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Fuzzy Controller Embedded in PLC for Multivariable Systems Using a Discrete Event System Approach

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Abstract— This paper presents the development of a control methodology based on computational intelligence using fuzzy control techniques embedded in a programmable logic controller (PLC) for multivariable systems. A fluid level plant with three tanks, in reduced scale, is set as study platform in order to evaluate and validate the proposed fuzzy control strategies, aiming at maintaining the tank levels of the supply system within a preset limit. The results obtained experimentally and by simulation aid on evaluating the performance of the fuzzy controller, providing a qualitative and quantitative basis of its effectiveness when compared to the performance of a proportional-integral (PI) controller.

Keywords—Computational Intelligence, Control Systems, Multivariable Plant, Fuzzy Controller, PI Controllers

I. INTRODUCTION

Several technologies present in manufacturing processes, communication networks, air traffic control etc., may be described for models with some features in common. In these systems, the state space is generally discrete, and finite in several cases, using an approach of discrete-time and state space representation. Furthermore, changes on the state take place only in response to the occurrence of events [1]. Such characteristics distinguish them from systems that have their dynamics time driven and their continuous state space, whose modelling is traditionally described through differential equations (Continuous Variable Systems - CVS). Those systems are denominated as Discrete Event Systems (DES). According to [2], "a Discrete Event System is defined as a system whose dynamic evolution depends on the occurrence of events".

In order for a DES to exist, it is necessary that actions occur, and that those, on the other hand, generate events. A system will only change state when an event takes place. If there is no event, the system will remain in the same sate [3].

A very efficacious and reliable equipment used for applications involving discrete action control in manufacturing process industry is the Programmable Logic Controller (PLC). The availability of PLCs with characteristics such as devices, machines and operations of processes through the implementation of specific functions, like control logic, sequencing, time control, loop control, advanced functional instructions, and improvement of the Graphic User Interface (GUI), in programming such controllers gave rise to the premises for the implementation of complex control algorithms [4] and [5].

The implementation of a control methodology based on computational intelligence in large scale PLCs, which improves the automation of industrial equipment, is the main contribution of the present paper. The development of the design and the implementation of a Fuzzy controller in an industrial PLC for multivariable systems are presented. A fluid level plant comprised of three tanks is used to test and validate the proposed fuzzy controller model. Moreover, a comparison of the obtained results of the fuzzy controller with those of the PI controller is presented.

The tank level control is an important application in several engineering areas such as steel mills, storage tanks of the petrochemical industries, power generating processes, chemical industry, cellulose, foods, central water distribution, the inflows and outflows can be controlled [6] and [7].

The paper is organized into sections as follows: Section II presents a description of the tank level system, its operation and the system modeling with mathematical formulations for both system CVS and DES. The fuzzy controller and its characteristics are approached in section III, and practical and computational experiments, besides the obtained results, are shown in Section IV, and finally in Section V the conclusion is presented.

II. DESCRIPTION OF THE TANK LEVEL SYSTEM

The tank system is composed of three pumps; five level sensors; switch for system drive; a PLC Compact Logix L32E; a computer; and four contactors, as shown in Figures 1 and 2. In Figure 1 shows a plant which was built in a reduced scale but having the characteristics of a full size plant and Figure 2 shows a graphical illustration of the tank system in a reduced scale used in the simulation and on the methodology validation adopted in the present paper.

Fig. 1 Platform of control test and validation

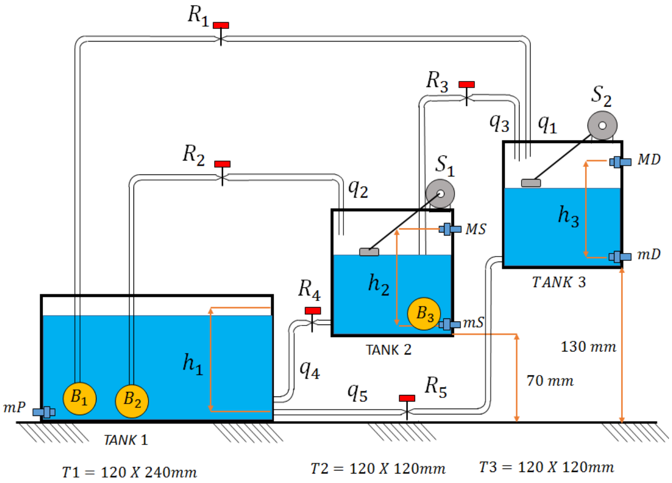


Fig. 2 Plant graphical illustration for level control

The dimensions and characteristics of the tanks are shown in Table I.

