the PWM signal generated by the microprocessor, and since the resolution of the microprocessor is 8 bits, the PWM output will have a value between 0 and 255 when you want to deliver 0 or 6 volts to the motor, respectively.

Figure 15 shows the control actions of the three techniques analyzed above, where the control action of the P-D regulator is the one that least requires the actuators. The value of the control action does not even reach 10%. The PD control does not saturate the actuator but is a little more aggressive than the previous controller. While the PD2DOF control reaches the maximum of the actuator and saturates it for less than 10 milliseconds, the control of two degrees of freedom generates a negative signal at a certain moment to compensate for the movement of the motor and avoid an overshoot in the response.

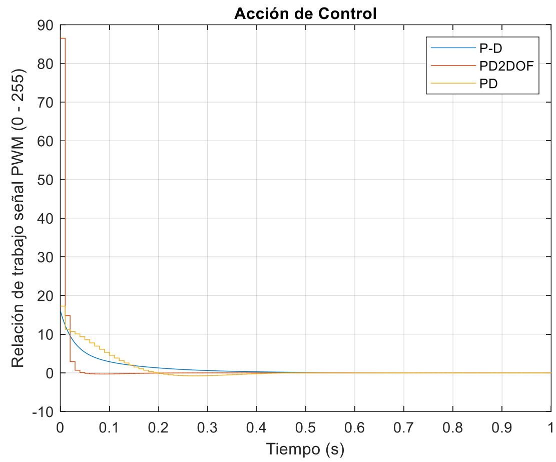


Figure 15. Response curves of the different control techniques.

Figure 16 shows the response of each system (including fuzzy control) to disturbances in the system output. These disturbances will represent curves through which the line follower robot will move. The test is carried out at a time of 4 seconds where two disturbances are generated; a positive one that generates a transient error of 2000 units (10.3º approx.) and a negative disturbance of 1500 units (-7.7º approx.) at instants 1 and 2.5 seconds respectively.

In Figure 16, it can be seen, in order of performance, that the PD2DOF controller generates the best response for the system. It presents the fastest response without any type of overshoot; the second fastest curve is that of the regular PD control; the third place is occupied by the fuzzy PD control, although with a very large oscillation; and the slowest response is that of the P-D control.

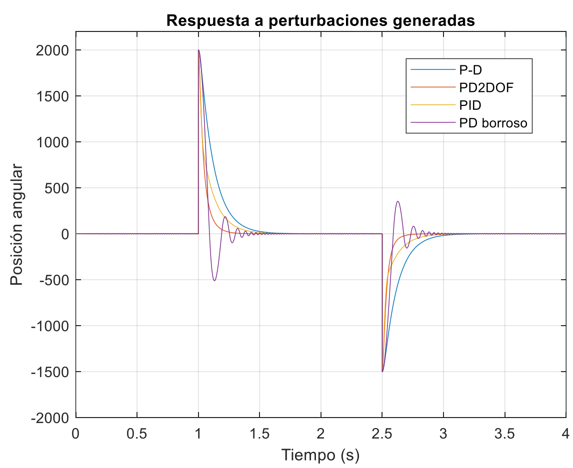


Figure 16. Response of controllers to disturbances.

As can be seen in Figure 16, the fuzzy PD control, which was the controller that took the longest to tune (without adjustment gains), does not present an adequate response. As can be seen in Figure 16, the response of the system is very oscillatory, which can lead to system instability.

Figure 17 shows the control actions generated by each analyzed strategy for the first test disturbance. From the curves, it can be concluded that the PD2DOF controller saturates the actuators for the longest time. It is obviously the one that corrects the disturbance the fastest, but it is also the strategy that consumes the most energy and the one that produces the most wear. In turn, the P-D control also saturates the actuators. the actuators but it does so in less time than the regular PD, finally, the fuzzy PD control does not saturate the actuators, but it presents a very large oscillation in its output, which also causes wear on the robot elements.

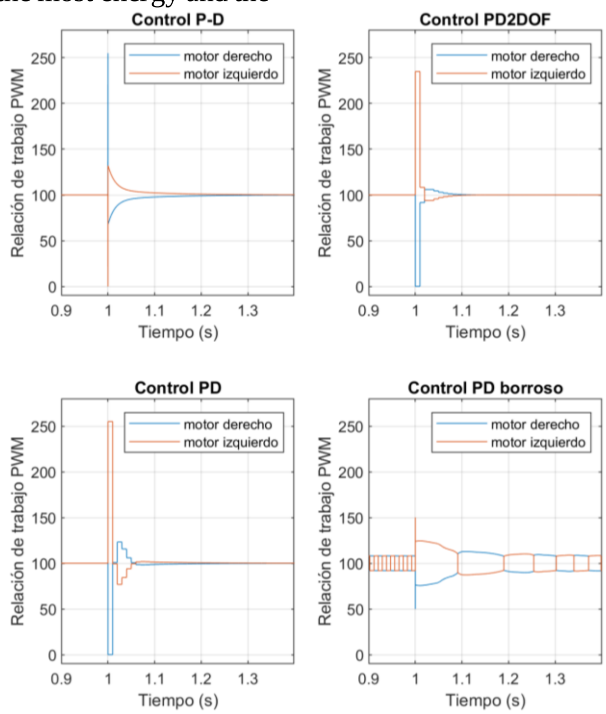


Figure 17. Control Actions.

