Methodology to Implement a Fuzzy Controller through an Embedded Device

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Abstract -**This paper makes a general description of the characteristics and properties of intelligent controllers, focusing on the design and implementation of a fuzzy controller for the control of a didactic level and flow plant (AMATROL T5552). The document shows the step by step development of the supported controller on the structuring and association of premises, in addition the structure and block diagram of the proposed solution is analyzed in detail, the analysis of the fuzzy rules used for the value control and the comparison of experimental results that validate the correct functioning of the proposed solution.**

Keyword-Fuzzy Controller, PSOC, Embedded Systems, Inference Method.

I. INTRODUCTION

The controllers allow to maintain or stabilize a system around a given value. This is achieved through various strategies, since there are different types of control, among which are: intelligent, conventional, modern, hybrids, among others. Between these trends, intelligent type controllers stand out, because they compensate the system in an adaptive manner and have the ability to control another system without the need for prior modeling [1-3].

The coupling between systems to be controlled and controllers carried out by means of techniques involving the development of models of the systems to be controlled, increase the steady-state error (difference between the expected value and the current value) when estimating an output value, due to the fact that designing the controller does not take into account all the physical interactions of the system to be controlled with its environment. As mentioned before, intelligent controllers partially solve this limitation by means of adaptive strategies that do not require prior knowledge of the system to be controlled. However, this issue is still under exploration because this type of controller is versatile enough to fit a totally unknown system [1-3].

The problem of controlling unknown systems has been addressed in different ways, including through the development of optimization algorithms, random search, bio-inspired, among others. In particular, through the use of fuzzy logic, controllers are designed based on the representation of the behavior of the different states of the system to be controlled. This technique gives controllers the ability to reason to solve problems, since they are constructed using sets of rules that regulate the behavior of the system to be treated [4-5].

These characteristics give fuzzy controllers an advantage over other intelligent controllers, because they emulate behavior similar to human reasoning. When inheriting this characteristic, the controller deduces and generates a logical action from a previous knowledge, which allows it to control one or more variables of the system of simultaneous way. However, one limitation of this technique is the large number of parameters that it may have, due to this they are usually implemented in centralized controllers that are mostly computers [5].

However, the development of technologies for the manufacture of electronic control systems of small size, has allowed to implement a large number of applications that are normally executed in a computer on embedded cards. Due to the importance of this type of systems, this article proposes a methodology to implement a fuzzy controller using an embedded system to control a real plant [6].

This article is arranged as follows: Section 1 presents the main characteristics of an intelligent controller. Section 2 presents a description of an intelligent controller. Section 3 and 4 show a way to implement a fuzzy controller and the results obtained by comparing the results obtained in the simulation and in practice when implementing the controller.

II. METHODOLOGY

A. Fuzzy Logic

Man has been identified scientifically with the name of Homo sapiens, to give a value to his cognitive abilities that give him a sense of his own and identity when developing certain types of abilities. This type of skills has allowed him to solve a large number of problems, by applying concepts that are developed in an abstract way, complex ideas can be materialized. It can be said that when constructing this type of concepts, a human being develops capacities to learn from experience and thus various types of problems [7].

In particular, the study of these concepts and skills has been approached from the point of view of artificial intelligence, which is defined as a capacity associated with certain types of machines or equipment, which seek to emulate characteristics of the human mind through intelligent behavior. However, the development of this subject has allowed it to become an area of study in itself, to establish the characteristics that artifacts that are considered intelligent should have [7].

These technologies with intelligent components, mostly have been developed through some type of software that emulates such behaviors; this software is known as intelligent system, since they are programs that have some characteristics or features of animal or human intelligence. Between the functions that intelligent systems must have are: Intelligence, Systematization, Objective, Sensory capacity, Conceptualization, Rules of action, Memory and Learning. These functions have allowed them to be adapted to several types of application, among which can be found: movement control in robots, character recognition systems, portfolio problem solving, optimization of computer networks, etcetera [8-10].

Some of the results obtained during the development of intelligent systems are based on: perception-action schemes, genetic algorithms, artificial neural networks and reasoning. The perception-action schemes allow you to react to the system from the information of sensory perception. Genetic algorithms are based on Darwinian evolution and when implemented in a system allow one to improve itself from previous experiences. Neural networks make up mechanisms that give a system a certain memory capacity from mathematical constructions. The reasoning has been emulated from the construction of programs that are based on formal logic applied to solving problems, including fuzzy logic [9].