Table I Characteristics of the tanks

	Tank 1	**Tank 2**	**Tank 3**
Height (cm)	12	12	12
Base (cm)	24 x 12	24 x 12	24x 12
Capacitance (cm)	288	144	144

According to the system presented in Figure 2 the following variables were defined: q_1 and q_2 are the inflows in tanks 02 and 03 provided by pumps 01 and 02 in cm^3/s, respectively; q_1 is the inflow in tank 02/03 provided by pump 03 cm^3/s; q4 and q5 are the flows between tanks 02/01 and 03/01 in cm^3/s, respectively; h_1, h_2 and h_3 are the fluid levels in tanks 01, 02 and 03 in m, respectively; R is the resistance to liquid flow in tabulation s/cm^2; C is the capacitance in cm^3; h_{set} is the reference height in cm^3; and E is the error E = $h_{set} - h$ in cm.

2.1 System Operation

The operation of the system is related to the water level control in the tanks. Tank 01 supplies tanks 02 and 03, being that, when it has a low water level, the supply of the distribution reservoir will be done by Tank 02.

Each tank has level sensors, which indicate the water level (to indicate the water height in every time instant). Tank 01 has only one low level sensor mP that when reached it is switched and will activate a signal lamp indicating LOW LEVEL. At this point, in case one of the pumps is on, pump 01 and/or pump 02, they will be switched off. For the other two tanks, sensors mD and mS have operating principle as of sensor mP. Sensors MD and MS are activated when the water level of the tanks reaches the maximum level. In such situation, the supply of liquid will be interrupted.

The pumps operating in the system are activated only when the water level in the reservoirs is above the low level. In case tanks 01 and 02 are with low level water, the lack of water signalling lamp is triggered. Sensors S1 and S2 provide the level of tanks 02 and 03 at each time instant. The control will be carried out within the limits pre-established by the plant under study.

2.2 Mathematical Model of the CVS

Real plant processes are mostly complex, and it is difficult to develop models which well represent their operation. For the mathematical modelling of the CVS, we took into account the resistance R to the fluid flow on the tabulation or restriction which is defined as the variation on the level difference necessary to cause flow unitary variation, are given by [8].

$$R = \frac{dh}{dq}, \tag{1}$$

with *dh* being the variation on the level difference and *dq* being the variation in the flow in volume.

The capacitance *C* of a tank is defined to be the change in quantity of stored liquid necessary to cause a unit change in the potential [8].

$$C = \frac{dv}{dh}, \tag{2}$$

being that *dv* is the variation in the amount of stored liquid.

Conditions of balance for Tank 2 are given by

$$C_2 \frac{dh_2}{dt} = q_2 - q_3 - q_4, \tag{3}$$

Conditions of balance for Tank 3 are given by

$$C_3 \frac{dh_3}{dt} = q_1 + q_3 - q_5, \tag{4}$$

where $\frac{dh_2}{dt} = \dot{h}_2$e and

$$\dot{h}_2 = -\frac{h_2}{R_4} \times \frac{1}{C_2} + (q_2 - q_3) \times \frac{1}{C_2}, \tag{5}$$

where $\frac{dh_3}{dt} = \dot{h}_3$and

$$\dot{h}_3 = -\frac{h_3}{R_5} \times \frac{1}{C_3} + (q_1 - q_3) \times \frac{1}{C_3}, \tag{6}$$

This system can be represented in state space by the following equations:

$$\dot{x} = \boldsymbol{A}x + \boldsymbol{B}u \tag{7}$$

$$y = \boldsymbol{C}x + \boldsymbol{D}u \tag{8}$$

where *x* is the state vector, u are the inputs and *y* are the outputs. Thus obtaining the matrices of state space, that are given by:

$$\begin{bmatrix} \dot{h}_2 \\ \dot{h}_3 \end{bmatrix} = \begin{bmatrix} -\frac{1}{R_4 C_2} & 0 \\ 0 & -\frac{1}{R_5 C_3} \end{bmatrix} \begin{bmatrix} h_2 \\ h_3 \end{bmatrix} + \begin{bmatrix} 0 & \frac{1}{C_2} & -\frac{1}{C_2} \\ \frac{1}{C_3} & 0 & \frac{1}{C_3} \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix}, \tag{9}$$

and output is given by

$$y = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} h_2 \\ h_3 \end{bmatrix} \tag{10}$$

2.3 Discrete-time systems

Considering the system of tanks in a reduced scale represented in Figure (2) and mathematically formulated in CVS according to Eqs.(9)-(10), this may be described by the discrete-time linear system of second order, according to Eqs.(11)-(12).

