Design and implementation of fuzzy-PI and fuzzy-PID controllers for an electronic underdamped system

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***Abstract*—This paper presents the design of two fuzzy controllers: a fuzzy-PID and a fuzzy-PI, in order to present basic strategies involving fuzzy control systems. The controllers were designed based on the identified model of a underdamped electronic system, using the look-up table method. When the controllers presented a satisfactory response in computational environment regarding the established requirements, a experimental test was made with each controller. These systems were implemented to work with the real physical system and in adverse conditions. The experimental results showed that the fuzzy-PID controller was unable to control the system in a non-ideal practical scenario, while the fuzzy-PI control was capable of control it with the desires specifications. To conclude, the fuzzy-PID and fuzzy-PI controllers proved to be good and interesting alternatives to their linear conventional counterparts, due to characteristics such as non-linearity and a higher number of tunable parameters.**

***Index Terms*—Applied control, fuzzy control, PID control, underdamped electronic system**

I. Introduction

Fuzzy systems theory gives the necessary tools to incorporate, in a systematic manner, the human logic into systems that help in the decision-making process, are capable of control and supervise other systems, along a lot of other possibilities [1]. Fuzzy systems quickly became a important topic in control theory, providing the control engineers solutions to control complex and nonlinear plants based on a set of IF-THEN rules [1], [2].

Maybe the most simple structures that can be studied when doing the transition from traditional and linear control to fuzzy control are the fuzzy-PID controllers. They can be seen as a bridge between the well-known Proportional-Integral-Derivative (PID) control to fuzzy control theory, since these fuzzy controllers provide different possible configurations that explore the new possibilities due to the addition of the fuzzy logic, but also share the same basic properties of PID controllers (like null steady-state error due to integral action) [1]–[3].

Based on the previous comments, this paper shows the design of two fuzzy control systems, a fuzzy-PID controller and a fuzzy-PI controller, in order to demonstrate the basic steps needed when designing this kind of system. Both the controllers were tested in a computational environment and then were applied in a real electronic underdamped system, used as a study object in this work.

The layout of this paper is as follows. Section II describes the studied system and the control problem that needs to be solved. Section III presents the design of the fuzzy-controllers, providing also a theoretical background about fuzzy-PID control. Section IV presents the results obtained after the experimental tests. Finally, section V presents some conclusions about the carried out study.

II. Study Object Description and Problem Definition

An underdamped electronic plant was designed in order to be used as a study object for this paper, with its schematics being shown in Fig. 1 and the assembled system in Fig. 2. To apply an input signal to the system and sample the output signal, an Arduino UNO was used. The control systems were designed using MATLAB, along with the DaqDuino software [4] , which is used to establish a connection between MATLAB and the Arduino UNO, so the control algorithm can be applied.

The dynamical model of the system was identified using the Recursive Least Squares (RLS) estimator, so the following AutoRegressive with eXogenous inputs (ARX) model could be obtained (the sampling time used was $0.004\ s$):

$$G\left(z\right) = \frac{0.01931z^{-2} + 0.0182z^{-3}}{1 - 1.90z^{-1} + 0.55z^{-2} + 0.79z^{-3} - 0.40z^{-4}} \tag{1}$$

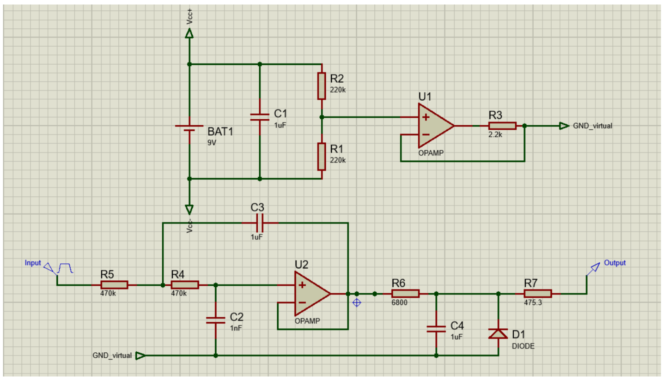

Fig. 1. Underdamped electronic system designed.