Fuzzy Logic is used to denote a technique by which sets of values are related, from prepositions to represent a statement using a numeric output value. This value is not always binary as is customary in Boolean logic, but it can partially express the truth of an affirmation through a decimal approximation, due to this it is also known as fuzzy logic [11-12].

These approximations are constructed by means of mathematical assumptions called membership functions, which construct linguistic variables to define a set of rules which is called knowledge representation. The composition of a fuzzy control scheme is observed in Fig. 1 and is described below [11]:

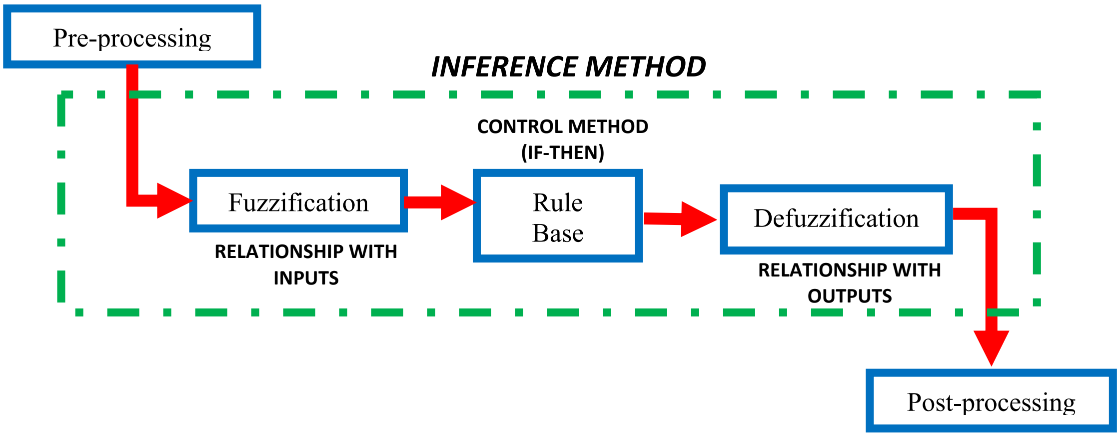


Fig. 1. Diagram of a fuzzy controller.

Pre-processing and Post-processing: Determine the necessary mechanisms to perform the operations of adjustment, acquisition and writing of the information coming from the sensors that are used to modify the operating parameters of the actuator.

Fuzzification: Establishes the relationship between the inputs of the system and the fuzzy relationships that have been established in the control system.

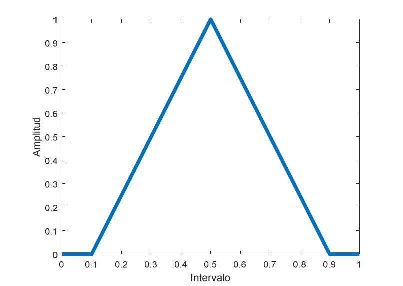
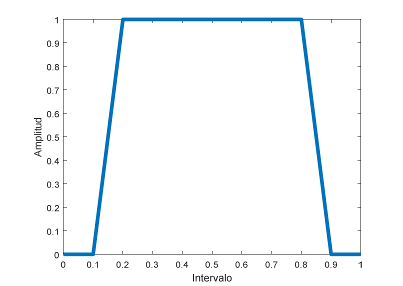
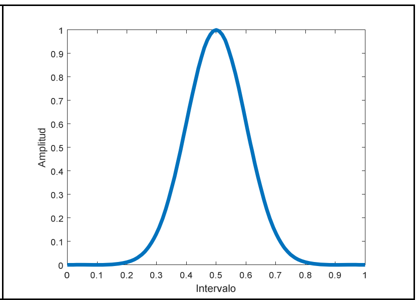
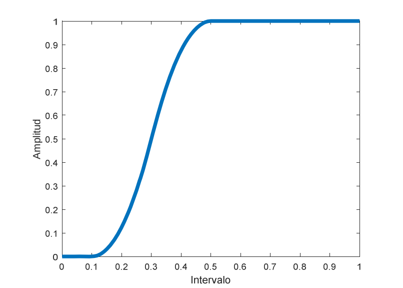
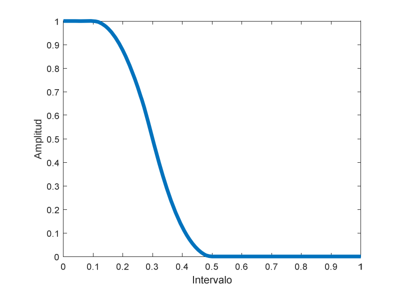
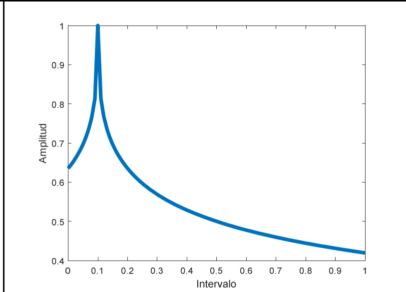
Control method: It allows to build all the possible combinations of rules that the controller can have and on which it is based to modify the output parameters. Normally they are represented as sets of instructions If (conditional) and then (do), that is, when activating the rule, the output behavior is determined.