The saturation of the actuators is similar for the PD and PD2DOF controllers, which could tip the balance towards the PD2DOF control, because it presents a faster response without having a higher energy consumption than the regular PD.

For its part, the fuzzy PD control, although it does not saturate the actuators, the control actions are much longer than any of the other techniques, and it precisely does not stabilize the system, it approximates it to a minimum error. This can be quite detrimental to the operation of the system and to the lifetime of the actuators, which will be continually subjected to a change in speed.

### 3.2. Experimental Results

To contrast and analyze the analytical results of each control strategy, each one was implemented in the line-following robot of Figure 3 and made to run along a "stadium-type" (oval) track for one exact lap, i.e., the robot traveled 2 long lines, 2 short lines, and 4 curves.

To establish the same analysis criteria, the operating parameters were maintained, such as: the base speed, the calibration of the sensors, the programming of a brake in the event of instability, and the setpoint.

Figure 18 shows the response curve (angular position) of the robot, product of the experimentation with the PD control, in addition, the control action produced by this controller during the same process is presented. Figures 19 to 21 show the same generated curves, but with the application of the different P-D, PD2DOF and fuzzy PD control techniques, respectively.

In each response curve four peaks can be visualized, these correspond to the curves that the robot had to make during its movement, in spite of these peaks; on the other hand, some curves show some oscillation around the set point (3500) and it is clearly due to the stability provided by the controller to the system.

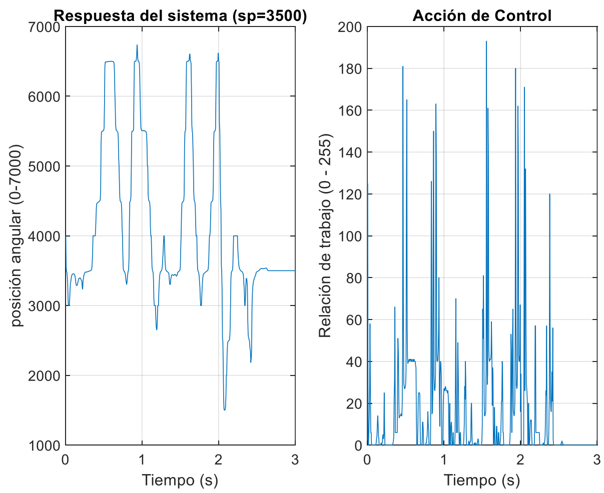


Figure 18. Response and control action of the PD regulator.

From the four response curves, it can be seen that the PD2DOF controller (Figure 20) is the control strategy that presents the fastest response; that is, it corrects the error in the shortest possible time and with the greatest linearity, unlike the rest. Of the drivers, it also has the least oscillation in the output. It can be said that the PD control is the one that generates the second-best response in terms of stability, since it is the second curve that shows the fewest oscillations around the set point.

On the other hand, both the fuzzy PD controller and the P-D control present large oscillations in their response. In addition, it should be mentioned that the P-D controller is at least one second slower than the rest of the control strategies.

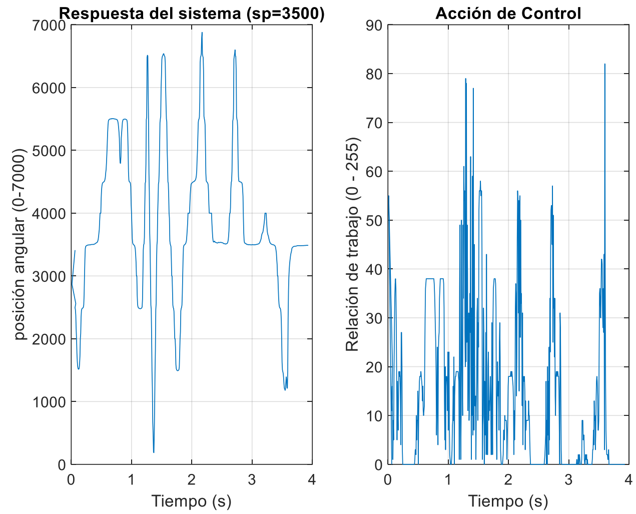


Figure 19. Response and control action of the PI-D regulator.

In terms of stability and response dynamics, the PD2DOF control takes first place in performance without a doubt. Regarding the control actions, it can be observed, in Figures 18 to 21, that the PD2DOF control generates the largest outputs; that is, it produces the greatest effort in the actuators. This response is quite logical, because it is the driver that clears the system error the fastest.

