Digital Control Using Low-Cost Laboratory Models

Henrique Simas; Augusto H. Bruciapaglia; Antonio A. R. Coelho
Department of Automation and Systems - Federal University of Santa Catarina
CP 476 - 88040-900 - Florianópolis - SC - Brazil
Fone: 55 48 3319202 - Fax: 55 48 3319770
E-mail: {simas; augusto; aarc}@lcmi.ufsc.br

Abstract: *This paper describes the application of three low-cost plants used for digital control experiment. Different digital control algorithms are tested on a wind tunnel, fan-and-plate and single-tank. Practical testes for analysis and design of digital controllers — self-tuning PI, minimum variance, predictive, fuzzy — are investigated. The main objective is to show that low-cost equipment can be used to educate students with a good knowledge of computer control. The prototype systems are excellent tools for investigating nonlinear effects, which influence the sensitivity of the control algorithms, and setpoint changes*.

Keywords: laboratory education, self-tuning control, fuzzy systems, predictive control.

Introduction

Nowadays digital technologies are increasingly present in our life and no where else that is more true than in the process control area. As processes to be controlled are becoming more complex, they demand a higher flexibility in the variation of parameter specifications while trying to attain a low cost benefit. To go around these new demands the application of powerful computer tools becomes vital. The employment of computerized process control requires knowledge of digital and discrete control systems. Software and hardware understanding are also essential to control efficiently a specific predetermined control system [1], [6].

Classical disciplines in process control area have been offered in universities for a number of years now, while courses on digital control emerged along with the advent of microprocessors in the late 60's. The challenge for institutions where digital control is taught is to offer students physical and material conditions so that they can have a quality education that will give them a practical understanding of digital control concepts such as *A/D* and *D/A* converter, digital instrumentation, digital control algorithm and real time programming. The real challenge for third world institutions is imposed by financial constraints [2], [3], [9].

One way to overcome these problems could be to support the students by providing simulation packages, such as Matlab/Simulink or VisSim. In the present day, it is necessary to ensure practical knowledge with real-time applications. Conventional lectures and simulation laboratory courses show limitation in evaluating practical aspects of dynamic systems [10], [11], [12].

The Process Control Laboratory at Federal University of Santa Catarina, has designed and built low-cost didactic plants to support, in a practical way, the theories taught in the various disciplines of the process control area. Some of these devices, such as wind tunnel, fan-and plate and level system, have been successfully utilized in laboratory classes and have enabled undergraduate and graduate students the opportunity to apply digital control concepts [2].

The several processes implemented at the laboratory are controlled by selecting control algorithms which are: self-tuning, adaptive, predictive and fuzzy. The choice for these emerging and sometime controversial algorithms is, on the one hand, based on the assumption that they can offer a better performance for nonlinear processes and, on the other hand, that they are increasingly becoming a reality in industry [5], [14].

The paper is organized as follows. In section 2, the wind tunnel, fan-and-plate and single-tank prototypes, as well as theirs mathematical models are described. In section 3, the design of digital control algorithms are presented. The experimental control station utilized by the students is shown in section 4. In order to provide a broad evaluation of the performance of each control technique, practical results and conclusions are discussed in sections 5 and 6, respectively.

Practical Process Description

The following small pilot plants were utilized in the experiments of digital control: wind tunnel, fan-and-plate and single-tank. All of them were designed in our laboratory and are standard equipment in many process control courses (due to economic reasons it is very difficult the use of commercial equipment in our laboratory). Some characteristics of the equipment are: low-cost of maintenance, high reliability, cheap, totally innocuous, time constant of the systems are adequate and acoustic sensations. The prototypes allow to show important theoretical aspects as stability, static error, rejection to the disturbances, nonlinear behavior and effect of different regulators. The goal of the set of prototype dynamic systems is to prepare the students in terms of design tools and physical reality, and to add an intensive experimental component to the process control course for visualizing control theory in practice [6], [10].