Defuzzification: Interprets the information from the rules to establish an output value.

The diagram presented in Fig. 1 is called "Method of Inference", since an evaluation of the input using prepositions updates an output. This method covers different types of mechanisms, which are statistical, stochastic, and logical, among others. However, fuzzy logic has been largely framed in logical inference methods, because they are based on set logic to determine the different states of the controller [11].

When based on set logic the relationships between the different elements are known as membership functions, since they determine the degree of belonging of an element to the set and are defined by labels. These functions are represented by mathematical expressions, which are shown graphically in Table I [13].

TABLE I. Membership functions used to express relationships between elements of a fuzzy set (Based on [13]).

		
Triangular	**Trapezoidal**	**Gaussian curve**
$f(x,a,b,c) = \begin{cases} 0 & x \le a \\ \frac{x-a}{b-a} & a \le x \le b \\ \frac{c-x}{c-b} & b \le x \le c \\ 0 & c < x \end{cases}$	$f(x,a,b,c,d) = \begin{cases} 0 & x < a \\ \frac{x-a}{b-a} & a \le x \le b \\ 1 & b \le x \le c \\ \frac{d-x}{d-c} & c \le x \le d \\ 0 & d \le x \end{cases}$	$f(x,\sigma,c) = e^{-\frac{(x-c)^2}{2\sigma^2}}$
		
S shape	**Z shape**	**Generalized Bell**
$f(x,a,b) = \begin{cases} 1 & x < a \\ \left(\frac{2(x-a)}{b-a}\right)^2 & a \le x \le \frac{(a+b)}{2} \\ 1-\left(\frac{2(x-a)}{b-a}\right)^2 & \frac{(a+b)}{2} \le x \le b \\ 0 & x > b \end{cases}$	$f(x,a,b) = \begin{cases} 1 & x < a \\ 1-\left(\frac{2(x-a)}{b-a}\right)^2 & a \le x \le \frac{(a+b)}{2} \\ \left(\frac{2(x-a)}{b-a}\right)^2 & \frac{(a+b)}{2} \le x \le b \\ 0 & x > b \end{cases}$	$f(x,a,b,c) = \left(\frac{1}{1+\left\lvert\frac{x-c}{a}\right\rvert^{2b}}\right)$

The relationship between membership functions is expressed through operations between sets, where the result is represented by another set. There are some basic operations among which are (μ represents the membership function and the subscript is the name of the set):

- ✓ Complement $\mu_{\bar{A}} = 1 - \mu_A$
- ✓ Union $\mu_{AUB} = \max\,[\mu_A, \mu_B]$
- ✓ Intersection $\mu_{A \cap B} = \min\,[\mu_A, \mu_B]$

Graphically in Fig. 2 the relationship established between two fuzzy sets is observed when performing an operation between them. The black line is the new set created when performing operations between sets. This set (μ_y) is the basis for determining the output value of the controller (y_s), which is determined by several mathematical assumptions, such as those shown in equations 1 and 2 [11].

$$y_s = \frac{\int_S y\mu_y dy}{\int_S \mu_y dy} \quad (1)$$

$$y_s = \frac{\sum_{i=1}^{R} \partial_1 \mu_y}{\sum_{i=1}^{R} \mu_y} \quad (2)$$

Equation 1 represents the controller output estimated by the center of gravity method, where S is the domain of the function and y is the output variable of the set of values μ_y. Equation 2 estimates the output of the controller by the area-center method, where ∂_1 represents the average value of the set of values $\mu_y$and R is its domain. The criterion of use of each mathematical expression depends on the system and the case of study, since they are strategies of linking the controller with a physical medium and the response of the controller depends on the approximations made by this type of mathematical assumptions. The following section shows the application of all the concepts presented in this section by designing the controller for a system [11].