A sampling interval equal to 1s was adopted for the mathematical formulation of the discrete time linear system.

$$h_{(k+1)} = \begin{bmatrix} 0,0035 & 0 \\ 0 & 0,0032 \end{bmatrix} h(k) + \begin{bmatrix} 0 & 0,0069 & -0,0069 \\ 0,0069 & 0 & 0,0069 \end{bmatrix} q(k) \tag{11}$$

$$y = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} h(k) \tag{12}$$

The system involves two states $h(k) = (h_2(k), h_3(k))^T$ corresponding to the filling levels of the reservoirs (tank 2 and tank 3) of water with the initial condition $h\ (0) = [\ 0\ 0\ ]^T$. The control inputs $q\ (k) = (q_1(k), q_2(k), q_3\ (k))^T$ are the stream flow of the three pumps. Sensors mS, MS, mD and MD are the measurements of the first and second state.

2.4 Discrete-Event Systems

Discrete Event System (DES) is a dynamic system evolving according to the abrupt occurrence of physical events in time intervals usually irregular and unknown [1]. It is a system where the signals assume values in a discrete set. The value changes, when they occur, are so quick that they may modelled as instantaneous at any instant; and they can be altered by two possible reasons: occurrence of external instantaneous events and the occurrence of internal events defined by strict logical chains.

For the situation where tanks 2 and 3 are full, pumps 1, 2 and 3 are switched off. These will only be triggered if there is a change in the states of the tank 2 and 3, that is, if the water levels of the tanks 2 and 3 are below the maximum level. On the other hand, if the water level of tank 1 is at the minimum level, pumps 1 and 2 will not work, so tank 3 will be supplied by tank 2, if it has the water level between the minimum and maximum level the pump 3 will be started. In case the water levels of tanks 1 and 2 are at minimum levels, pumps 1, 2 and 3 will be switched off. Therefore, the tank level system under study can be considered a DES, since the pump on / off events only change if there are changes in the tank level sensor actuations. Table II shows all the events that occur in the tanks plant process presented in this paper.

Table II Plant Events

STAGES	EVENTS	ACTIONS
1	Tanks 02 and 03 empty	mD and mS triggered
2	Fill tank 02	Pump 02 triggered
3	Fill tank 03	Pumps 01 and 03 triggered
4	Tanks 03 full	MD triggered
5	Tanks 02 full	MS triggered
6	If tanks 02 and 03 full	Luminous Signals
7	Tank 01 empty	mP turn off pumps 01 and 02
8	Pump Failure 01, 02 and 03	Luminous Signals

III. DESIGN OF CONTROL SYSTEM

The control system was designed using computational intelligence techniques for the development of a fuzzy controller for controlling the level of the tanks and compared with the results of a PI controller. According to Figure 3, the process of the tanks (level sensors and pumps) is in level 1, and in level 2 is the PLC with the DES control and the CVS control, and in the CVS control are the fuzzy controller and the PI controller.