Fig. 3 shows the comparison between the step response of the identified model and the experimental data collected in

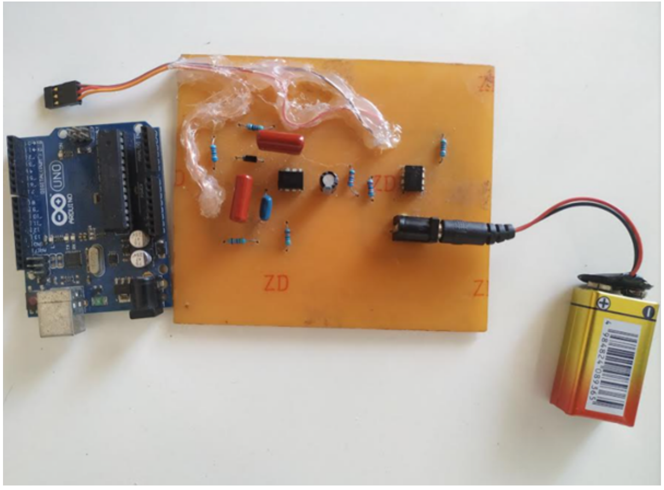

Fig. 2. Designed PCB alongside the Arduino UNO.

the validation process. The calculated coefficient of determination, R^2, was equal 0.9478, which is adequate for many practical applications involving systems identification [5].

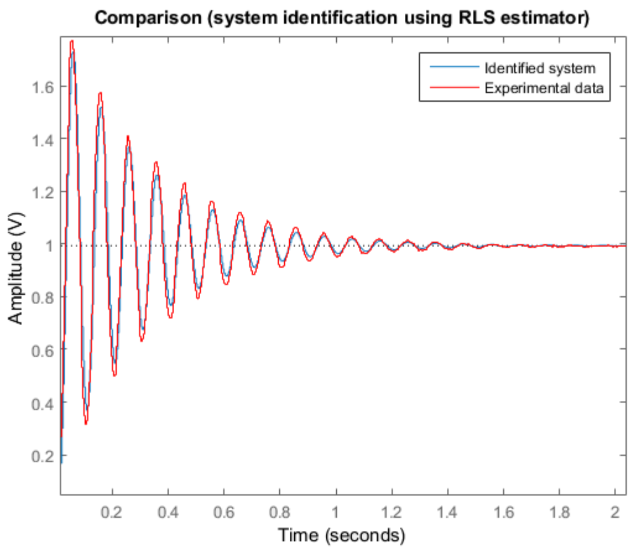

Fig. 3. Comparison between experimental data and the step response of the identified model.

The design of the fuzzy controllers were based in the presented identified model, so the systems could be further tested with the real electronic plant. The project's requirements that must be attended by these controllers were defined as:

- The closed-loop system must track a step reference;
- It must have a null steady-state error;
- The oscillations in the system's output must be dumped, having a maximum overshoot of 5%;
- The settling time of the system must be equal or less than $1\ s$ (considering the 5% criteria);
- The control signal must be limited between $[0, 5]\ V$ when a step between $[0, 4]\ V$ is applied to the closed-loop system.

The following section describes the methodology used to project the fuzzy controllers that fulfill the defined criteria.

III. Design of the fuzzy-PID and fuzzy-PI controllers

A. Theoretical background

PID control is the one where the controller performs the operations of gain, integration and differentiation on the error signal, given by the reference signal minus the system's output [6]. Its description in the continuous-time domain is given by the following equation:

$$u(t) = K_p \cdot e(t) + K_d \cdot \frac{d\left[e(t)\right]}{dt} + K_i \cdot \int_0^{\infty} e(\tau)\, d\tau \qquad (2)$$

Where $u(t)$ is the output of the controller, $e(t)$ is the error signal, K_p is the proportional gain, K_d is the derivative gain and K_i is the integral gain. In the discrete time domain, the PID controller, considering a sampling time T_s, is describe as follows:

$$u[k] = K_p \cdot e[k] + K_d \cdot \frac{e[k] - e[k-1]}{T_s} + T_s \cdot K_i \cdot \left(\sum_{n=1}^{k} e[n] \right) \qquad (3)$$

