DESIGN ISSUES AND LABORATORY EXPERIMENTS IN FUZZY PID CONTROL TEACHING

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Abstract ¾ *This article presents a proposal of how the graphical user interface composed of MATLAB, SIMULINK and the Fuzzy Logic and Real-Time Toolboxes could be used to develop an easy and integrated environment to design and simulate fuzzy logic controllers. Some approaches regarding fuzzy logic controllers are shown and tested in a real laboratory, by means of non-linear and minimal phase process, as a fan-and-plate model. It is suggested that these experiments could be used to inspire real-life implementations of fuzzy logic controllers, thereby motivating graduate and undergraduate students, to employ that technique, which is becoming increasingly popular and important in a great range of applications.*

Key Words : Fuzzy control, PID control, self-adaptive control, intelligent control.

1. Introduction

The availability of practical control activities in teaching control techniques has been considered as an important requisite to provide students with real-life implementations (Kheir et al., 1996). The practical engineering education must be based not only on simulated experiments but also on realistic laboratory trialing (Zilouchian, 1992). As industrial processes are becoming more complex and demanding**,** a higher flexibility concerning the variation of parameter specifications combined with low cost-benefit ratios is needed. In this way, courses in control processes must consider not only conventional techniques but also advanced procedures such as self-tuning, adaptive, predictive and soft computing (Åström and Lundh, 1991, Simas et al., 1998). Among other conventional control methods, the

Proportional-Integral-Derivative (PID) controllers have found wide acceptance and applications in the industry for the past few decades (Åström and Wittenmark, 1989), mainly because of its simplicity and robustness. Among recent soft computing techniques, the fuzzy control has been the most widely used in industrial processes, particularly where conventional control design techniques are difficult to apply (Coelho et al., 1998a). Experiments in control engineering, based on computational tools and laboratory prototyping provide a good basis for understanding the theoretical contents of that techniques (Almeida et al., 1999a, Zilouchian, 1992). Software packages such as MATLAB/SIMULINK with Control, Fuzzy and Real-Time toolboxes have been used as good options to conventional and non conventional control teaching (Wilkinson, 1997, Al-Sumi, 1997). Pertinent design issues must be organized synchronously regarding lecturing and theoretical exercises.

In this paper, the PID controller design and the fuzzy PID controller approach combined in a nonlinear practical laboratory scale process called fan-and-plate (Almeida et al., 1999b). Control design methodologies are: PID controller as a conventional technique and Fuzzy PID controller as a non conventional technique. The fuzzy PID approaches are: fuzzy PI-plus-conventional D controller (FPI+Dc), fuzzy PD-plus-conventional I controller (FD+Ic), fuzzy PD-plus-fuzzy I controller (FPD+FI) and fuzzy PI-plus-fuzzy PD controller (FPI+PD), (Golub, 1998, Liu, 1997, Qin, 1994, Yeger, 1994, Ying, 1993, Kowk, 1990, Malk, 1997, Li, 1995, Li, 1997, Coelho, 1998a). The main reason for justifying this issue is that the vast majority of industrial controllers are of the PID type. The fuzzy PID controller can be tuned based on PID settling. The design of fuzzy controllers for teaching is important as an emergent technology for application in industry, to balance theoretical and practical exercises.

This paper is organized as follows. The description of fan-and-plate process and the detection of the nonlinear characteristic of the process are presented in section 2, followed in section 3 by the fuzzy control approaches. Sections 4 and 5 contain some experimental results and conclusions, respectively .

2. Description of the process

A fan-and-plate prototypical process designed at the Department of Automation and Systems (DAS/CTC/UFSC) was used to implement the fuzzy PID control algorithms. Further information of the process is available in Simas et al. (1998) and in http://lwww.lcmi.ufsc.br/lcp/. The fan-and-plate control system represented in figure 1 is composed of a fan driven by a DC motor, a 50 cm long air duct with funneling characteristics, having on its left extremity a small rectangular plate. The 24 volts DC motor is driven by an actuator circuit whose input is compatible with the D/A converter output. The angular deflection of the plate is measured by a photoconductive cell (light from led that passes through a disk painted with varying shades, from white to black, whose incidence on a photo element will cause it to change its conductive properties) and connected to the measurement circuit. The control problem is to regulate the angular deflection of the plate (controlled variable) actuating on the input voltage of the DC motor (manipulated variable). The distance between fan-and-plate can be changed and defines an important parameter of the system. The prototype, containing non-minimum phase, dead time, resonant and turbulent disturbance behavior, can serve as tangible evidence of the usefulness of self-tuning, predictive and fuzzy control techniques in difficult situations.