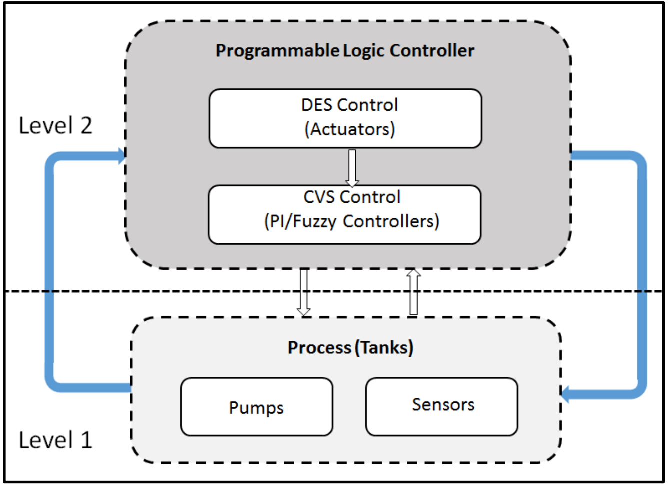


Fig. 3 Hierarchical Control of Automation

3.1 System Operation

The controller design and its parameters must be performed before the implementation of the PLC as follows: First, the engineer needs to configure the controller parameters (I/O, rules, etc.) [9]. Second, the user has to specify and register in the PLC the following parameters of fuzzy controller: input variables (numbers, points that define fuzzy subsets); output variable (points defining fuzzy subsets); Rules (number, premises and conclusions); and Fuzzy Logic operation (AND or OR, with minimum or Product options for AND).

The basic configuration of a fuzzy system is divided in three parts: Fuzzification, Inference and Defuzzification.

3.1.1 Fuzzification

The Fuzzification interface is responsible for the identification of the numeric values supplied by the sensors and normalizing these values in a standardized universe of discourse forming a fuzzy set [10].

The linguistic variables can be configured in five different ways: Trapezoidal, S, Z, Triangular and Singleton. The trapezoidal and triangular types were used as membership functions. For utilizing the triangular form, points b and c must be equal. To set these functions, the user has to enter the values of 4 points marked by *a*, *b*, *c* e *d* as shown in Figure 4 for all subsets of each variable [11].

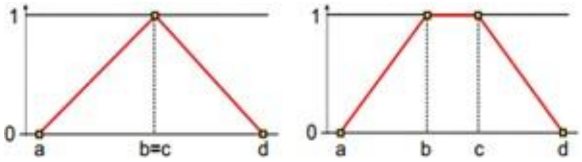


Fig. 4 Points required for a triangular and trapezoidal membership function

3.1.2 Defuzzification

The Defuzzification gets a single action control from the fuzzy set obtained, the procedure comprises the identification of the domain of the output variables in a single universe of discourse and the fuzzy control action inferred, a non-fuzzy control action is taken [12].

We used the defuzzification by the centroid method. This method assumes that the control action resulting from the communication of the membership functions, corresponding to the center of gravity calculated on the distribution of membership functions, is given by

$$y_c = \frac{\sum_{i=1}^{n} y_i \mu b(y_i)}{\sum_{i=1}^{n} \mu b(z_i)} \qquad (13)$$

being the term n the number of output levels, y_i is the value corresponding to the exits at the input level and i , and µb (z_i)) is the membership value.

IV. EXPERIMENTS

The experiments are carried out for the plant shown in Figure 1, which adopts the CVS and EDS modelling, shown in sections 2.2 and 2.3. For the methods validation used in this work, a methodology based on computational intelligence applied in an industrial PLC, in which the fuzzy controller and PI controller are embedded was developed.

4.1 Simulation in Fuzzy Logic Toolbox - MATLAB

Initially, tanks simulation system is carried out using the Simulink, represented by the block diagram of Figure 5. The first step in developing a fuzzy logic controller is the identification of antecedent variables which are important variables in the control of action. Input Error and Height for the level control tank system, was adopted. The next step is to select the action or consequent variables that when adjusted change the system state. There are two possibilities for this system: The inflows in tanks q_1, q_2 and q_3 can be controlled, or the outflows q_4 and q_5 can be controlled. The purpose of the controller in question is to adjust the input flow of the value of the tanks 02 and 03. After choosing the consequent variables, linguistic variables were chosen. Then, the interval of each language term was delimited [13].

