

Performance of a Simple Tuned Fuzzy Controller and a PID Controller on a DC Motor

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Abstract — We are presenting the usefulness of an innovative method called Simple Tuning Algorithm (STA) for tuning fuzzy controllers, it has only one variable to adjust to achieve the tuning goal, this in counterpart to other methods like the Proportional Integral Derivative (PID) controller which has three variables to adjust for the same goal. Comparative examples of the STA and the PID methods are presented in a speed control of a real DC gear motor application. The PID controller was tuned using the Ziegler-Nichols. In base of the obtained quantitative and qualitative measures and observations, we are concluding that the fuzzy controller performance outperformed the PID controller; moreover, the tuning process using the STA method was easier than using the Ziegler-Nichols method.

Keywords: Fuzzy Logic, Simple Tuning Algorithm, DC motor, PID.

1. Introduction

Nowadays, the quest for new controllers which provide functionality and guarantee a precise performance has led the technology into the field of Fuzzy Logic. New ways to control systems have been developed based mostly in this area of knowledge, some examples are control of DC motors [1][2], security systems [3], antilock braking systems (ABS) [4], speech enhancement [5], path planning [6][7], among others. Despite this, practical applications involving fuzzy controllers as a proved option to conventional controllers are hard to find.

One of the most popular controllers used in industrial processes is the Proportional Integral Derivative (PID) controller [8]. The real strength of this kind of controller is its simplicity to understand,

explain and implement them [9]. The main problem of using PID controllers is the effect acquired as a result of disturbances and environmental conditions on the structure of the system [10], adding complexity to the controller's design. However it is not easy to find another controller with such a simple structure to be comparable in performance.

A very important step in the use of controllers is the tuning process. In a PID controller, each mode (proportional, integral and derivative mode) has a gain to be tuned, giving as a result three variables involved in the tuning process.

On the other hand, the tuning of a fuzzy controller is a heuristic work, sometimes becomes overwhelming to find the optimal parameters necessary for a well performance of the controller; then, the use of these at industry is not so popular. Applying the STA, it is possible to facilitate the tuning process, since STA only needs the tuning factor k to do it [11]. This paper is focused on the experimental results of the simple tuned fuzzy controller of Pulse Width Modulation (PWM) applied to regulate the revolutions per minute (rpm) of a DC motor [1], see Figure 1. Then a comparison with the PID controller's performance is made.

This work is organized as follows. Section 2 introduces the description of the fuzzy model employed, with its membership functions and rules. Section 3 describes the methodology of the STA used to manipulate the settling time of the system. Section 4 describes the PID controller and its tuning process. In Section 5, the obtained results of the physical experimentation with both controllers are presented. Finally, in Section 6 we have the conclusion.

2. Fuzzy Model Description

The fuzzy controller consists of 25 rules based on five fuzzy regions. This design considers the speed error and the change of the error as the input sets. The output is the duty cycle of the PWM signal sent to the power stage so the desired no-load speed is reached. Table I shows the controller fuzzy variables employed.

Figures 1, 2, 3 and 4 show the membership functions of the error input variable, the change of error input variable, the duty cycle output variable and the control surface of the fuzzy controller, respectively, under their initial conditions before applying the STA. The fuzzy associative memory, integrated by 25 rules, is shown in Table II.

TABLE I
FUZZY CONTROLLER'S VARIABLES.

Input variables		Output variable
Error	Error change	Control Action (Duty Cycle)
NB: Negative Big N: Negative Z: Zero P: Positive PB: Positive Big	NB: Negative Big N: Negative Z: Zero P: Positive PB: Positive Big	BD: Big Decrease D: Decrease H: Hold I: Increase BI: Big Increase

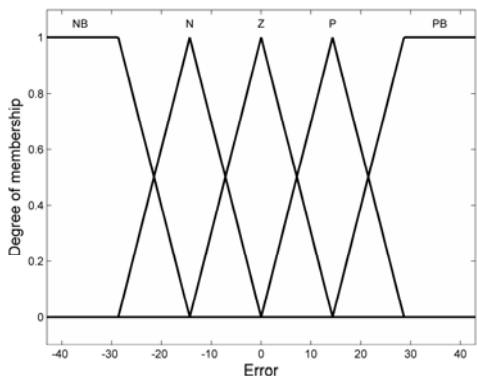


Figure 1. Membership functions of the error input variable.