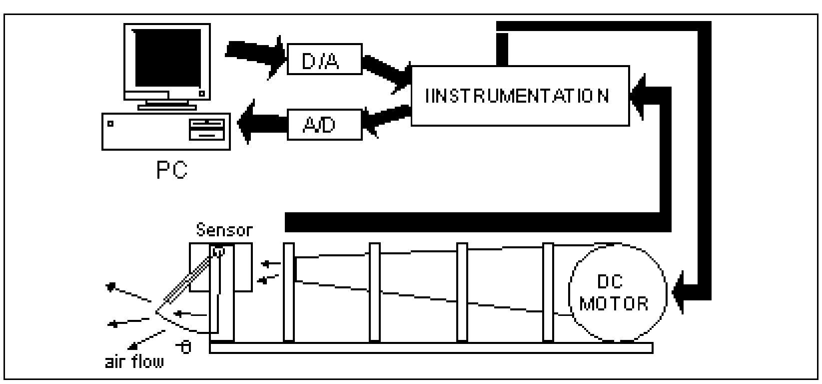

Figure 1. Fan-and-plate process in laboratory

3 Fuzzy Control Toolbox

The MATLAB Fuzzy logic toolbox and SIMULINK were used to implement the fuzzy PID approaches. The MATLAB Fuzzy logic toolbox is a powerful interactive environment that allows the users create and prototype fuzzy inference systems by hand, using either graphical interface tools or command-line functions. SIMULINK is a simulation tool that runs alongside MATLAB. By using the SIMULINK toolbox the fuzzy system can be run in a block diagram simulation environment. Using DLL files and S-functions developed based on target hardware, MATLAB, SIMULINK and Fuzzy Logic Toolbox were enabled to perform real time simulations.

Figure 2 shows the MATLAB integrated environment, where the user can create his or her own tools to customize the fuzzy toolbox or connect it with another toolbox in real time.

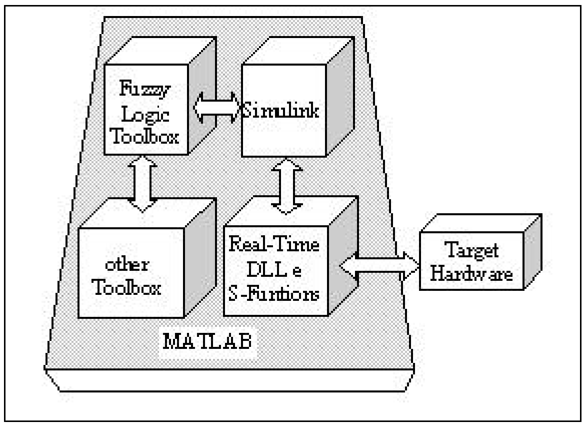

Figure 2. Computational framework used with the fan-and-plate process

The real time DLL was developed with Borland C++ 4.0 compiler and CMEX-files. The SIMULINK *CAD* and *CDA* blocks were built using real time DLL, m-files and S-functions. The system obtained is completely open and with minimal changes can be adapted to any other target hardware. The MATLAB environment configured with these utilities prove itself a powerful tool for teaching fuzzy logic control, both in theory and practice.

4 Fuzzy PID Control Approaches

The fuzzy PID control approaches are implemented as sequential experiments.