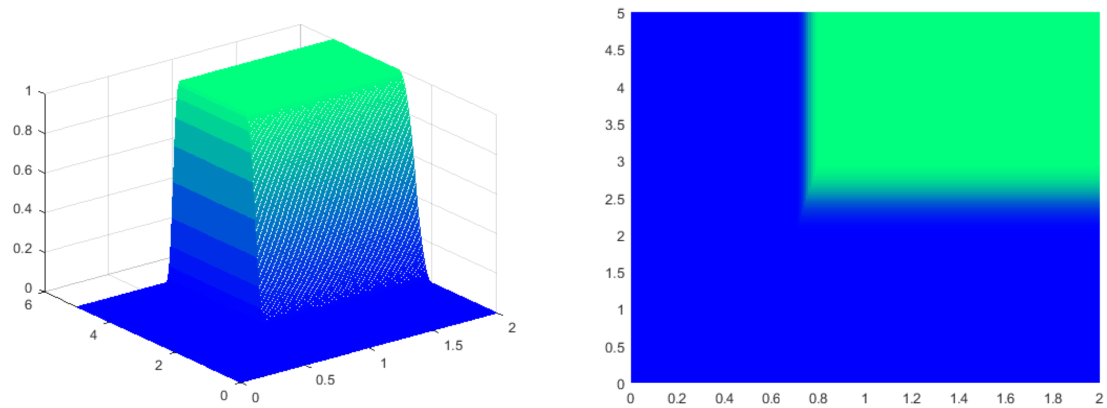
III. DESIGN AND IMPLEMENTATION

As mentioned above, a controller is a device that is responsible for correcting the error between the measured value and the expected value, modifying the transient response it has in the output. This behavior can be emulated using fuzzy logic, from the construction of different premises that allow to compensate the output from a series of rules. The premises or prepositions are evaluated using the operations between sets (mentioned in the previous number).

Normally a controller is constructed using premises that relate variables and linguistic values. Where a linguistic variable indicates the possible states of the system and are called linguistic values (or belonging functions) to the set of values that have the states of the system.

For example, the design of a controller that operates a valve when detecting a very high pressure in a tank by means of fuzzy logic could be structured in the following way:

- ✓ Raise the premise
  - o If the **pressure** is **high**, then the **valve** is **on**.
- ✓ As it is observed x and y are linguistic variables in this case ***x*** would be the **pressure** e and the **valve**. There is also a set of possible values to determine their status (Linguistic values) A and B, which are **high** and **on** respectively. The premise can be represented by a diffuse relation$R = AXB$, which is mathematically described as a Cartesian product.
- ✓ Now the possible values of A and B must be defined by means of a membership function. In case 1 the term "high" is associated with the pressure when it exceeds a range of 2 to 3 PSI and in case 2 an ignition value can be the threshold of excitation of the transistor, that is, the change of a work voltage between 0.7 and 0.8 volts.
- ✓ Since they are functions that represent binary states, the function in the form of S and Z is normally used to define these variables, as shown below:
  - o $High\ Pressure = \mu_A = sigmf(x, [2,3]),$
    $x\epsilon[0,5]\ Pressure\ range\ in\ the\ boiler.$
  - o $TurnonValve = \mu_B = sigmf(y, [0.7,0.8]),$
    $y\epsilon[0,2]$Activation voltage of the transistor that drives the valve.
- ✓ Then the Cartesian product is made between sets, remember that a Cartesian product is the combination of all the elements that define two sets. In this case, because the assemblies have many elements, the operation was carried out using software, the result of which is presented graphically in Fig. 2.



a) b)

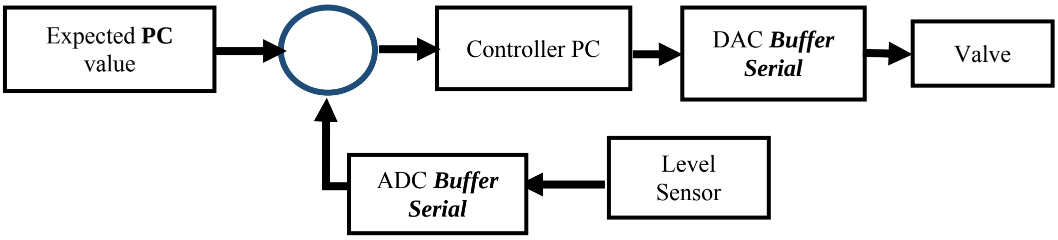
Fig. 2. Cartesian product represented graphically.a) Set of output values. b) Top view of the Output