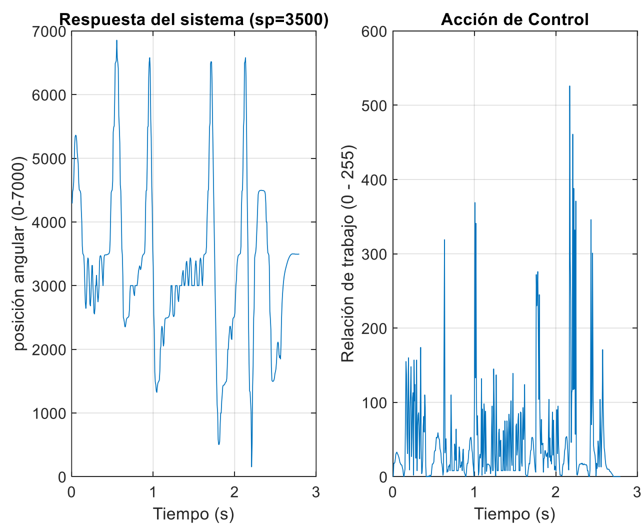


Figure 20. Response and control action of the PD2DOF regulator.

According to Figure 20, the control with two degrees of freedom has the least oscillation in its control action, which may compensate for the saturation that it causes in the actuators in terms of wear and energy consumption.

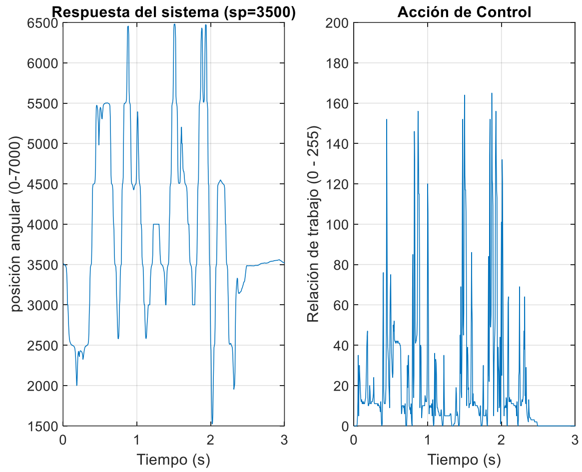


Figure 21. Response and control action of the fuzzy PD regulator

Again, the PD controller generates the second-best performance. Now speaking of control actions, this controller does not saturate its actuators at any moment of the experimentation and, in addition, it meets the test in a time similar to that of the PD2DOF controller. The P-D controller presents the most oscillating and late control actions, while the fuzzy PD control presents the smallest control actions. This means that it could be a great control alternative if the objective is to extend the life time of the actuators and reduce the energy consumption.

Apart from the results of the controlled and manipulable variables, the time it took for the line follower robot to complete the experimental lap was verified. The results are shown in Table 3.

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Table 3: Response times of each controller.

| Controller | Time (seconds) |
|---|---|
| P.S. | 2.6 |
| PI-D | 3.9 |
| PD2DOF | 2.48 |
| blurred PD | 2.42 |

As shown in Table 3, the controller that covers the track in less time is the fuzzy PD control, followed by the PD2DOF control, the PD control, and finally the P-D control, which presents a response far removed from the rest.

Under the experimentation and the demonstration that the classic PD control and the PD control with two degrees of freedom present the best response and stability characteristics, a maximum speed test was also carried out between these two control techniques; the two degrees of freedom PD control managed to lap the track in a minimum time of 2.35 seconds at a base speed of 48.6% (124) PWM signal duty ratio. On one side, the classic PD control was able to make a complete turn in a minimum time of 2.25 seconds, 10 hundredths of a second faster than with the control with two degrees of freedom, and its base speed could be increased up to 50.98% (130) of the duty ratio of the PWM signal. This result shows that any controller is not able to meet all conditions. The PD control with two degrees of freedom is more robust, faster, and maintains the system with the least error in a permanent state, but the classic PD control adapts better to changes in operation, as in this case, the base speed of movement.

## 4. Conclusions

Once the experimentation was carried out, there were several lessons learned and conclusions that were intended to contribute to the scientific and development community. First of all, it is important to mention the validity of the developed model, which presents a fairly good approximation to the real system in such a way that the tuning of the different controllers, by means of simulation software, is very similar to what you end up getting in reality.

Regarding the control systems, it is concluded that PD control with two degrees of freedom provides the best dynamic and static characteristics for the system. Its tuning depended clearly on the system model, and its fine adjustment was achieved in a short time of testing. approximately two hours. In general, its greatest weakness is the energy expenditure due to overexerting the system's actuators.

From the point of view of this research work, PD control turns out to be the second-best control strategy for a line-following robot, closely followed by fuzzy PD control. The PD control presents greater stability, but the fuzzy PD control presents higher speed and lower power consumption.

Although the P-D controlit avoids the saturation of the actuators as the theory indicates, it returns the system to a slow state, so its use is not recommended in this type of system. Its tuning took much longer than the PD control of two degrees of freedom, reaching 5 continuous hours of work. It does not support very large variations in base speed, and its oscillations are quite problematic for the stability of the system.

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