4.1 Conventional PID Controller

The aim of conventional PID controller design is to provide some insight in the problems of fuzzy scale determination. Ziegler and Nichols (Coelho et al., 1998b) have developed simple tuning rules to find the PID controller parameters based on the step response of the open-loop (reaction method) or closed-loop (oscillation method) systems (conventional methodology). In order to implement a PID control, three parameters (K_p, T_i and T_d) must be set for a given process. Normally, the gains need on-line retuning if the process presents a poor performance due to plant parameter variations or non-linearities. Sometimes, it is difficult to find an appropriate set of control parameters that ensures stabilization when there are setpoint and/or load change (Coelho et al., 1998b). Auto-tuning methods have been proposed to overcome these problems. For example, in the method given by Åström and Wittenmark (1989), a limit cycle oscillation is imposed on the process to be controlled by a relay with suitable amplitude values and hysteresis. Thus, angular frequency and critical values of gain can be found from the amplitude and frequency outputs of the resulting process with controlled oscillation. The discrete PID control Law is given by

$$u(k) = K_p e(k) + K_i ie(k) + K_d de(k) \quad (1)$$

where $e(k)$ is the error, $de(k)=(e(k)-e(k-1))/T$ is the change of error and $ie(k)=ie(k-1)+Te(k-1)$ is the numerically approximated integral of error.

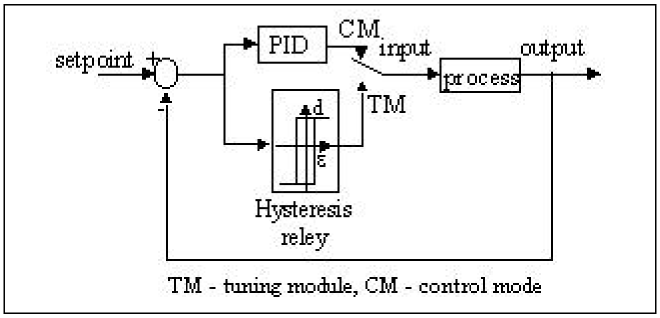

Figure 3. Auto-tuning *PID* controller.

The PID tuning parameters (K_p, K_i and K_d) can be determined by automatic rules that account for phase and amplitude margins specifications (Almeida and Coelho, 1999b) and using the relay feedback experiment, figure 3. The control scheme is simple from **a** computational viewpoint, is easy to be understood by process operators, and can be supervised by the user.

4.2 Fuzzy Controller

The Fuzzy Logic Controller (FLC) is based on heuristic rules, that makes use of Zadeh's fuzzy set theory to translate the linguistic control rules into a coherent control strategy. A block diagram of a FLC is shown in figure 4.

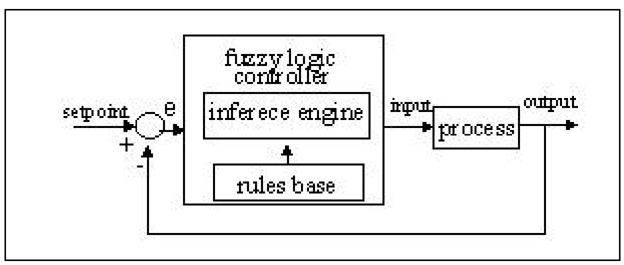

Figure 4. Fuzzy logic controller.

A fuzzy logic control law is described by a knowledge-based system consisting of IF-THEN rules with imprecise predicates and a fuzzy logic inference mechanism, (Coelho et al., 1998a). The rule base is the main part of a FLC. It is formed by a family of logical rules that describe the relationships between the input *e* and the output *u* of the controller. In general, the conventional FLC control law can be represented by:

$$u(k) = \text{`}\ \{ e(k),\ de(k), ie(k) \} \quad (2)$$

where the function $\Im\{.\}$ is non linear and described by a rule base and by fuzzy parameters. Each rule base of a FLC is characterized by an IF part, called the antecedent, and a THEN part, called consequent. An example of a rule base is presented in table 1.

Table 1: Example of a fuzzy rule base.

	u(k)	e(k) N	e(k) Z	e(k) P
de(k)	N	N	N	Z
	Z	N	Z	P
	P	Z	P	P

The linguistic labels of the antecedents and consequents are represented by membership functions and implemented as shown in figure 5. Table 1 shows the implemented rules.

The input of the inference engine of a FLC is the output of the fuzzification process of crisp input values, which are operated according to a rule base and generate fuzzy outputs. These outputs are then submitted to a defuzzification process, producing final crisp output values (Yager and Filev, 1994).