The PID controllers can benefit when fuzzy logic is incorporated in its structure, since it will give the controllers specific characteristics, like adaptability and non-linearity [2]. The fuzzy-PID controllers can be divided in three main categories [1], [7], [8]:

- **Fuzzy gain scheduling type**: a fuzzy system is projected to adjust the gains of the PID according to some criteria, giving the controller adaptive capabilities;
- **Direct action type**: the fuzzy system emulates the PID controller's operation using IF-THEN rules. Since fuzzy systems are non-linear systems, this results in a non-linear controller;
- **Hybrid type**: It combines the fuzzy system with linear structures. For example: a PID with its Proportional-Derivative (PD) part being a fuzzy system and its integral part being a linear integrator. Suming the output of these systems, the PID controller will be in the I+PD form, but with part of it functioning through fuzzy logic.

In this paper, the controllers synthesized were both direct action type. The structure of the fuzzy-PID was the PI+PD one, where the controller is composed by two fuzzy-systems: a fuzzy-PD part and a fuzzy-PI part [9]. The fuzzy-PI controller is composed only by the fuzzy-PI part, excluding the fuzzy-PD one.

Both controllers take, as input, the error signal, $e[k]$, and the variation of the error signal, $\Delta e[k]$. The block diagram of the fuzzy-PID in question is shown in Fig. 4. In the block diagram, GE is the gain of the first input of the fuzzy system (the error signal); GCE is the gain of the second input (the error signal variation); GU is the gain of the fuzzy-PD system's output; GCU is the gain of the fuzzy-PI system's output.

For the fuzzy-PI system, the following relations apply [9]:

$$GCE \cdot GCU \propto K_p \qquad (4)$$

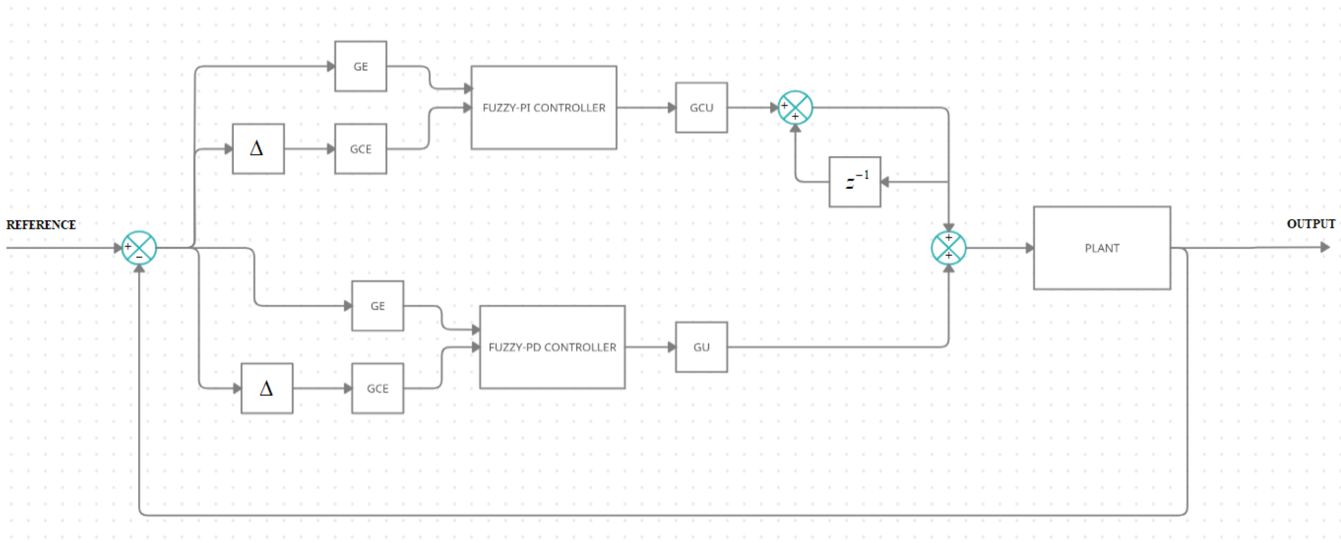

Fig. 4. Block diagram of a fuzzy-PID controller (PI+PD structure).

$$GE \cdot GCU \propto K_i \tag{5}$$

Meanwhile, for the fuzzy-PD system, we have:

$$GE \cdot GU \propto K_p \tag{6}$$

$$GCE \cdot GU \propto K_d \tag{7}$$

Relations (4) to (7) translate the gains of the fuzzy-PID controller in terms of the classical PID controller, in order to show the effects of each gain in the response of the closed-loop system. Notice that the fuzzy-PI and the fuzzy-PD systems can have different gains for each output, giving the designer more degrees of freedom to tune the controller.