First Experimental Setup: Wind Tunnel

The wind tunnel process is implemented over an aluminum base and consists of an 9 cm wide and 60 cm long air duct having on its left extremity a DC motor with a working range from zero to 24 volts. On the opposite extremity there is another DC motor (tachometer) driven by the air flow made by the first motor (the voltage arising from the rotation is proportional to the air flow). The transmission circuit utilizes several operational amplifiers and adjusts the output voltage of the measurement motor from zero to 5 volts range while the actuator circuit works at the range from zero to 24 volts and employs a power transistor bridge. It is possible to insert a disturbance in the process variable by switching a key which will add a step voltage to the output signal. The wind tunnel control system is shown in Figure 1.

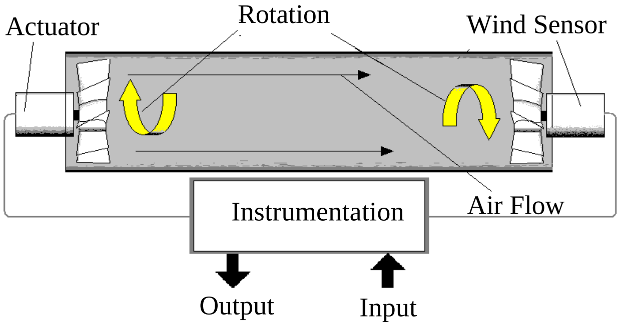

Figure 1 - Physical setup of the wind tunnel.

Experimental observation from the step response indicate that the behavior of the process is given by a discrete-time first-order transfer function of the form

$$G_{WT}(z) = \frac{z^{-1}(b_0 + b_1 z^{-1})}{(1 + a_1 z^{-1})}$$

Second Experimental Setup: Fan-and-Plate

The well-known fan-and-plate experiment, another practical application example, is utilized to evaluate the digital control algorithms. The fan-and-plate control system, represented in Figure 2, is composed of a fan driven by a DC motor, a 50 cm long air duct with funneling characteristic and 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.

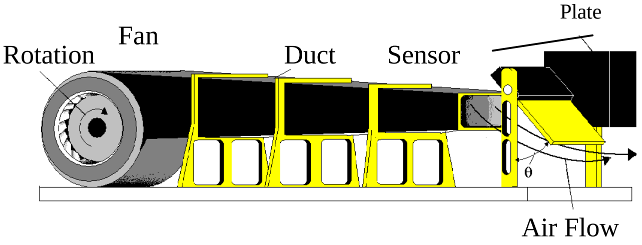

Figure 2 - Physical setup of the fan-and-plate.

The dynamic of the fan-and-plate process involves a nonlinear differential equation. For self-tuning control implementation, a discrete linear model is required. The corresponding discrete transfer function is

$$G_{FP}(z) = \frac{z^{-1}(b_0 + b_1 z^{-1})}{(1 + a_1 z^{-1} + a_2 z^{-2})}$$

Third Experimental Setup: Level Process

The level control system consists of a single-tank process and was designed in our laboratory to simulate a real system found in the chemical industry. The level process consists of a rectangular glass tank with dimension 29cmx12cmx28cm and capacity of 9.7 liters. At the bottom of the process there is a reservoir capable of storing approximately 10 liters of the fluid. The water is pumped into the tank from the reservoir by a small DC electric pump, with voltage varying up to +12 volts. The desired level is measured by a potentiometer/float attached to the top of the tank. The change in the resistance of the level sensor is converted to an analog voltage by a Wheatstone bridge with zero adjust. An operational amplifier, implemented in the gain configuration (span adjust), is utilized to calibrate the level from 0 to +5 volts. The photograph of the apparatus used in this case study appears in Figure 3.

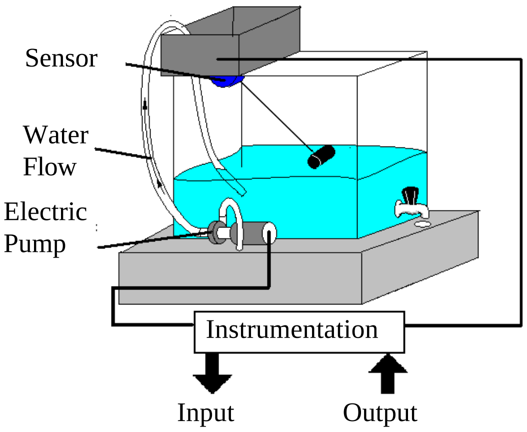

Figure 3 - Physical setup of the level experiment.