As shown in Fig. 2a, it is obtained a surface of which we can say that a set of them will only activate the valve when fulfilling the condition, more specifically, in Fig. 2b, a group of combinations of values is observed in the upper part, which the valve is activated in a lighter color.

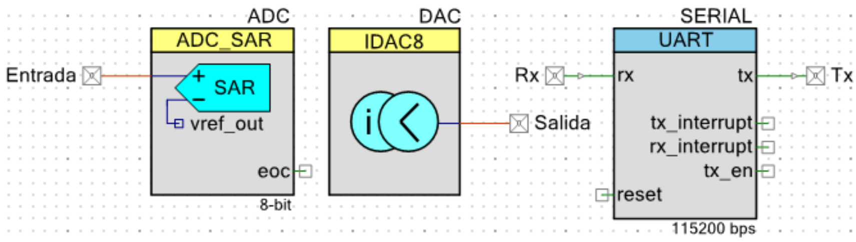
In practice, the way to associate the premises with the controller is to perform the mapping of the input value, which represents a term of the set of solutions given by the Cartesian product, then this term approaches a decimal number and is sent as output from the controller. However, due to the large number of operations that must be performed to estimate the output values, there are different assistants to design fuzzy controllers, such as: FuzzyLogic, FuzzyLite or Fuzzytech.

These assistants allow to design the fuzzy controller and in some cases to foresee its operation through a simulation, which can be linked with a controller to manipulate the physical variable. In this case a control will be made to regulate the level of a system regulating a proportional valve that works in a range of 4-20mA. The level will be regulated using a fuzzy controller located on a computer, which will be linked by serial communication (Speed of 115200bps, odd parity, stop bit 0) to a PSLO 5LP. The PSOC feeds the controller with the status of the sensor, to update its output based on the estimated value.

To use this method, normalization of the input and output variables must be done before sending them through the serial port, except that the variables that define the physical inputs and outputs must be modified and addressed. Basically an analog-digital converter is required that is responsible for reading the level sensor and a digital-analog converter that is responsible for setting the output value that will have the proportional valve (As shown in Fig. 3).



a)



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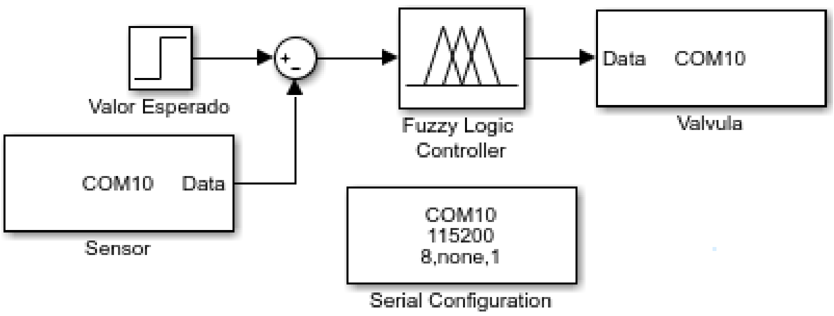
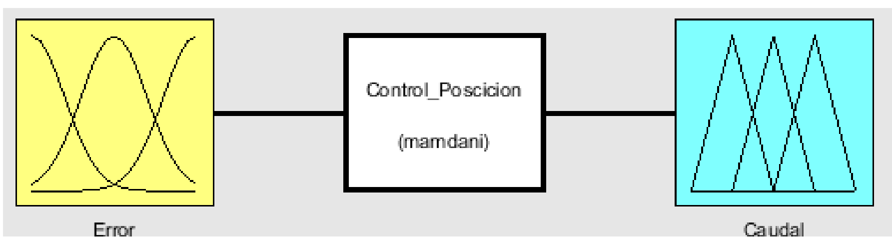