It is also important to highlight that besides the gains GE, GCE, GU and GCU, other properties of fuzzy systems greatly increase the degrees of freedon available to tune the controller: the types of membership function used; the considered universe of discourse of the fuzzy sets; the number of IF-THEN rules; the type of fuzzy inference engine being used; among other factors [2].

B. Design of the fuzzy-PI and fuzzy-PD systems

The fuzzy-PI and fuzzy-PD systems were designed as the same fuzzy system, since we can adjust the integral or derivative action through the external input and output gains. Thus, they will have the sames fuzzifier, fuzzy inference engine, defuzzifier and the same set of rules IF-THEN.

The IF-THEN rules chosen were based on [9]–[11], which presents a look-up table for a fuzzy-PI/fuzzy-PD system with $e[k]$ and $\Delta e[k]$ inputs. For the controllers proposed here, the IF-THEN rules are summarized by the look-up table illustrated in Fig. 5, where "P" means positive; "N" means negative; "Z" means zero; "PB" is positive big; "PM" is positive medium; "NB" is negative big; and "NM" is negative medium.

All the membership functions are triangular for both the inputs and the outputs. The universe of discourse for the input variables were all equal to $U = [4; -4]$. The interval was

$e[k]$ \ $\Delta e[k]$	**N**	**Z**	**P**
N	**NB**	**NM**	**NM**
Z	**NB**	**Z**	**PB**
P	**PM**	**PM**	**PB**

Fig. 5. Look-up table for the designed fuzzy system.

defined based on the characteristics of the electronic plant: it has linear behaviour only for inputs between $[0; 4]\ V$, and the input of the system is always within this interval. Thus, the maximum absolute value of the error signal or its variation is always equal or less than $4\ V$ or $4\ V/s$. For the output of the fuzzy system, the same universe of discourse was adopted to simplify the design process. Fig. 6 and Fig. 7 illustrate the membership functions plot for the error signal input and the output, respectively. The plot for the variation of the error signal will be the same as the one shown in Fig. 6.

Regarding the fuzzy inference system, its t-norm and implication method were product type, its s-norm was the maximum type and its defuzzification method was the center average type. With these information, the fuzzy system is defined, and the PID system can be tuned (adjusting its gains) and simulated in computational environment.

C. Computational simulation

The fuzzy-PID and the fuzzy-PI controllers were tuned through trial and error. For the fuzzy-PID controller, the following gains were found: $GE_{PD} = GE_{PI} = 0.05$,

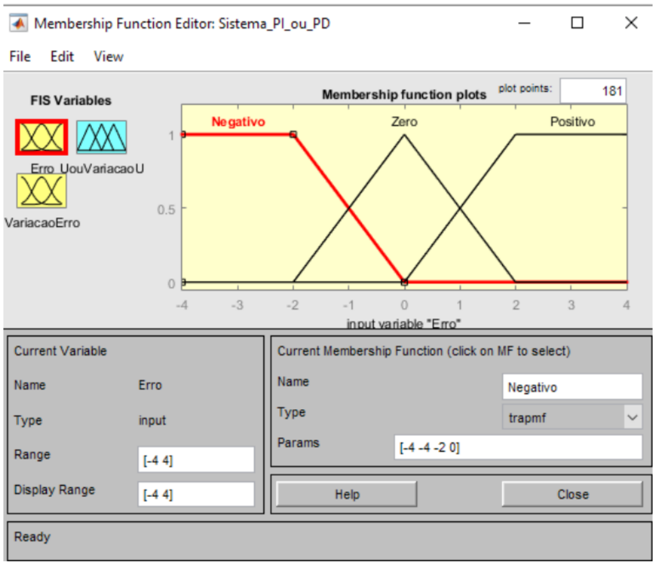

Fig. 6. Membership functions plot for the input of the fuzzy system related to the error signal.