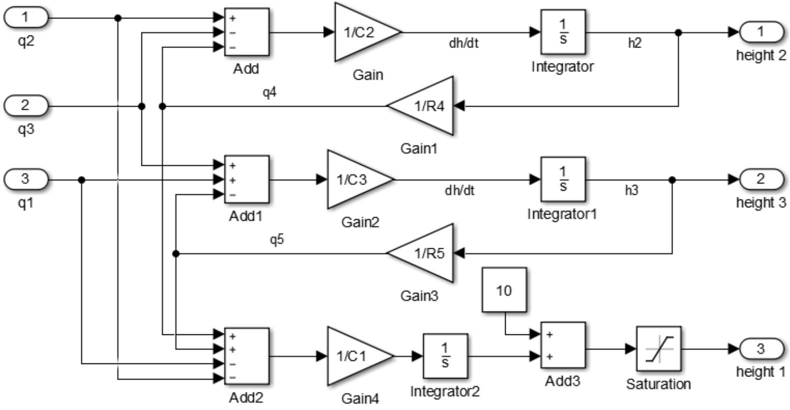


Fig. 5 Plant for level control

The membership functions of Error and Height input variables, and the output variable (pumps flow), are represented by Figures 6-8. For the input variable Error an interval ranging between −7 e 7cm was adopted, as this is the maximum error related to heights that the tanks may present. For the Height input variable, an interval of 0 to 7cm was adopted. The system does not allow values greater than this height because of the level sensors that the plant presents.

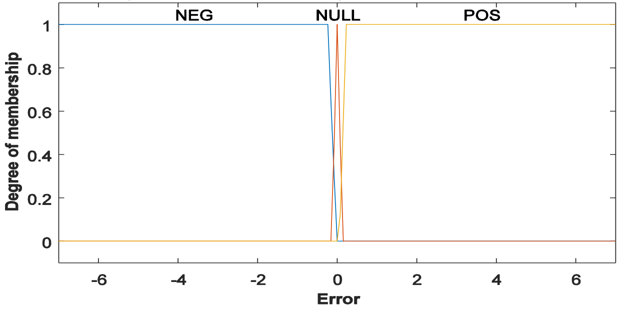


Fig. 6 Membership function for the Error input variable

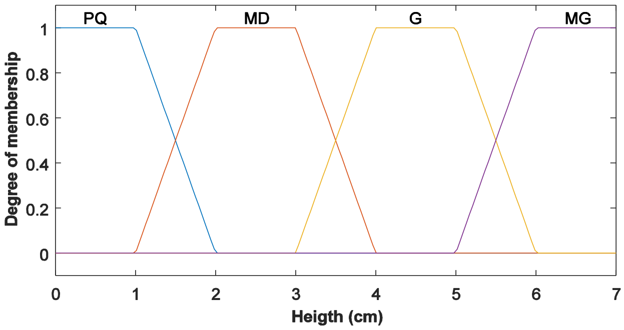


Fig. 7 Membership function for the Height input variable

For the Flow output variable, the choice of values was carried out to meet the hydraulic pumps operating conditions.

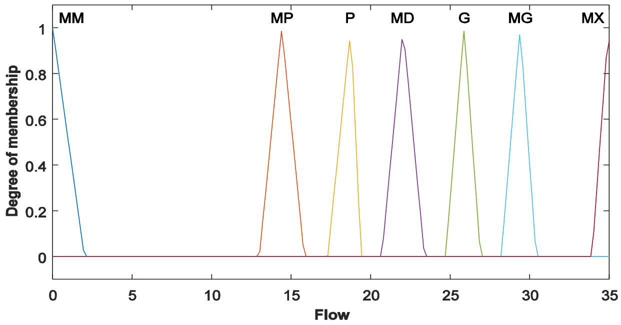


Fig. 8 Membership function for the Flow output variable

The designed fuzzy controller is based the following operating principles: for negative error values, the flow should be minimal (MM); for null error values, the flow is very small (MP); for positive error values, the pump flow will be changed according to the level at which the liquid is. The inference rules for this controller are:

1. If (Error is NEG) then (Flow is MM) (1);
2. If (Error is NULO) then (Flow is MP) (1);
3. If (Error is POS) and (Height is PQ) then (Flow is MX) (1);
4. If (Error is POS) and (Height is MD) then (Flow is G) (1);
5. If (Error is POS) and (Height is G) then (Flow is MD) (1);
6. If (Error is POS) and (Height is MG) then (Flow is P) (1)

Figure 9 shows the fuzzy controller in the closed loop plant.