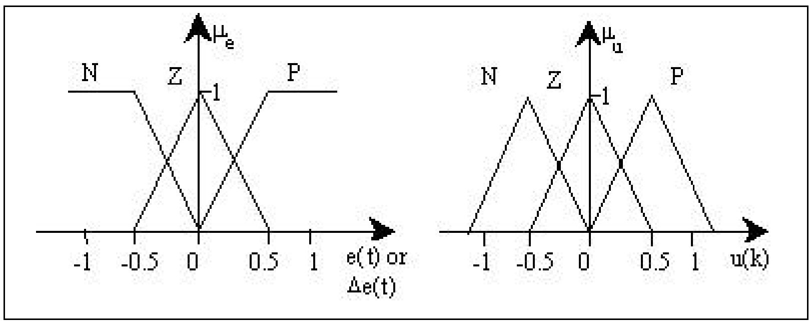

Figure 5. Membership function for e(t) and, de(t) and u(t).

The output of a general fuzzy controller *u(k)* is given by eq. (2) and the control algorithm of a general fuzzy PID controller is given by

$$u(k) = defuzz\left\{ R \circ fuzz(e(k)) \circ fuzz(de(k)) \circ fuzz(ie(k)) \right\} \tag{2}$$

where *fuzz(·)* is the fuzzification operator, *defuzz(·)* is the defuzzification operator, ° is the composition operator of fuzzy relations and *R* the fuzzy relation of the fuzzy controller rule-base (Golob and Tovornik, 1999, Yager and Filev, 1994).

5 Experiments Issue

Five sequential real time experiments are shown below. This experiments are arranged in increasing grade of complexity.

5.1 First experiment: Tuning PID controller

The PID controller proposed by (Åström and Wittemark, 1989) with tuning parameters strategy by (Almeida, 1999) is implemented as a first experiment. It is an initial and useful procedure to help tuning the FLC parameters based on adjusted PID parameters instead of the trial-and-error approach. The output, the setpoint and the input signal of the fan-and-plate controlled by a digital PID are shown in figure 6. This PID was adjusted using the method presented in section 4.1 (figure 3).

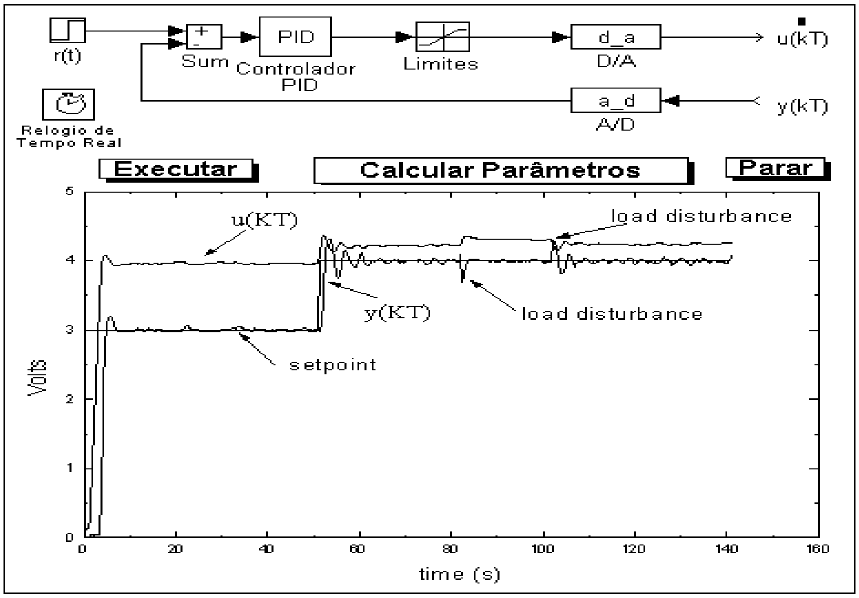

Figure 6. Digital PID controller

5.2. Second experiment: Fuzzy PI-plus- D conventional (FPI+Dc)

One could begin to implement Fuzzy-PID controllers by a Fuzzy-PI plus Conventional Derivative structure. To achieve derivative action in the Fuzzy-PI control structure, a single derivative implementation could be used, but to avoid derivative kicks originated by this conventional implementation, an alternative structure (Qin, 1994) was implemented. The automatic setup of the fuzzy scales was proposed by (Almeida, 1999b). The basic control diagram and simulating results are shown in figure 7. The FPI+Dc control law is given by