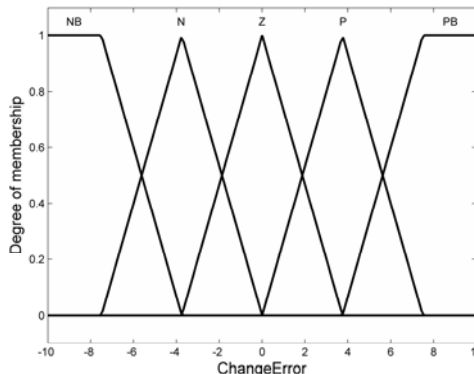


Figure 2. Membership functions of the change of error input variable.

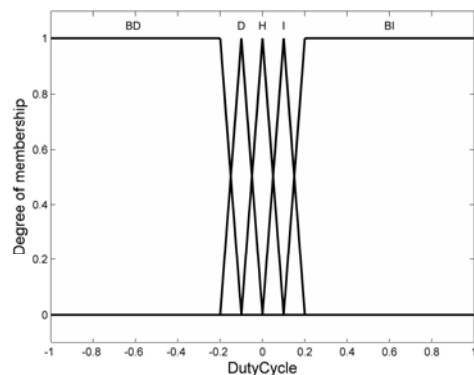


Figure 3. Membership functions of the duty cycle output variable

3. Simple Tuning Algorithm (STA) for a Fuzzy Controller.

In the implementation of a fuzzy controller is necessary to consider many parameters to compute, like, number and ranges of membership functions, rules, shapes, percentages of overlap, etc. [12]. The algorithm implemented in this system was proposed by Eduardo Gómez Ramírez in [11]. It is based on the properties of the control surface, allowing the modification of the controller's behavior by means of manipulating the ranges of the membership functions of the input variables, and it only implies a single variable (instead of a PID controller, which needs to find at least three parameters for tuning). The membership functions of the output fuzzy variable remain constant.

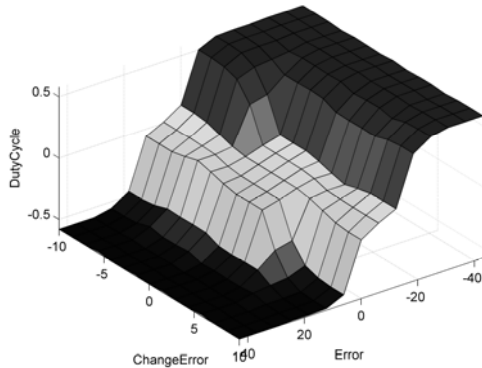


Figure 4. Control surface of the fuzzy controller.

TABLE II
FUZZY ASSOCIATIVE MEMORY FOR THE CONTROL SYSTEM.

ce	e	NB	N	Z	P	PB
NB		BI	BI	I	D	BD
N		BI	I	H	H	BD
Z		BI	I	H	D	BD
P		BI	H	H	D	BD
PB		BI	I	D	BD	BD

Experiments were made with the STA in an application of controlling the no-load speed of a real DC gear motor. The goal of the experiments was to manipulate the settling time of the system. The method consists basically in four steps:

- 1. Tuning Factor Selection.** A number $k \in [0,1]$ is used to define the tuning adjustment level. $k = 0$ is the biggest settling time and $k = 1$ the smallest.
- 2. Normalization of the ranges of the Fuzzy Controller's variables.** The range of each input fuzzy variable is modified in order to have the lower and upper limits equal to -1 and +1, respectively.
- 3. Tuning Factor Processing.** Once the range is normalized, the new vector of operation points will be given by:

$$Vop_{final} = (Vop_{initial})^{r(k)} \quad (1)$$

Where $Vop_{initial}$ are the normalized values of the membership functions in the x-axis and $r(k)$ is the polynomial:

$$r(k) = \frac{30k^3 + 37k^2 + 52k + 1}{40} \quad (2)$$

- 4. Renormalization of the ranges of the fuzzy variables.** Convert the normalized range to the previous range of the system. This can be computed only multiplying the Vop vector by a constant factor.

4. PID Controller

In the industry, PID controllers are the most common control methodology to use in real applications. Fundamentally, it is composed of three basic control actions (see Table III). They are simple to implement and they provide good performance.