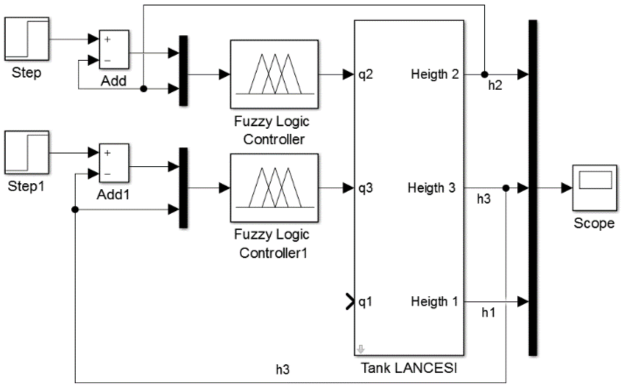


Fig. 9 Fuzzy Controller of the Closed-Loop System

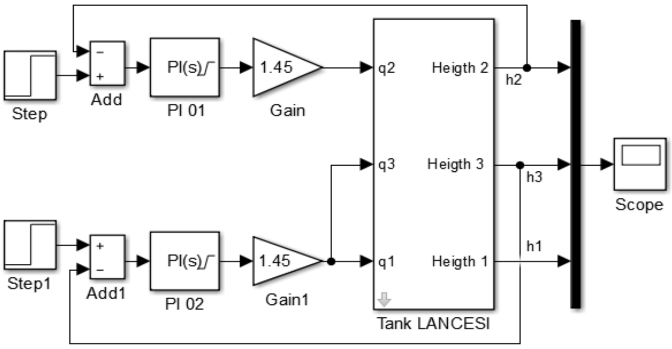


Fig. 10 PI Controller of the Closed-Loop System

4.2 PI controller

The controller normally used in the industry is the PID controller with proportional, integral and derivative control action.

$$D_c = k_p\left(1+\frac{1}{T_i s}+T_D s\right) \tag{14}$$

The PI controller was tuned through ZiegleNichols method and then the gains values for reducing the oscillations and reduce the response time were adjusted.

For the controller design, observing the tank system dynamics, the values overshoot and rise time were adjusted so that the tank 02 had filling time greater than the tank 03. The PI controller in the closed loop plant is shown in Figure 10.

4.3 Fuzzy Controller for Applications in Industrial PLCs

The implementation of the fuzzy controller comprised the following steps: Design the fuzzy system through FuzzyDesigner; Generate additional instructions or Add-On; Integrate additional instruction for the project in RSLogix 5000; and monitor and adjust the fuzzy AOI control running on Logix online using FuzzyDesigner.

The input, output, and rules membership functions are the same as shown in Figures 6-8. Firstly, for the configuration of the blocks of Linguistic Variables, one has to define the Block Name and links between the Input or Output Ports, Units and their Range. Then, the values for each language variable are defined by the Membership Function Editor. For the Rules block, one must define its Name and create the links between the blocks of the input and output language variables. Through the Rule Editor we can define the rules using IF, AND and THEN operations. It has the option to create the rules automatically and the user has the option to change them. The nebulous controller for level control of tanks can be observed in Figure 11.

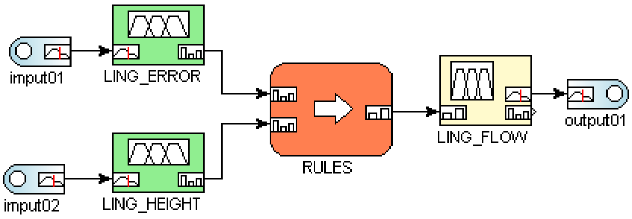
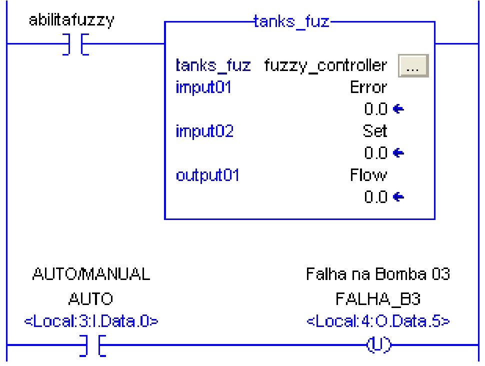


Fig. 11 Fuzzy Controller

Then, an AOI was generated to be exported to RSLogix 5000. After that, the instruction was inserted in the design in Ladder language, which follows the assumptions described in section 2.1, as can be observed in Figure 12.


abilitafuzzy
tanks_fuz
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imput01 Error
0.0
imput02 Set
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output01 Flow
0.0
AUTO/MANUAL
AUTO
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<Local:4:O.Data.5>
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Fig. 12 Fuzzy controller implemented in PLC

4.4 Obtained Results

In order to observe the behavior of the Fuzzy and PI controllers, reference heights were applied at 7cm and 5cm for the filling of tanks 03 and 02, respectively. The results obtained for the two controllers are shown in Figures 13 and 14.