$$u(K) = u(k-1) \; + \; T\,defuzz\left\{ K_e \circ fuzz(e(k)) \wedge K_{de} \circ fuzz(de(k)) \right\} + \; u_D(k) \tag{3}$$

where T is the sample period time and

$$u_D = k_{f1} u(k-1) + k_{f2}\left[y(k) - y(k-1) \right]$$

k_{f1} e k_{f2} are relative to the constants of the derivative filter (Åström and Wittenmark, 1989).

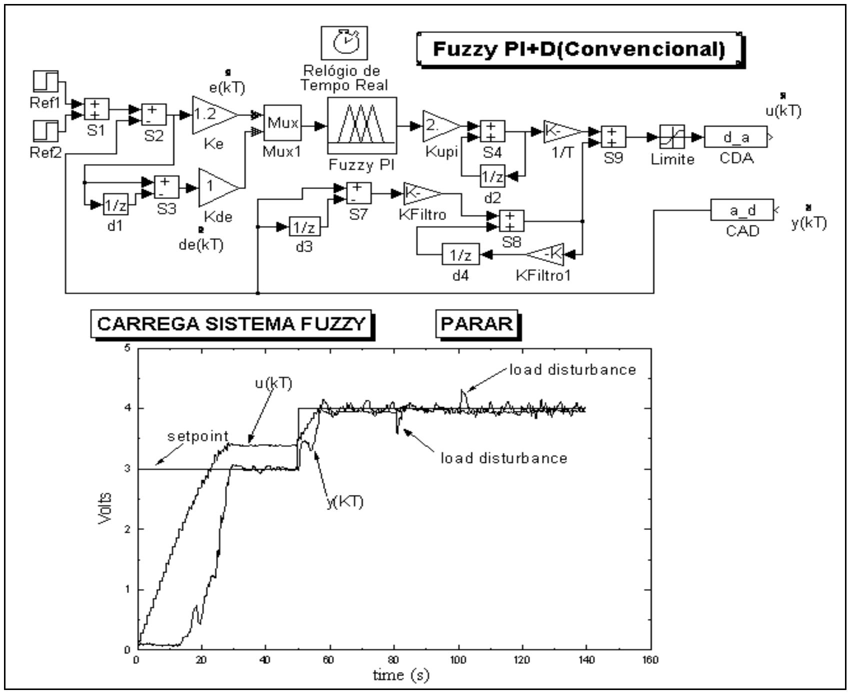

Figure 7. Fuzzy PI-plus-D conventional controller

As could be seen in figure 7, this derivative action exhibits a good initial behavior but poor performance outside the projected range - for initial response, the first 50 seconds.

5.3. Third experiment: fuzzy PD-plus-I conventional (FPD+Ic)

An alternative to fuzzyfy the derivative action in a FPD+Ic structure consists of a fuzzy PD operating in parallel with a conventional I controller. The basic control diagram is shown in figure 8.