For self-tuning control implementation purposes, in order to regulate the water level in the single-tank to a specified value with acceptable transient and steady-state performance, a simple linear model is required. The self-tuning control algorithms are based on a class of plant whose dynamic of the open-loop control system can be described by a linear discrete-time transfer function as

$$G_{MT}(z) = \frac{z^{-1} b_0}{(1 + a_1 z^{-1})}$$

Digital Control Design

In recent decades, the theory and the practice relative to process control area have received great attention and the importance of having well-behaved control loops has been recognized in the academic and industrial environments for a long time. Despite the huge development in control theory, the majority of the industrial process is controlled by the well-established proportional plus integral plus derivative (*PID*) controller. The popularity of *PID* control can be attributed to its simplicity (in terms of design and from the point of view of parameter tuning) and to its good performance in a wide range of operating conditions. However, *PID* controllers present as a disadvantage the need of retuning whenever the processes are subjected to some kind of disturbance or when processes present complexities (nonlinearities). So, over the last few years, significant development has been proposed to adjust the controller parameters automatically, to ensure adequate servo and regulatory behavior for the closed-loop plant.

Ideally, a controller should be able to automatically adjust its gains to achieve a given control objective, leading to the concept of self-tuning control (*STC*). Essentially, *STC* involves the on-line implementation of two algorithms: one for parameter estimation and the other for calculating an appropriate control action. Whilst the *STC* concept is not new, with the idea first emerging in the late 1950s, it is only recently with the rapid developments in microcomputer technology, that such approaches are being seriously considered with a view to implementation on industrial systems. The implementation of self-tuning control algorithms in a particular case of the minimum variance and predictive controllers has shown several difficulties to the process engineer and researchers. These control algorithms need to be fed with information about the controlled process utilize a parametric mathematical model and, thus, they require an on-line identification procedure (complex engineering).

Other control solution to deal with complex processes is the implementation of control systems based on knowledge and learning. These systems collect process information and select values for the control variable from heuristic rules to bring and to maintain the process output at the desired operating point. The principle is easy to be understood by engineers and process operators, the implementation of the controller is simple, with large applicability in the industrial sector, and the computational effort of the algorithms is relatively modest. Fuzzy logic is typical example and can be employed in intelligent control conceptions.

The objective of this section is to review intelligent, predictive and self-tuning control strategies, that have been proposed in the literature, besides the application of the controllers in different processes.

Self-Tuning PI Control

An important class of self-tuning *PI* control algorithms, close to the original design philosophy of self-tuning regulators, is composed by two loops. One loop comprises a recursive parameter estimation algorithm that identifies the process model. As soon as the new parameters have been obtained, they are employed in a controller design stage that constitutes the other loop.

The structure or the *PI* controller is chosen to be

$$u(t) = u(t-1) + q_0 e(t) + q_1 e(t-1) \qquad (1)$$

where $u(t)$ is the control signal, $e(t)$ is the error given by $e(t) = y_r(t) - y(t)$, $y_r(t)$ is the reference and $y(t)$ is the output. At every sampling interval, based on the latest estimated parameters, the controller parameters are set to

$$q_0 = (1 - p_d) / \hat{b}_0 \qquad , \qquad q_1 = q_0 \hat{a}_1$$

so that the closed-loop control system pole is assigned to the desired value p_d. The problem of how to place the system poles with unknown coefficients is of practical importance and has attracted the attention of many researches.

MV Controller Based on Furuta's Approach

The structure of the controller proposed by K. Furuta, in 1989 [4], compensates the deficiency in the transient behavior of the controlled system which is inherent to some adaptive control strategies. Besides the incremental control, this control design utilizes the system error weighted by user-specified parameters. The control law equation utilizes the following cost function to be minimized:

$$J_F = s\left[e(t+1) + k_1 e(t) + k_2 e(t-1)\right]^2 + r\left[\Delta u(t)\right]^2 \qquad (2)$$

where $e(t) = y_r(t) - y(t)$ and the control law is

$$u(t) = \frac{ru(t-1) + \hat{b}_0 s\left[y_r(t+1) + k_1 e(t) + k_2 e(t-1) + \hat{a}_1 y(t)\right]}{\hat{b}_0^{\,2} s + r} \qquad (3)$$

where s and r are positive weighting factors. The first term on the right side of equation (2) characterizes the transient behavior of the plant output. By setting this term to zero, *i.e.*, $e(t) + k_1 e(t - 1) + k_2 e(t - 2)$, it can be seen that the error may tend asymptotically to zero or diverge, depending on the values of k_1 and k_2.