The tuning process of the gains of PID controllers can be complex because is iterative: first, it is necessary to tune the "Proportional" mode, then the "Integral", and then add the "Derivative" mode to stabilize the overshoot, then add more "Proportional", and so on.

TABLE III
BASIC CONTROL ACTIONS.

Proportional Control	$u(t) = K_p e(t)$
Integral Control	$u(t) = K_i \int_0^t e(t) dt$
Derivative Control	$u(t) = K_d \frac{d}{dt} e(t)$

a) Controller description

The PID controller has the following form in the time domain [8]

$$u(t) = K_p \left[e(t) + T_d \frac{de(t)}{dt} + \frac{1}{T_i} \int_0^t e(\tau) d\tau \right] \quad (3)$$

where $e(t)$ is the system error (difference between the reference input and the system output), $u(t)$ the control

variable, K_p the proportional gain, T_d the derivative time constant and T_i the integral time constant. Equation (3) can also be written as

$$u(t) = K_p e(t) + K_d \frac{de(t)}{dt} + K_i \int_0^t e(\tau) d\tau \quad (4)$$

where $K_d = K_p T_d$ and $K_i = K_p / T_i$. Each coefficient of the PID controller adds some special characteristics to the output response of the system. Because of this, choosing the right parameters becomes a crucial decision for putting into practice this controller. The effects of these parameters on the output response of the system are shown in Table IV.

b) *Control objective*

A PID controller does not "know" the correct output to bring the system to the setpoint. It moves the output in the direction which should move the process toward the setpoint and needs to have feedback (measurements) to perform.

TABLE IV
EFFECTS OF THE GAINS IN THE RESPONSE OF THE SYSTEM.

Gain	Raise time	Overshoot	Settling time	Steady-State error
K_p	Dec	Inc	—	Dec
K_d	Inc	Dec	Dec	—
K_i	Dec	Inc	Inc	Zero
Inc = Increases — Dec=Decreases				

The objective of the PID controller is to ensure that the DC motor reaches a desired velocity. For this, a velocity-error, denoted by $e(t) \in \mathfrak{R}$, is defined as

$$e(t) = v(t) - v_d(t) \quad (5)$$

where $v_d(t) \in \mathfrak{R}$ denotes the desired velocity for the DC motor.

c) *PID Tuning Process — The Ziegler-Nichols of closed loop method*

Controller tuning involves the selection of the best values of the gains of K_p , K_i and K_d of the PID control law. This is often a subjective procedure and is

certainly process dependent. A number of methods have been proposed in the literature over the last 50 years [13].

Then tuning a PID algorithm, generally the aim is to match some preconceived 'ideal' response profile for the closed loop system. Many algorithms have been developed to guarantee the best performance of the PID controller. We used the Ziegler-Nichols method to optimize the parameters of the proportional (P), integral (I), and derivative (D) modes of the PID controller.

The Ziegler-Nichols method tunes the gains of the PID law of control. This algorithm can be described by the following steps:

- Set the controller to P mode only.
- Set the gain of the controller (K_p) to a small value.
- Make a small setpoint change and observe the response of the controlled variable.
- Increase K_p by a factor of two and make another small change in the setpoint.
- Keep increasing K_p (by a factor of two) until the response becomes oscillatory.
- Find the period between oscillations.
- Apply the criteria of Table V for the other parameters of the controller.

The control law settings are then obtained adjusting the controller's parameters according to Table V, considering Ku as the final value of K_p and Pu as the period of the oscillations. When the load and the noise in the system is zero, K_p should be a high value in order to ensure that the process output is close to the desired setpoint. If exists noise in the system, K_p should be moderate or the system will be too sensitive to noise. Obviously the setting of K_p is a balance between stability, noise sensitivity and load regulation [14].

TABLE V
ZIEGLER-NICHOLS PARAMETERS ADJUSTMENTS.

Control Action	K_p	K_i	K_d
P	$Ku/2$		
PI	$Ku/2.2$	$Pu/1.2$	
PID	$Ku/1.7$	$Pu/2$	$Pu/8$

5. Experiments and Results

a) Application description

In order to measure the behavior of the controller's output over the DC motor application, the model of both controllers was designed in Simulink[®] of Matlab[®] (see Figures 5 and 6).