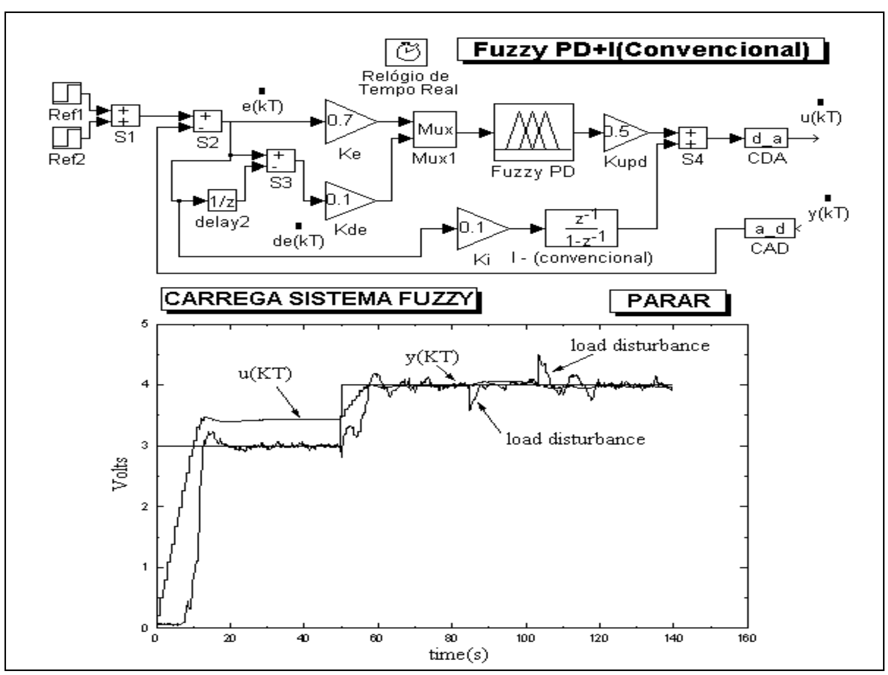

Figure 8. Fuzzy PD-plus-I conventional controller

The Integral action is still necessary to prevent steady state errors. The FPD+Ic control law is given by

$$u(K) = u(k-1) + \frac{KT}{T_i} e(k) + defuzz\{ K_e \circ fuzz(e(k)) \wedge K_{de} \circ fuzz(de(k)) \} \quad (4)$$

where K and T_i correspond to the proportional gain and to the integral time, respectively.

As illustrated in figure 8, the fuzzy derivative exhibits a faster response than a conventional derivative action**,** but this controller has difficulty in achieving a better performance (see the oscillatory response when the setpoint changes) because of the nonlinear characteristic of the plant being controlled. So, in the next experiment, a complete nonlinear controller will be tested (Fuzzy-PI + Fuzzy-D actions).

5.4 Fourth Fuzzy PD-plus-fuzzy I controller (FPD+FI)

The FPD+FI was proposed by (Li and Ng, 1997). The control law of this controller is formed by sum of the fuzzy PD action and the fuzzy I action. Two rule bases are necessary for each part of this controller**.** The PD rule base is two-dimensional and the I rule base is one dimensional. The output of the FPD+FI controller is given by

$$u(K) = u(k-1) + T\, defuzz[K_i \circ fuzz(e(k))] + defuzz[K_e \circ fuzz(e(k)) \wedge K_{de} \circ fuzz(de(k))] \quad (5)$$

The basic control diagram, output, setpoint and input signal of the fan-and-plate under the action of this controller are shown in figure 9.

As could be expected, this structure reveals better performance than the others that were investigated. Another choice of a completely nonlinear implementation comprises of accommodating a Fuzzy-PI plus a Fuzzy-PD action.