To have a stable closed-loop system, the roots of the corresponding equation $z^2 + k_1 z + k_2 = 0$ must lie inside the unit circle. So, following the relationship between the roots and the coefficients, the values of k_1 and k_2 can be determined easily. The second term is used to limit the control effort and is also used to avoid the presence of a pole on the unit circle when sampling period is short.

MV Controller Based on Lim's Approach

In 1990, using D. W. Clarke's conventional control structure, C. M. Lim proposed a simple predictive control law which adds the process output derivative term in the cost function [7], as follows

$$J_L = \left[y(t+1) - y_r(t)\right]^2 + q'\left[\frac{dy(t+1)}{dt}\right]^2 + r\left[\Delta u(t)\right]^2 \qquad (4)$$

where q' and r are design parameters to be tuned by the user for the controlled process. Utilizing a first-order approximation for the derivative term, optimum control law is given by

$$u(t) = \frac{1}{\alpha}\left\{ru(t-1) + \hat{b}_0\left[y_r(t) + \beta\, y(t)\right]\right\}$$
$$\alpha = \left[r + \hat{b}_0^{\,2}(1+q)\right] \quad \beta = \hat{a}_1(1+q) + q \qquad (5)$$

where $q = q'/T_s^2$ (T_s - sampling interval). This controller provides an anticipatory characteristic thanks to the derivative term. So, by adjusting the contribution of the derivative term it is possible to minimize the overshoot of the process output. The r design parameter, besides compensating the closed-loop dynamic, is important to weight the control input, specially when digital control action is constraint between zero to five volts. The generalized minimum variance control (*GMV*) has emerged over the 22 years as a powerful tool for feedback control for solving many of the problems for which other control approaches proved to be a tough challenge, such as nonminimum phase problems. In comparison with the generalized predictive control approach the *GMV* strategy is more computationally efficient, with fewer *a priori* parameters to be selected.

Generalized Predictive Control

In the mid-seventies, a new digital control algorithm came to light. Its design is based on the assumption that there is a control horizon beyond which all the control increments are null. The controller is based on the following steps: i) forecast the process output over a long-range horizon through the use of a predictive model (composed of one term dependent only of the past input/output measurements and another function of the future control inputs); ii) determine future inputs in order to satisfy the control objectives in terms of desired future references. This predictive control strategy generates a control law that may be considered as one of the most effective control algorithm to handle industrial complexities. Presently, predictive control schemes are amongst the most popular linear control methods for adaptive control. Generalized predictive controller (*GPC*) has been widely used in adaptive context and it is an extremely flexible approach for control due to its performance and the large number of design and tuning parameters. The objective of the *GPC* is to guide future plant outputs to follow setpoint changes.

The Controlled Auto-Regressive and Integrated Moving-Average (*CARIMA*) model is utilized to develop the control algorithm. The overall closed-loop behavior (servo and regulatory) depends upon the choice of the design parameters: weighting factor of the controller, output horizon and input horizon.

The controller computes the future incremental control vector by the minimization of the follow criterion of the form:

$$J_{GPC} = \sum_{j=1}^{HY}\left[y_f(t+j) - y_r(t+j)\right]^2 + \sum_{j=0}^{HU-1}\Gamma\Delta u^2(t+j) \qquad (6)$$

where *HY* is the output prediction horizon, *HU* is the control horizon, *G* is the control weighting sequence and $y_f(t + j)$ is the filtered output. The control law is required to minimize the cost function, equation (6), and can be obtained separating the predictive output vector into two terms as: one uses the future control increments vector *DU* to be optimized and the other *YFA* uses the available input/output data. then the filtered output prediction becomes

$$YF = G\Delta U + YFA \qquad (7)$$

where the *G* dynamic matrix is computed with the step response elements for a controlled process. The minimization of the cost function in equation (6) leads to the following incremental control law:

$$\Delta U = [G^T G + \Gamma I]^{-1} G^T [YR - YFA] \qquad (8)$$

$$\Delta U = [\Delta u(t), \Delta u(t+1), \ldots, \Delta u(t + HU - 1)]^T \qquad (9)$$