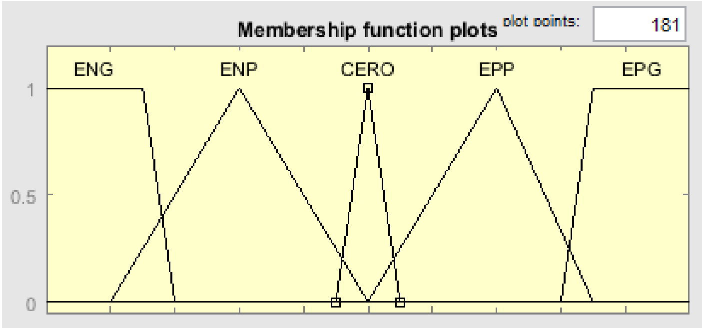
c)

Fig. 3. Basic structure of the controller. a) Scheme of the fuzzy controller. b) Architecture defined in the PSOC 5LP. c) Controller Diagram.

Initially, to design the controller, the membership functions are defined for the linguistic variables that determine the possible states of the inputs and outputs as shown in Fig. 4. The meanings of the belonging functions are described in Table II, since from the combinations between them, the behavior of the fuzzy controller is established (Fig. 5). Keeping in mind that the possible values of the error go from -100 to 100 and those of exit of 0 to 20 because it is the range of operation of the valve.



a)



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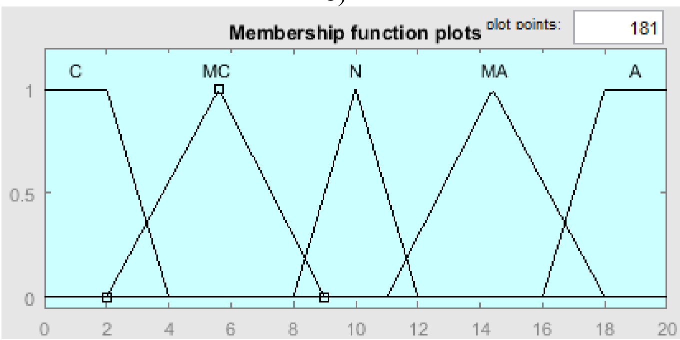


c)

Fig. 4. Controller composition. a) Controller architecture. b) Input linguistic variable.c) Output linguistic variable.

TABLE II. Composition of linguistic variables

Variable Input	Output Variable
ENG = Large negative error value	C = Valve Closed
ENP = Small negative error value	MC = Valve open at 25%
CERO = No error	N = Valve open at 50%
EPP = Small positive error value	MA = Valve open at 75%
EPG = Large positive error value	A = Open Valve

1. If (Error is CERO) then (Nivel is C) (1)
2. If (Error is ENP) then (Nivel is MC) (1)
3. If (Error is EPP) then (Nivel is MA) (1)
4. If (Error is EPG) then (Nivel is A) (1)
5. If (Error is ENG) then (Nivel is N) (1)

Fig. 5.Rules established to determine the behavior of the valve to regulate the level.

When designing the controller, it must be linked to the PSOC through the implementation of a C ++ code, which is based on the following algorithm:

Algorithm 1.Operation of PSOC 5LP

While Terminating Condition = True **do**
    Input = Read digital analog converter;
    Error = Desired Value-Entry;
    Send via serial (Error)
    Memory = Fuzzification (Error);
    Memory = Evaluate rule (Memory);
    Memory = Defuzzification by means of the centroid method (Memory);
    Receive via Serial (Memory)
    Output = Normalize value (Memory);
    Send value to the analog digital converter (Output);
End While

IV. EXPERIMENTAL RESULTS

The performance of the designed controller was evaluated through an assembly that was carried out in the T5552 level and flow control system of the AMATROL brand. The output of the ultrasound level sensor gives a current signal that varies between 4-20mA, due to this a resistance of 250 ohms was connected to convert the current into electrical voltage and the output was connected directly to the valve, since, the PSOS 5LP generates a current loop of 4 to 20 mA (as shown in Fig. 6).

Initially, the behavior of the system was simulated with a conventional controller using the transfer function, which was estimated from experimental data measured using an oscilloscope to know if the system is stable. The method used to find the transfer function was a polynomial approximation, which determines the order of the polynomials of the numerator and denominator as shown in Fig. 7. When estimating the transfer function, a correlation coefficient of 76.67% was obtained. Which allows estimating the behavior of the real actuator in different states as shown in Table III.