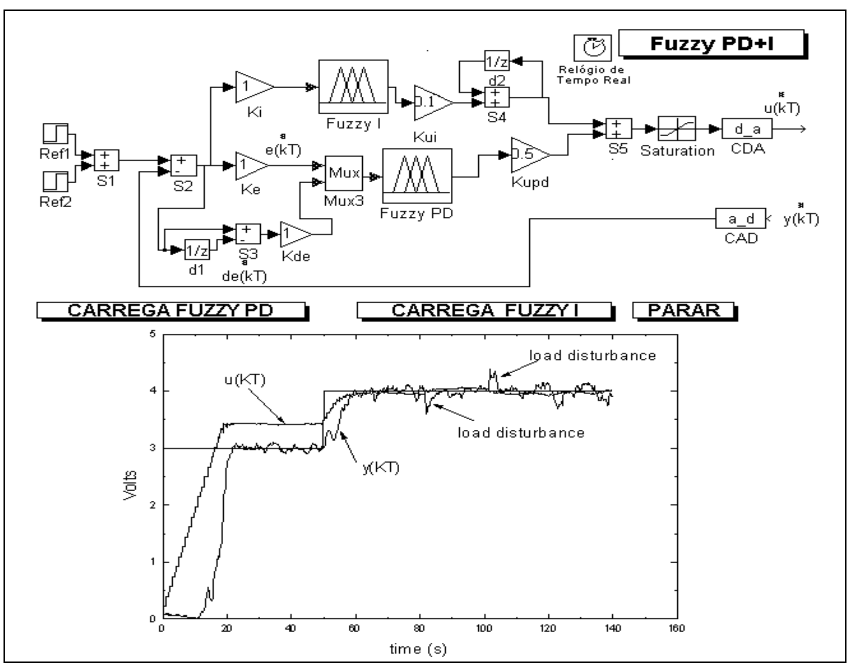

Figure 9. Fuzzy-PD plus Fuzzy-I controller

5.5. Fifth experiment: Fuzzy-PI plus fuzzy-PD controller (FPI+PD)

The FPI+PD design is presented by (Kwok et al., 1990). It consists of a fuzzy PI in parallel with a fuzzy PD. This controller is made up by two rule bases. Note that the rule base related with the fuzzy PD controllers and the fuzzy PI are both two-dimensional. The control diagram is shown in figure 10.

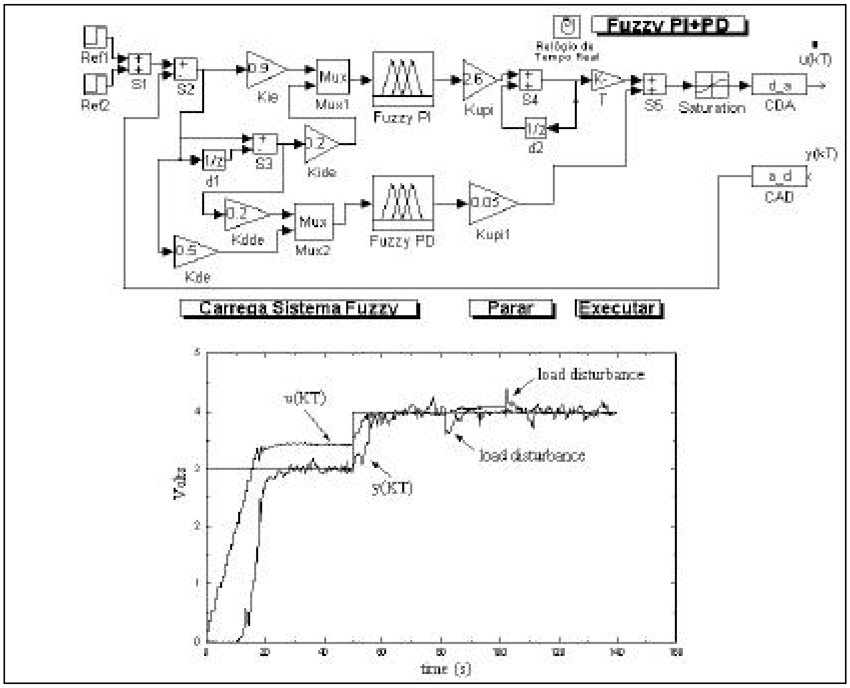

Figure 10. Fuzzy-PI plus Fuzzy-PD controller

The FPI+FPD control law is given by

$$u(K) = u(k-1) + T\,defuzz\left\{ K_e \circ fuzz(e(k)) \wedge K_{de} \circ fuzz(de(k)) \right\} + \\ + defuzz\left\{ K_e \circ fuzz(e(k)) \wedge K_{de} \circ fuzz(de(k)) \right\} \qquad (6)$$

The last two controllers (FPD+FI and FPI+FPD) exhibit a better performance than the others because of a more complete project. Note that the characteristic response of a FPD + (FI or FPI) controller is more reliable over the full range of the plant operation than a conventional PID or some fuzzy structure combined with a conventional (linear) block, as seen in figure 8 (oscillatory behavior for setpoints out of 3 Volts).

6 Conclusion

A sequence of real time fuzzy control experiments for laboratory classes of intelligent controllers was proposed. MATLAB/SIMULINK is a widely accepted software for analysis, design and simulation of control systems. In the laboratory, it has already been successfully employed as an interface with a general and single controller board internally developed. For those reasons, we encourage our students to make their initial contact with fuzzy logic using the toolbox supplied by MATLAB. This framework allows a design environment that motivates its application in graduate and undergraduate courses. Any extra programming skills are not necessary to develop efficient fuzzy logic controllers, considering that almost no time is dispended with programming tasks.

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