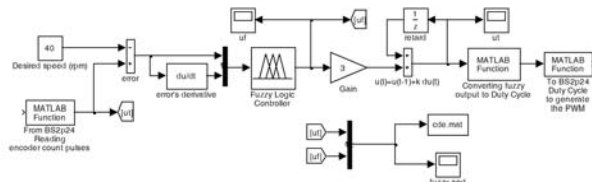


Figure 5. Simulink[®] system model for the fuzzy controller.

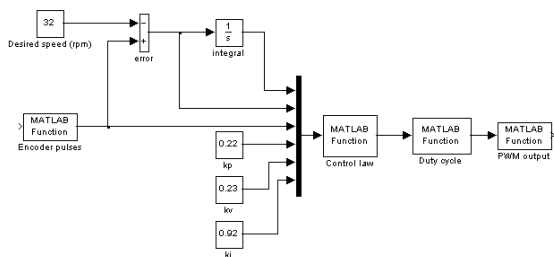


Figure 6. Simulink[®] system model for the PID controller.

b) Optimal tuning factor k test for the fuzzy controller using the STA

Following the STA [11], the first step is the selection of the tuning factor k , which defines the slope adjustment for the membership functions. For the DC motor it is necessary a value near to $k = 1$, since the smallest settling time is desired. Therefore, previous to comparison with the PID controller, several runs were made for different values of k , taking the DC motor's no-load speed from 0 to 32 rpm.

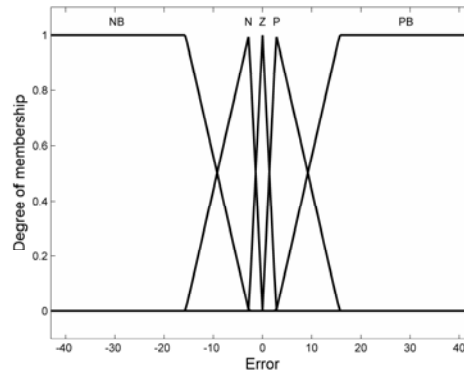


Figure 7. Membership functions of the error with $k = 0.91$.

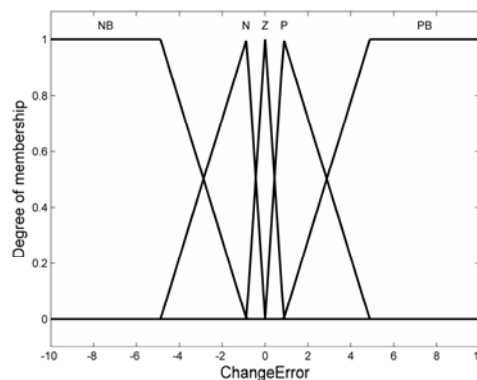


Figure 8. Membership functions for change of error with $k = 0.91$.

The intention is to find an optimal tuning factor k considering these premises:

1. The system needs sensitivity to disturbances and the smallest settling time. This happens at the nearest k values to 1.
2. The optimal k is the one that makes the fuzzy controller to reach the no-load speed target in the minimum time with a smooth curve.
3. The controller reaches the target till the fuzzy controller input change of error is minor than $\delta = 0.001$.

Under these premises, the simulation ran for $k = 0.5$ to $k = 1$ with steps of 0.01, rejecting values of $k < 0.5$ because of premise 1. The experiments results show that the optimal value of k is $k = 0.91$. The settling time for $k = 0.91$ it is around 200 ms, and the system response presents a smooth curve. The effect in the membership functions of each input value and the control surface are shown in Figures 7, 8, 9, respectively.

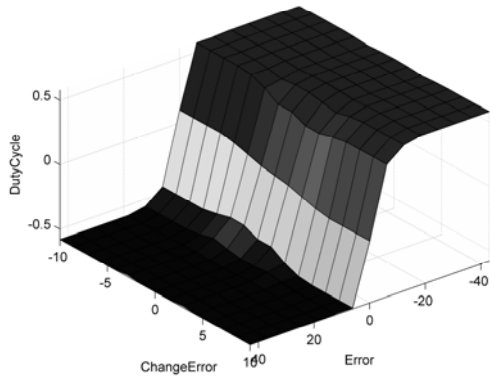


Figure 9. Control surface for the fuzzy controller for $k = 0.91$.