The predictive control is implemented using a receding-horizon approach: the first element of *DU* is *Du(t)* so that the current control *u(t)* given by

$$u(t) = u(t-1) + \Delta u(t)$$

is applied to the process. *GPC* is a linear controller that the literature claims can control nonminimum phase plants, open-loop unstable plants, and plants with variable or unknown dead time, and can systematically take into account real plant constraints in real-time. *GPC* is robust with respect to modeling errors, over- and underparametrization, and sensor noise. *GPC* algorithm is fairly mathematically complex and require a substantial amount of computing power for real-time implementations.

Fuzzy Control

Recently, *FLC* has made a real impact in control engineering. Fuzzy control research was initiated by the work of E. H. Mamdani and S. Assilian [8], who was motivated by Professor L. A. Zadeh [13] in his outstanding paper, about 30 years ago. The *FLC* is getting a considerable importance in the implementation of process control algorithms, mainly in cases where modeling is difficult. Moreover, fuzzy logic controllers often yield superior results compared to conventional control approaches. Human expertise is utilized in the form of a rule of the type:

If <fuzzy conditions on input variable> then <fuzzy control actions>

These rules are applied to the inference engine. The fuzzyfication procedure enables us to define a degree of membership to fuzzy sets for input variables. The defuzzyfication procedure enables us to calculate the effective control from all the rules applicable to a given input set. Fuzzy controllers can be viewed as models of the human knowledge and engineering judgment determining the appropriate values of the control signal or the control increment from observation of the process variables, as for example the error signal of a control loop and the deviation in error. The membership function of the *FLC* can be first obtained by studying the response of a traditional *PID* controller and then finally tuned to achieve a good response by the trial and error method. The rule base utilized in the implementation of the *FLC* is essentially heuristic (from the viewpoint of practical system operation). Fuzzy logic control issues are now being introduced in the process control course. Students learn the fundamentals and practice *FLC* with laboratory equipment. Figure 4 shows the fuzzy control system structure.

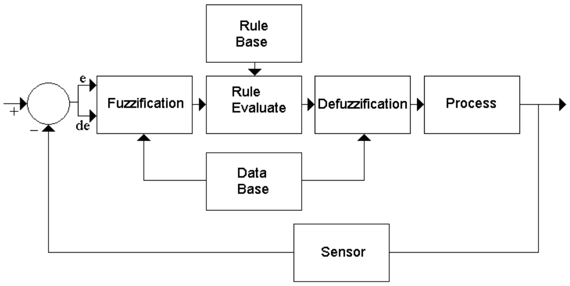

Figure 4 - Fuzzy control system structure.

The following simple linguist set can be selected: *NM* (Negative Medium), *NS* (Negative Small), *Z* (Zero), *PS* (Positive Small), *PM* (Positive Medium). In the practical applications the shape of the fuzzy variable is triangular type, the centroid defuzzyfication method is utilized and the set of rules is given by

Table 1 - Rule Base

Error Δerror	NS	ZE	PS
NS	NS	PS	ZE
ZE	PS	ZE	NS
PS	ZE	NS	PS

Experimental Control Station

Each experimental station is equipped of a physical process, measurement and actuator circuits, a digital computer and an *A/D* and *D/A* converters. Figure 5 shows the structure of our experimental control station.

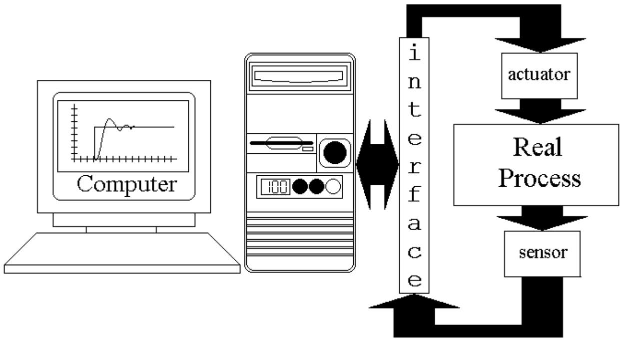

Figure 5 - Computer station for experimental activities in digital control.