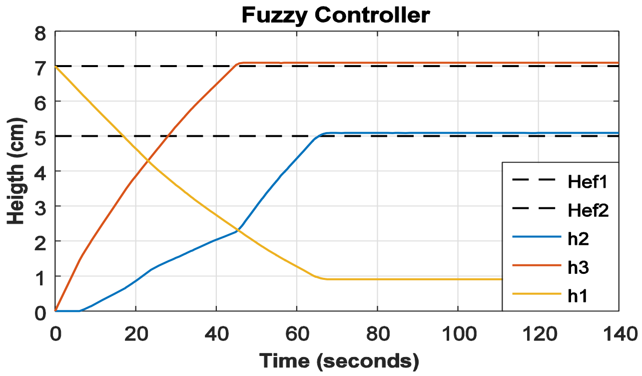

Fig. 13 Step response applied to the fuzzy controller

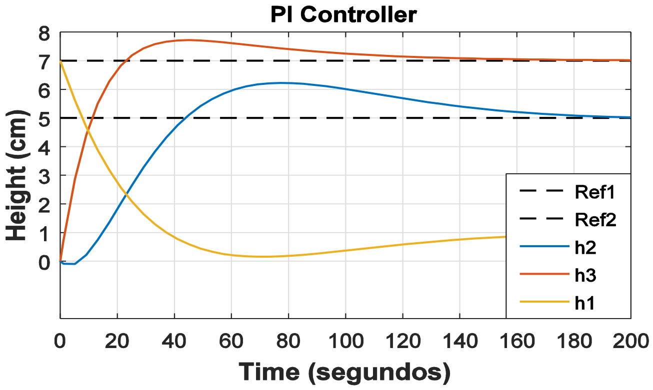

Fig. 14 Step response applied to the PI controller

Figura 14: Step response applied to the PI controller

Comparing the results, the behavior of the tanks was observed using the Fuzzy and PI controllers. For the established references, the Fuzzy controller had a shorter stabilization time and presented lower values of the overshoot.

In order to perform the tests in the system, a square wave with reference period of 100s and amplitude of 1cm was chosen, and it was applied in several points of the tanks to observe the performance of the embedded control strategies.

In general, the Fuzzy controller presented a better result for the system at several different reference points, as shown in Figures 15 and 16.

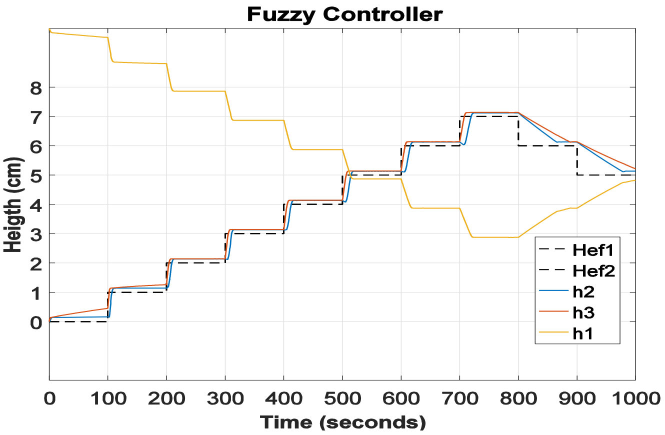

Fig. 15 Fuzzy control at various operating points

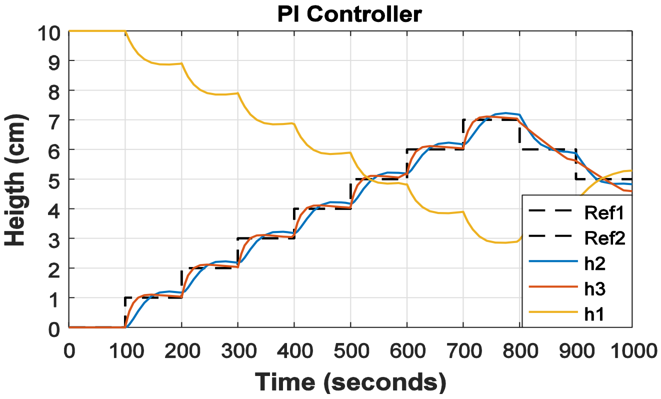

Figure 16: PI control at various operating points

Values obtained through the computer defuzzification were compared with the values obtained from the PLC. The data of the input and output variables are presented in Table III.