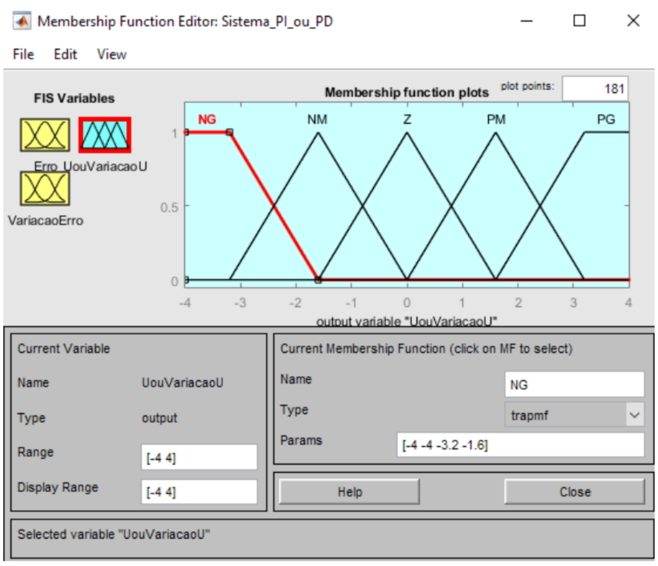

Fig. 7. Membership functions plot for the output of the fuzzy system.

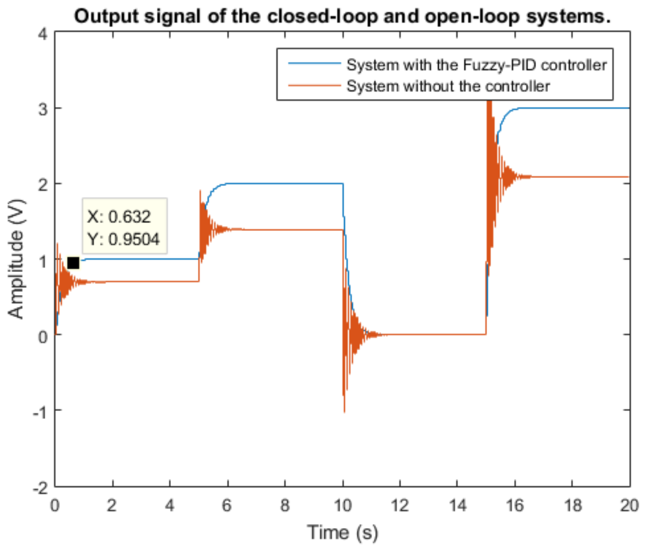

Fig. 8. Output of the computational model with and without the fuzzy-PID controller.

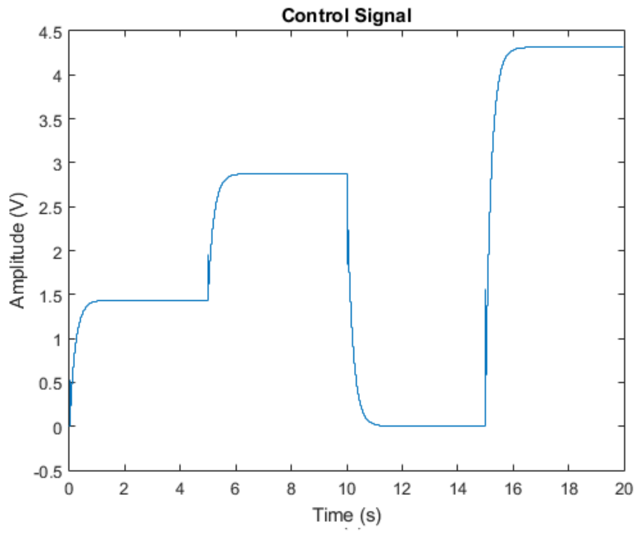

Fig. 9. Control signal of the fuzzy-PID controller.

$GCE_{PD} = 0.3$, $GCE_{PI} = 0.01$ and $GU = GCU = 1$ (the subscript indicates if the input gain is related to the fuzzy-PI or fuzzy-PD part). The identified model was given, in the computational environment, a static gain of $0.7\ V/V$, in order to evaluate the integral action of the closed-loop systems (which results in null steady-state error [3]).