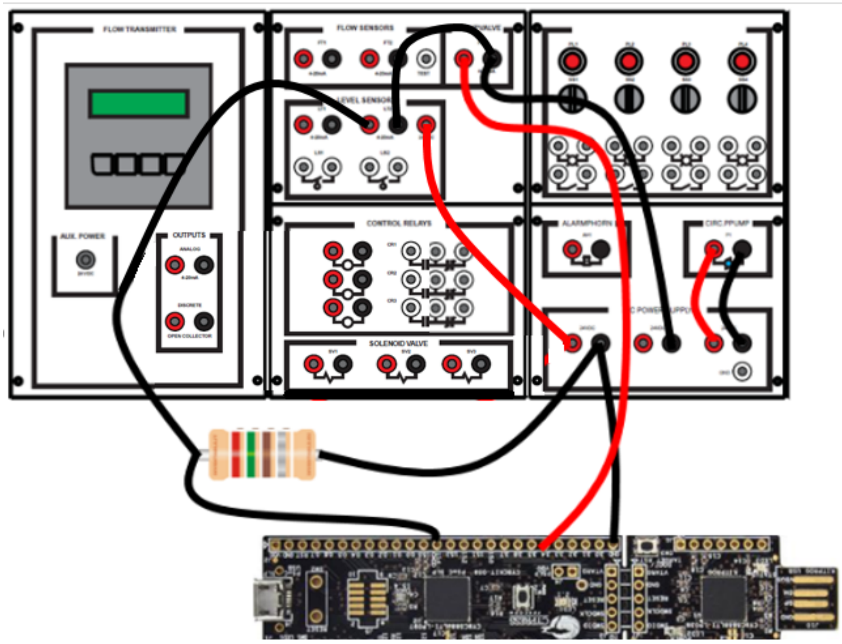
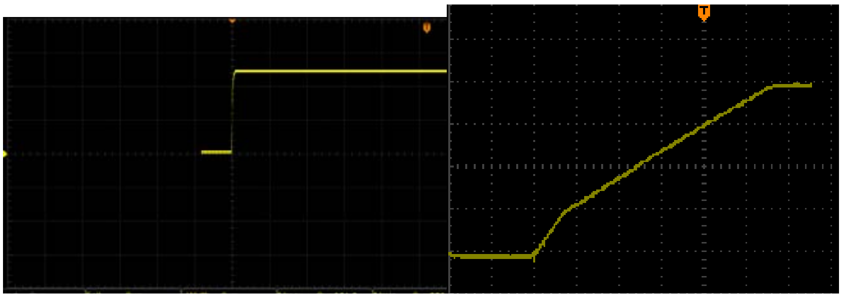
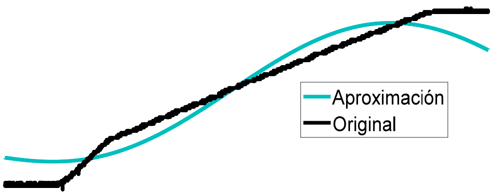


Fig. 6. Control panel connections of the T5552 process control system.



a) b)

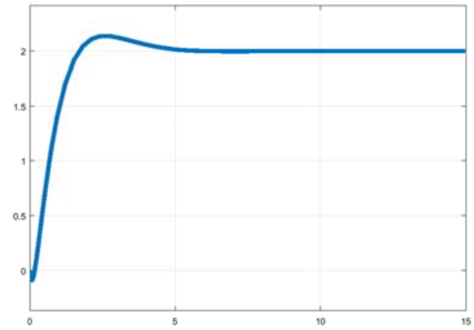
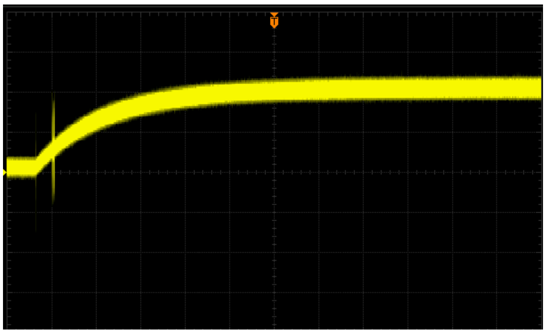


$$H(s) = \frac{5.253e{-}06s - 4.783e{-}09}{s\text{^}2 + 0.0006044\, s + 3.666e{-}08}$$

c) d)

Fig. 7.Components of the transfer function. a) Input signal (activation of the pump). b) Output signal in open loop (tank filling). c) Response of the transfer function. d) Mathematical expression

TABLEIII. Response of a conventional controller and a fuzzy one when arriving at a level of 2 inches or 8mA approximately

Simulation (Conventional PID)	Reality (Fuzzy Controller)
	

V. CONCLUSIONS

The proposed methodology allows the implementation of fuzzy controllers, to control second order systems as shown in Table III. The implemented controller emulates the behavior of a PID controller. However, there is a margin of error due to the type of approach performed and the data measured, since the simulated system does not perfectly emulate all the physical interactions of the controller and the environment.