Table III Comparison Between Real And Simulated Results

ERROR	HEIGTH	FLOW (PLC)	FLOW (PC)
0.5	2	25.827	25.8
1	3	25.827	25.8
0	3.5	14.410	14.4

0.75	4	22.04	22
-0.5	5	0.667	0.557
0	1	14.410	14.4
0.1	1	23.858	20.1
0.2	1	34.640	34.7
0.3	2	25.857	28.8
0.8	4	22.040	22
2	1	34.640	37.7
3	6	18.483	18.5

V. CONCLUSION

In this paper, a design of a fuzzy controller for multivariable systems, embedded in PLC was presented. In addition, application of the traditional PI controller so that it could analyse the advantages and disadvantages of each one was carried out. Based on Figures 13 and 14, the best results obtained for settling time and overshoot were obtained by the fuzzy controller. On the other hand the PI controller has advantages in values with respect to rise time with less value.

Based on analysis of outputs shown in Figures 15 and 16 we can conclude that both controllers showed good results, according to the criteria adopted, when applied to the plant. It is also seen in the figures that for emptying the tanks, the output cannot follow the setpoint, due to the resistance used and the lack of a pump for quick emptying, which in no way impairs the control efficiency because the purpose of work is to fill and maintain the level at a certain height.

The fuzzy controller in an industrial PLC and applied to the tank level plant control was embedded. The results obtained with the fuzzy controller embedded in the PLC were satisfactory, since they presented a very small error value compared to the values obtained through simulation, as noted in Table III. For future projects, we intend to use fuzzy logic to tune the PID controller gains. The multivariable control using Adaptive control and Dynamic Programming techniques is also being developed in the laboratory.

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REFERENCES

[1] L. Chwif And A. C. Medina, Modelagem e Simulação de Eventos Discretos: Teoria & Aplicações, vol. 4, São Paulo: Elsevier Brasil, 2010.

[2] E. M. M. Costa, Introdução aos Sistemas a Eventos Discretos e à Teoria de Controle Supervisório, 1ª ed., Alta Books, 2004.

[3] P. E. Miyagi, Controle programável: fundamentos do controle de sistemas a eventos discretos.

[4] A.-V. Duka, "PLC Implementation of a Fuzzy System," in *Interdisciplinarity in Engineering International Conference* , Petru Maior, Romania, 2012.

[5] C. M. Franchi And V. L. A. d. Camargo, Controladores lógicos programáveis: sistemas discretos, 1 ed., Érica, 2008.

[6] D. Cartes And L. Wu, "Experimental evaluation of adaptive three-tank level control," *ISA Transactions,* vol. 44, pp. 283-293, 2005.

[7] F. D. M. L. Filho, H. L. Gosmann and A. Bauchpiess, "Controle Fuzzy para Sistema de Nível De Líquidos," *XIV - Congresso Brasileiro de Automática,* pp. 3017-3022, Setembro 2002.

[8] K. Ogata, Engenharia De Controle Moderno, 5 ed., Pearson, 2010.

[9] I. G. Pérez, A. J. C. Godoy and M. C. Gogoy, "Fuzzy Controller based on PLC S7-1200 Application to a Servomotor," in *Informatics in Control, Automation and Robotics (ICINCO),* Viena, 2014.

[10] P. Cintula, C. Fermüller and C. Noguera, Handbook of Mathematical Fuzzy Logic, vol. Iii, 2015.

[11] L. Zadeh, Fuzzy sets as a basis for a theory of possibility, Fuzzy sets and systems, 1978.

[12] L. X. Wang, A course in Fuzzy Systems and Control, 1 ed., Pratice Hall PTR, 1997.

[13] E. A. Elayan, "Design of heuristic fuzzy logic controller for liquid level control," *Fifth International Conference on Intelligent Systems, Modelling and Simulation,* pp. 131-136, 2014.

[14] F. G. Fernandes Júnior, J. S. B. Lopes, A. L. Maitelli, F. . M. U. de Araújo and L. A. H. G. de Oliveira, "Implementação de Controladores PID utilizando Lógica Fuzzy E Instrumentação Industrial," in *VII Simpósio Brasileiro de Automação Inteligente,* São Luís, 2005.