The output of this system in closed-loop, simulated in MATLAB, is shown in Fig. 8. The control signal of this fuzzy controller is shown in Fig. 9. The fuzzy-PID controller generated a smooth output for the closed-loop system, but also had spikes in the control signal. Both these effects are well-known characteristics of the derivative action, which causes the presence of a impulse in when the system suffer a set-poin transition [6]. This effect, called *derivative kick*, can be suppressed with the usage of a derivative filter, for example, which limits the bandwidth of the derivative part [3], [6]. This topic, however, is out of the scope of this work.

The fuzzy-PI controller was synthesized by maintaining the gains of the fuzzy-PID controller, but removing the fuzzy-PD system. The output of the plant in closed-loop with this controller is shown in Fig. 10, and its control signal in Fig. 11. A zoom-in was made in Fig. 10 to give a better visualization of the transitory response in this case, resulting in Fig. 12.

It is possible to notice that the control signal has no longer any kind of spikes, but the transitory response is not as good as before, having more oscillations. This output response reinforces the effects of the derivative part of a PID controller, and shows that the fuzzy-PID controller really emulate its effects.

From the simulations, it is possible to conclude that both controllers attended the established project requirements. With the design procedure finished, the controllers can now be tested in the real electronic plant.

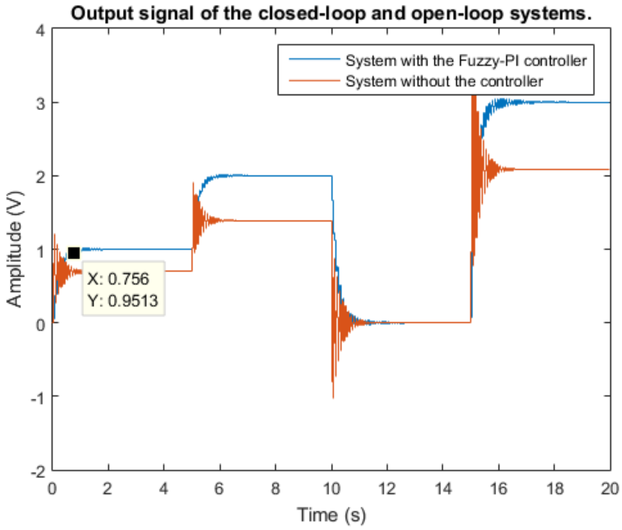

Fig. 10. Output of the computational model with and without the fuzzy-PI controller.

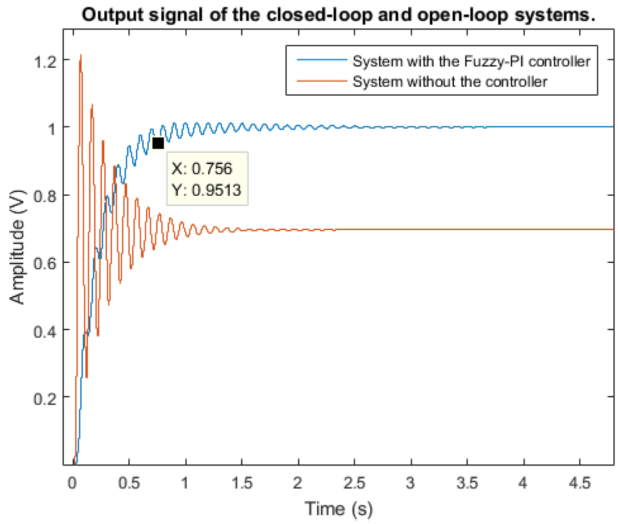

Fig. 12. Zoom-in made in the transitory response of Fig. 10.