The PSLO 5LP works perfectly as a coupling interface between the computer and the process control system T5552, since it allows the transfer of information without any type of inconvenience. However, this strategy is limited to systems with a response time of at least 500 milliseconds, because the exchange of information acts as a delay reducing the response time of the controller and preventing it from being in real time.

The transfer function has an order of 2 since, when increasing the number of coefficients, a response that can be considered significantly better was not found, that is, no response proposed by the approach method used exceeds 80% of correlation.

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REFERENCES

[1] V. S. Pinnamaraju and A. K. Tangirala, "Identification of approximate models for LTI multiscale systems," 2018 Indian Control Conference (ICC), Kanpur, 2018, pp. 71-76. doi: 10.1109/INDIANCC.2018.8307956.
[2] G. C. Calafiore and C. Novara, "Control of MIMO nonlinear systems via approximate model inversion," 2017 IEEE 56th Annual Conference on Decision and Control (CDC), Melbourne, VIC, 2017, pp. 6726-6731.
[3] V. Sherstjuk and M. Zharikova, "Approximate model of spatially distributed Markov process for GIS-based decision support system," 2017 12th International Scientific and Technical Conference on Computer Sciences and Information Technologies (CSIT), Lviv, 2017, pp. 300-304.
[4] V. Sherstjuk, M. Zharikova and I. Sokol, "Approximate spatial model based on fuzzy-rough topology for real-time decision support systems," 2017 IEEE First Ukraine Conference on Electrical and Computer Engineering (UKRCON), Kiev, 2017, pp. 1037-1042.
[5] W. Premchaiswadi, P. Porouhan and N. Premchaiswadi, "Process Modeling, Behavior Analytics and Group Performance Assessment of e-Learning Logs Via Fuzzy Miner Algorithm," 2018 IEEE 42nd Annual Computer Software and Applications Conference (COMPSAC), Tokyo, Japan, 2018, pp. 304-309.
[6] O. Elkeelany and S. Moosa, "Towards real-time embeded system design for video capturing and privacy protection," 2016 Future Technologies Conference (FTC), San Francisco, CA, 2016, pp. 593-599.
[7] S. Chinchole and S. Patel, "Artificial intelligence and sensors based assistive system for the visually impaired people," 2017 International Conference on Intelligent Sustainable Systems (ICISS), Palladam, India, 2017, pp. 16-19.
[8] M. Deshpande and V. Rao, "Depression detection using emotion artificial intelligence," 2017 International Conference on Intelligent Sustainable Systems (ICISS), Palladam, India, 2017, pp. 858-862.
[9] A. K. Rathinam, Y. Lee, D. N. C. Ling and R. Singh, "A review of image processing leading to artificial intelligence methods to detect instruments in ultrasound guided minimally invasive surgical procedures," 2017 IEEE International Conference on Power, Control, Signals and Instrumentation Engineering (ICPCSI), Chennai, India, 2017, pp. 3074-3079.
[10] A. Rego, A. Canovas, J. M. Jimenez and J. Lloret, "An Artificial Intelligence System for QoS and QoE Guarantee in IoT using Software Defined Networks," in IEEE Access.
[11] F. Topaloğlu and H. Pehlıvan, "Analysis of the effects of different fuzzy membership functions for wind power plant installation parameters," 2018 6th International Symposium on Digital Forensic and Security (ISDFS), Antalya, 2018, pp. 1-6.
[12] E. H. Mamdani, "Application of Fuzzy Logic to Approximate Reasoning Using Linguistic Synthesis," in IEEE Transactions on Computers, vol. C-26, no. 12, pp. 1182-1191, Dec. 1977.
[13] Ulrich Höhle, Fuzzy sets and sheaves. Part I: Basic concepts, Fuzzy Sets and Systems, Volume 158, Issue 11, 2007, Pages 1143-1174, ISSN 0165-0114.