The basic devices that constitute the input/output card are eight channels for the *A/D* converter, one channel for the *D/A* converter and, four channels for eight-bit parallel communication of eight-bit, including two digital inputs and two digital outputs. The connection between the *ADA* (analog-digital-analog) card and the microcomputer for measuring, analyzing and controlling the prototype processes, is implemented in a slot available in the mother-board of the computer. The *A/D* converter is obtained through integrated circuit which has the following characteristics: eight channels, conversion time of 60 μsec for a clock frequency of 1 MHz and data resolution of eight-bit. It is also possible to use the ADC0809 integrated circuit. The *D/A* converter is implemented with the LM324 integrated circuit and a *R-2R* resistor circuit. This converter has data resolution of eight-bit and the final band selection adjusted to operate in the standard ranges of 0 to +5 volts or 0 to +10 volts (output range).

Control Experiment

In this section, some experimental results that demonstrate the applicability of the plants and capability of the digital control methods are given. Real-time programs of each digital control algorithm were written in Pascal language.

First experimentation is based on the practical results of the single-tank control system (Figure 6). The Furuta's controller was tuned at s=1 and r=0.09, with transient performance fixed by k_1=-0.77 and k_2=0.075. The Lim's controller had adjusted with q' = 10 and r = 0.01. The implementation of both self-tuning controllers were utilizing the first-order parameter estimation, with sampling period of 300 msec. The implementation of adaptive control algorithms required an exhaustive search in order to get best tuning of the control parameter. It is due to nonlinear constants that are influencing the linear parameters in the self-tuning algorithms.

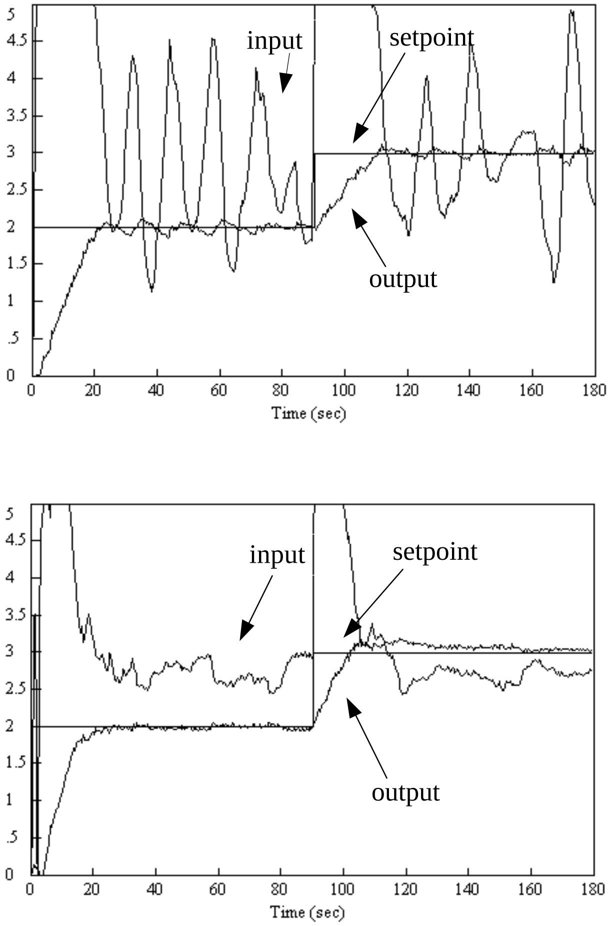

Figure 6 - Level process: Furuta and Lim algorithms.

Figure 7 illustrates the second experimentation based on the practical results of the wind tunnel control system. The parameters of the adaptive *PI* control are: closed-loop pole is 0.91, $\theta(0) = 0.15I_2$ and sampling period of 300msec. In the implementation of the fuzzy controller, the priority was the control precision. The results shown that the adaptive *PI* control presented a faster response than fuzzy control. It is due to the good linearity of the process in the operation range (output calibrated from 1 to 4 volts).