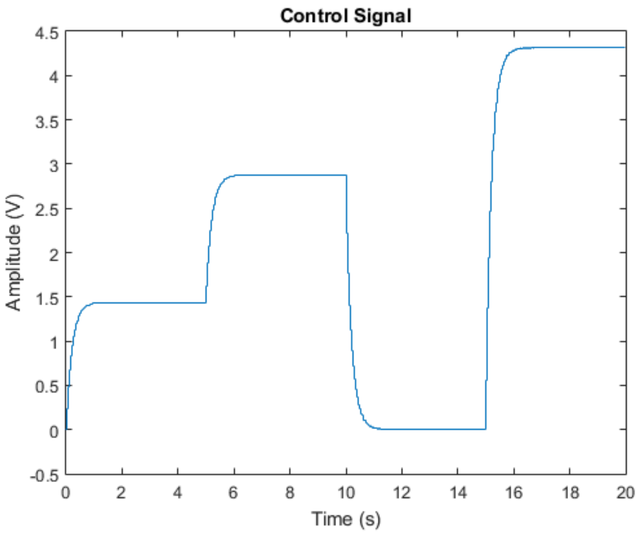

Fig. 11. Control signal of the fuzzy-PI controller.

IV. Experimental tests

The experimental setup available had two non-ideal characteristics: the presence of measurement noise in the underdamped electronic system; and the mismatch between the sampling time used to identify the computational model and the sampling time that the DaqDuino could reach. This latter problem is due to a limitation between the serial connection of the Arduino UNO and the computer, which provides a minimum stable sampling period of $0.1\ s$ for the DaqDuino. It must also be highlighted that the system does not have the modified static gain used in the simulation environment, though this should not cause great impact in the experimental procedure.

Fig. 13 and Fig. 14 show the experimental output of the closed-loop system with the fuzzy-PID controller and the control signal obtained, respectively. Evaluating its response, one can affirm that this controller failed to control the plant in an adequate way. This happened probably because the derivative action could not handle the noise presented in the system, which is a well-known effect [6]. The differences between the conditions simulated and the real conditions regarding the sampling time must also had a negative effect in the controller's performance.

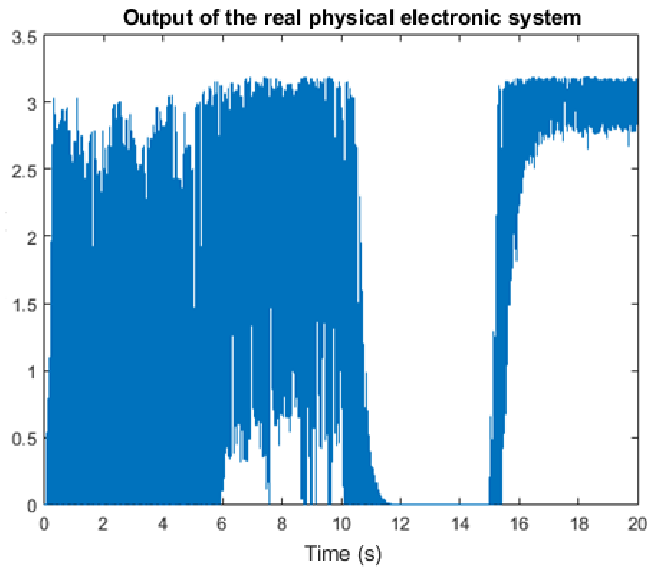

Fig. 13. Output of the electronic system in closed-loop with the fuzzy-PID controller.

Fig. 15 and Fig. 16 show the experimental output of the closed-loop system with the fuzzy-PI controller and the control signal obtained, respectively. In this case, the controller was able to perform the desired task, working even on adverse conditions. The transitory response, although not the same as in the simulation environment, presented the desired characteristics regarding the project requirements.

To end this section, it must be noticed that the adversities in the experimental procedure should be seen as a good thing: in the real world, the systems have unmodeled dynamics, the sensors used can be very noisy and the AD/DA conversion system can present some kind of problem. All these non-idealities exist in the experimental setup used, providing the information that the fuzzy-PI controller, in this case, is