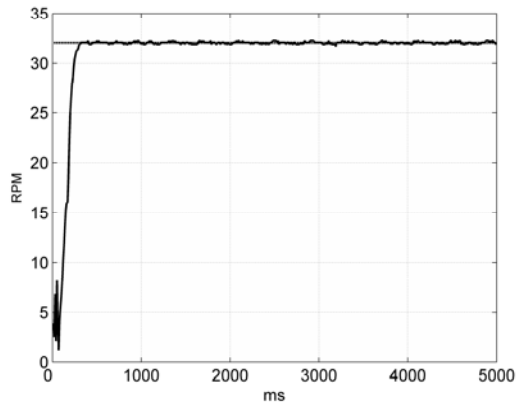


Figure 10. System response with the Simple Tuned Fuzzy controller.

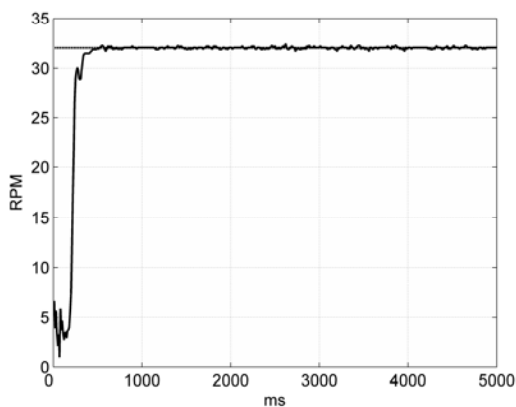


Figure 11. System response with the PID controller.

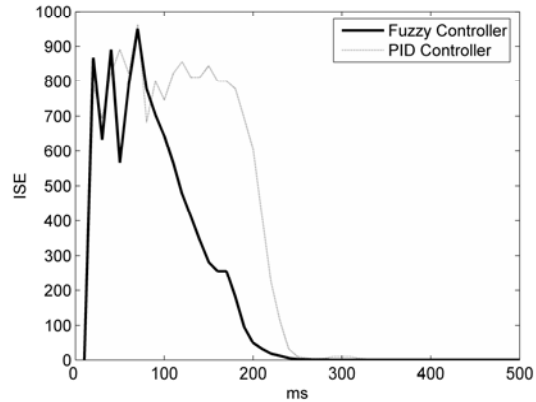


Figure 12. An ISE comparison for both controllers, note the graph shows only till 400 ms for a better appreciation of the differences of each ISE values.

c) PID controller tuning results

For the PID, several experiments were made in order to tune the optimal values of K_p , K_i and K_d of the controller.

The experimental values for K_u and P_u respectively were 0.374 and 1.84. Applying the Ziegler-Nichols criteria of Table V, the optimized tuned values of K_p , K_i and K_d of the PID controller are shown in Table VI.

TABLE VI
ZIEGLER-NICHOLS PARAMETERS ADJUSTMENTS OF THE PID CONTROLLER FOR THE EXPERIMENTS.

Control Action	Kp	Ki	Kd
P	0.187		
PI	0.170	1.533	
PID	0.22	0.920	0.230

d) Comparison of results

As mentioned before, the optimal tuning factor is $k = 0.91$, according to physical experimentation. The system response of the fuzzy controller is shown in Figure 10.

For the PID, the target is reached also around 200 ms. The system response is shown in Figure 11.

In order to compare the results about the performance of both controllers in discussion, an Integral Square Error (ISE) performance criteria is applied to the experimental results obtained. For the PID controller, the ISE is 15834, and for the fuzzy controller is 9818. Figure 12 shows the ISE graph of each controller.

6. Conclusions

The tuning process of the fuzzy controller applying the STA falls into making a decision about the tuning factor k . *The adequate selection of the k value is necessary to obtain the desired settling time for the system.*

The tuning of the PID controller implies an iterative method of finding the appropriated value for the proportional gain of a reduced model in P mode, when this gain of the simplified model of the PID controller has been found, it is necessary to change to a PD mode, and then compute the integral gain. The process should be repeated until the full tuning of the PID controller has been achieved.

In the development of this application was easier to tune the fuzzy controller using the STA compared with the tuning of the PID controller because the STA needs only to adjust one parameter. Contrary to this, the PID controller needs an entire iterative process to find the better constant values for the proportional, integral and derivative mode to provide a good performance.

According the results, it is remarkable that the use of fuzzy controllers tuned with the STA can be considered as a viable and efficient technology to substitute PID controllers in real control applications.

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