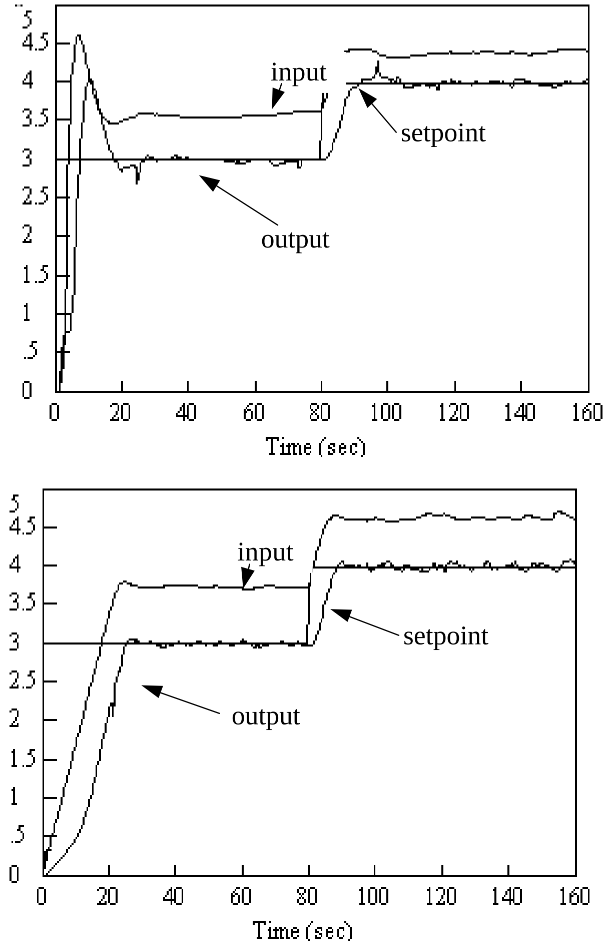

Figure 7 - Wind tunnel: Adaptive PI and fuzzy control.

Third experimentation is based on the practical results of the fan-and-plate control system (Figure 8). It can be observed that the *GPC* controller (Γ=10,HY=5,HU=2) shown an excessive variance of the output signal when compared to fuzzy control application. In this case, the fuzzy control provided an adequate servo and regulatory performance.

The experiments shown the applicability and the possibility of evaluating different digital controllers. The application of processes in experimental laboratory courses, such as level, wind-tunnel and fan-and-plate plants, were attractive to apply and to test in the practice the theoretical aspects of various digital control algorithms (adaptive, self-tuning, predictive, fuzzy). In addition, it should be noticed that an exhaustive search by trial-and-error, to design of controller parameters, was necessary.