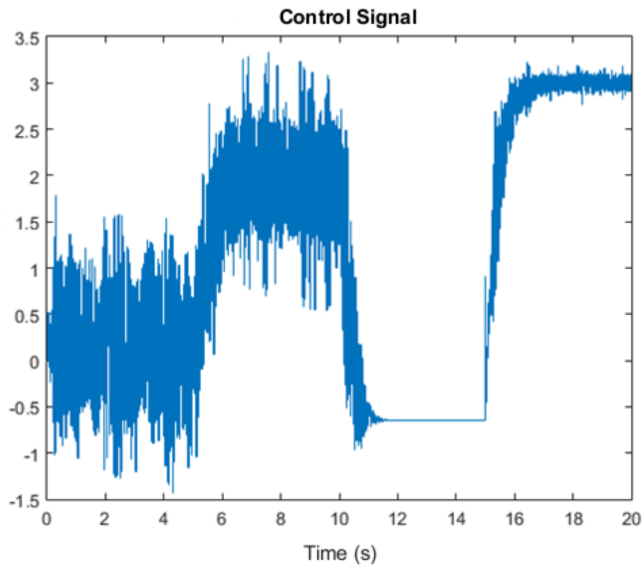

Fig. 14. Experimental control signal for the fuzzy-PID controller.

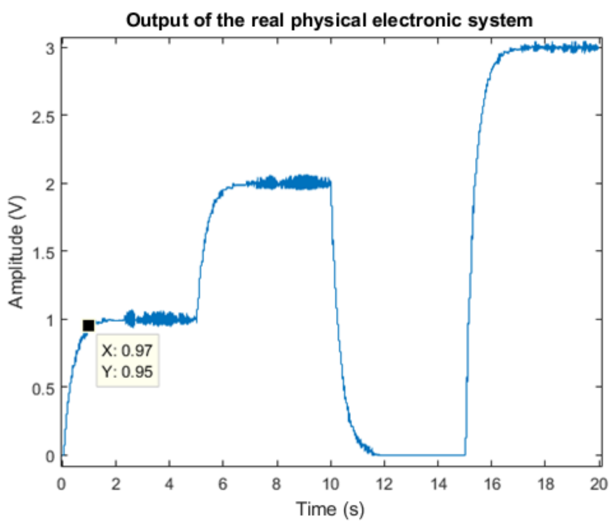

Fig. 15. Output of the electronic system in closed-loop with the fuzzy-PI controller.

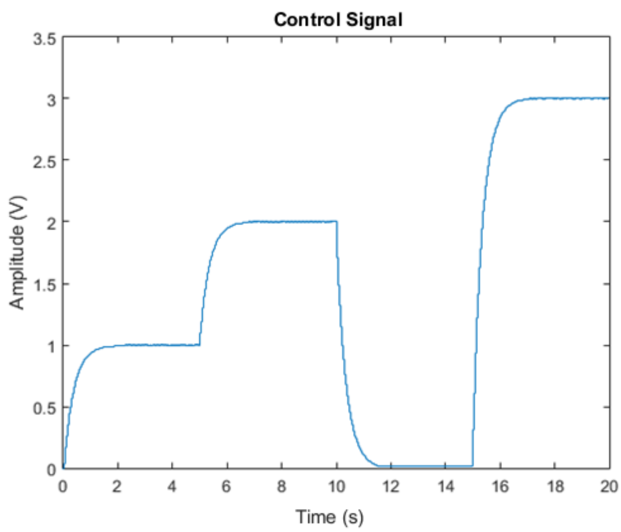

Fig. 16. Experimental control signal for the fuzzy-PI controller.

more reliable. This kind of information can help the control engineer in the next necessary steps to improve a specific design.

V. Conclusion

This paper described the design procedure to obtain a fuzzy-PID and a fuzzy-PI controller. Although the systems presented a good response in the simulation environment, with the fuzzy-PID controller having a more well-behaved control signal, the experimental results showed that, in a practical scenario, this system is not as robust as the fuzzy-PI controller (with the latter working even with non-ideal conditions).

The structures adopted for the fuzzy controllers, although simple, give a lot more liberty to the designer when compared to the conventional PID controller, since it has a significantly higher number of adjustable parameters. These systems are also non-linear, which expands the range of possible applications for more complex problems.

To conclude, the fuzzy-PID and fuzzy-PI controllers proved to be a good alternative to their linear and conventional counterparts. The relation between the gains in the two cases provided a good initial understanding on the principles of fuzzy control, being a useful study topic to those who have a solid base in linear control theory, but seek to better understand and apply non-linear control techniques involving fuzzy systems.

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