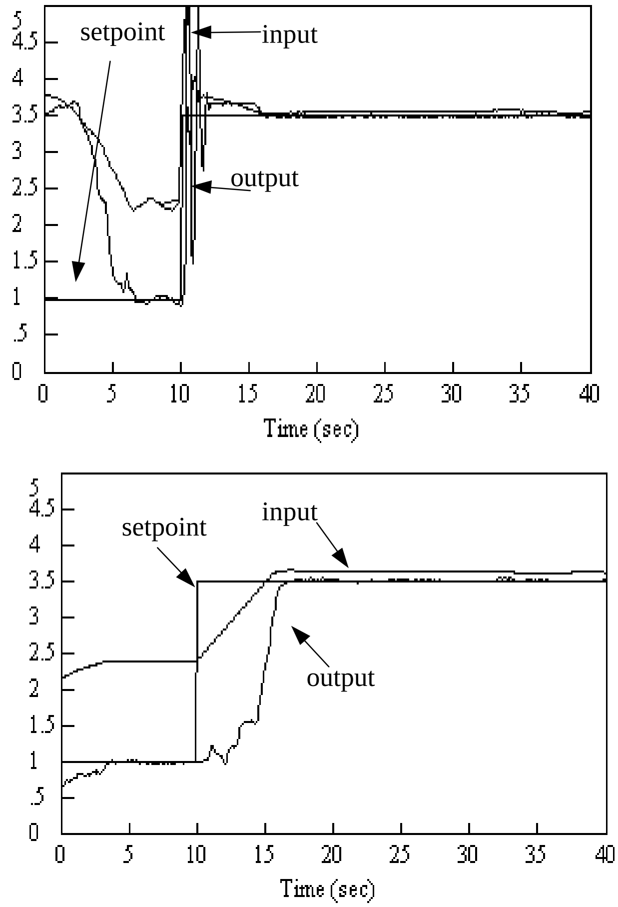

Figure 8 - Fan-and-plate: GPC and fuzzy control for setpoint from 1 to 3.5 volts.

Conclusion

This paper examined the practical implementation of three low-cost prototypes (wind tunnel, fan-and-plate, single-tank) in the context of digital control conception. The several processes were controlled by self-tuning, adaptive, predictive and fuzzy control algorithms.

The laboratory control station integrates digital and analog tools, and offers educational possibilities in many fields connected with software and hardware, such as modeling, instrumentation, data acquisition and digital control. Furthermore, the experiments provided the students with an opportunity for experimental validation of the digital control theory and they also prepare control students in the activities of the practical world. The proposed control systems are useful for not only university students but also for training courses to industry control engineers.

The practical implementations have been conducted as projects by students and are being added to our laboratory. There are other processes (heat tunnel and horizontal balance) that are being built and tested, and were omitted in this paper.

References

[1] Åström, K. and Lundh, M., "Lund Control Program Combines Theory with Hands-on Experience," *IEEE Control Systems*, 1991, pp. 22-30.

[2] Coelho, A. A. R.; Bruciapaglia, A. H.; Simas, H. and Gomes, F. J., "Low Cost Laboratory Equipament for Analysis and Design of Dynamics Systems,". *4th Symposium on Advances in Control Education*, Istanbul, Turkey, 1997, pp. 125-130.

[3] Franklin, G. F. and Powell, J. D. ,"Digital Control at Stanford," *IEEE Control Systems*, 1988, pp. 10-13.

[4] Furuta, K.; Kosuge, K. and Kobayashi, K., "VSS-Type Self-Tuning Control of Direct-Drive Motor,", *Proceedings of IECON*, 1989, pp. 281-286.

[5] Grega, W. and Maciejczyk, A., "Digital Control of an Tank System," *IEEE Trans. on Education*, vol. 37,1994, pp.271-276.

[6] Kheir, N. A; Åström, K. J; Auslander, D.; Cheok, K.C.; Franklin, G. F., Masten, M. and Rabins, M., "Control Systems Engineering Education," *Automatica*, vol. 32, 1996, pp. 147-166.

[7] Lim, C. M., "Experimental Evaluation of a Self-Tuning Controller," *IEEE Trans. Industrial Electronics*, vol.37, 1990 pp. 193-194.

[8] Mamdani, H. E. and Assilian, S., "An Experiment in Linguist Synthesis with a Fuzzy Logic Controller," *Int. J. Man-Mach. Stud*., 1975, pp. 1-13.

[9] Milek, J. J., "A Lecture Demonstration for a Course in Digital Control," *13th World Congress of IFAC, San Francisco, USA*, 1996, pp. 13-18.

[10] Schmidtbauer, B., "New First Course in Analog Digital Control," *11th World Congress of IFAC*, 1990, pp. 161-165.

[11] Shoureshi, R. and Meckl, P. H., "Control Education in the Era of Microprocessors," *Proc. of American Control Conference, Chicago, IL, USA*, 1992, pp. 455-459.

[12] Yurkovich, S. and Passino. K. M., "An Intelligent Control Laboratory Course," *13th World Congress of IFAC, San Francisco, USA*, 1996, pp 83-88.

[13] Zadeh, L. A., "Outline of a New Approach to the Analysis of Complex Systems and Decision Processes," *IEEE Trans. Syst. Cyber, SMC-1*, 1973, pp. 28-44.

[14] Zilouchian, A., "Development of a Real-Time Digital Computer Control Laboratory," *Proc. of American Control Conference, Chicago, IL, USA*, 1992, pp. 473-474.