Fuzzy Controller based on PLC S7-1200
Application to a Servomotor

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Abstract: This paper presents the design and validation of a fuzzy logic controller implemented with an industrial programmable logic controller (PLC). The chosen device belongs to the S7-1200 series of Siemens, whereas the code has been developed in Ladder Diagram language using the software TIA Portal. The fuzzy controller is of Mamdani type and is applied to control the speed of a servomotor. A comparison with a Simulink/Matlab fuzzy controller is done to validate the developed software module and to show the feasibility of the PLC to manage this kind of control algorithm.

1 INTRODUCTION

Fuzzy logic emerged from studies of Lofti A. Zadeh in 1965. It is a mathematical formalism to represent the human reasoning so it is very useful in Expert Systems and Artificial Intelligence applications. Fuzzy based control or fuzzy control began to develop at 70's. Nowadays it is applied in several processes with demonstrated effectiveness and great interest from the scientific and technologic community.

The main advantages of fuzzy logic for process control are fast decision capability, applicability to nonlinear systems, and intuitive definition of the controller behaviour. Furthermore, there is no need of either historical data or mathematical models like other intelligent controllers such as neural networks or genetic algorithms.

PLC are electronic devices to control sequential processes. Their main features are high reliability and robustness. They are widely applied in industrial processes, but are used in other fields such as home and building automation, renewable energies systems, etc.

It is evident the interest of combining and integrating an advanced control method, like fuzzy logic, with traditional automation devices, PLC. This way, PLC can be applied in systems where it is difficult to obtain accurate models or with nonlinearities, delays, etc.

The calculation power of modern PLC allows implementing advanced control strategies in their programs. The implementation of fuzzy controllers in PLC makes them useful for many applications in industrial environment.

Lots of PLC manufacturers offer additional software packages or modules to program fuzzy controllers, FLC (Fuzzy Logic Controller). The disadvantages are the consequent cost increment and, mainly, an absolute lack of flexibility to modify their codification.

On the other hand, due to the growing interest and application to process control, fuzzy control has a specific section in the open international standard IEC 1131, which is referred to PLC standardization. In 1997, the part IEC 1131-7 defined the Fuzzy Control Language, FCL, i.e., a group of functions to program applications of fuzzy control. In addition, several research works study advanced fuzzy methods such as fuzzy modelling and control (Piegat, 2001; Zhang and Liu, 2006), and neuro-fuzzy controllers (Joelianto, 2013).

Scientific literature about controllers based on fuzzy logic implemented by means of PLC is scarce. In the case of Siemens s7-1200 model, no works have been found in the studied bibliography. Despite that scarcity, there are some examples which are exposed from this point.

In (Ruan and Van der Wal, 1998), a fuzzy controller is developed in an Omron PLC (Sysmac C200HS) to control the output power of a nuclear reactor. The programming of the FLC is performed using specific software and module. In (Li and Tso, 1999) a fuzzy controller with an Omron PLC is

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applied to a thermal process. The limitation in the processing capacity of the PLC led to the authors to run a program in a PC to solve the knowledge base.

Karasakal et al. (Karasakal, 2005) use a Siemens PLC s7-200 to implement a fuzzy PID controller with auto tuning and compare it with classical PID. Bogdan et al. (Bogdan, 2007) implement a Self-Learning Fuzzy Logic Controller, SLFLC, for Simatic PLC which is applied to control the position of a servo motor. Song et al. (Song, 2007) develop a fuzzy controller based on a Siemens PLC s7-200 to automate the processing of egg powder. Sun et al. (2009) apply a fuzzy controller with a Siemens PLC s7-300 to a sewage disposal system of a chemical plant. The authors indicate the high cost of modules for fuzzy logic of the manufacturer. They allege that the developed controller is accurate and flexible due to the ability to adapt to user demands.

Aydogmus (Aydogmus, 2009) present a fuzzy controller implemented with a Siemens PLC s7-200 to control a tank level. This researcher describes his proposal as a low cost solution because of the fact that it has been developed without using fuzzy logic software packages. In (Saad and Arrofiq, 2012) a method to develop fuzzy-PID controllers in PLC for PWM-driven induction motors is presented. In (Cingolani and Alcalá, 2012) an open code library based on Java, iFuzzyLogic, to design and implement fuzzy controllers following the standard IEC 61131-7 for Fuzzy Control Language is exposed. Furthermore, a review of 25 software packages dedicated to develop fuzzy controllers is performed, highlighting the interest received by this control technique.

On the other hand, Bosque et al. (Bosque, 2014) assert that the programming flexibility and the cost of PLC contribute to the implementation of fuzzy control in industrial environments.

The main objective of this work is the design and validation of a software module to implement fuzzy logic controllers with a PLC. The case of speed control for a servomotor is considered for this purpose.

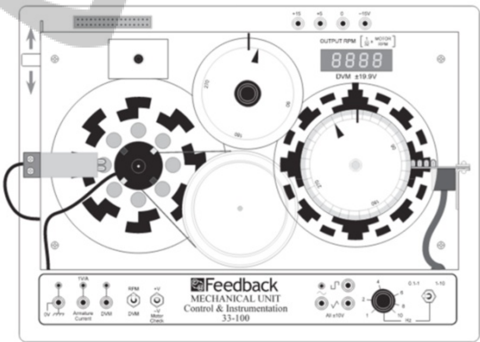
The rest of the paper is organized as follows. Section 2 describes the main features of the PLC, the servomotor and the software involved. In section 3 the programming of the module for fuzzy control with the PLC s7-1200 is shown. In section 4 a fuzzy controller designed for speed control of the servomotor is described. The experimental results are shown in section 5. Finally, conclusions and further works are outlined.

2 SYSTEM DESCRIPTION

The module for fuzzy control has been developed for the PLC s7-1200 of Siemens. TIA Portal V11 (Totally Integrated Automation Portal) of Siemens is the software used to program and configure the PLC. WinCC flexible 2008 Runtime is used to design a Human-Machine Interface, HMI, based on PC to monitor the process under control and to store the data for further analysis.

The CPU model of the PLC is the 1214C which incorporates Ethernet/PROFINET interface and 2 analogue inputs. In addition, an added Signal Board, SB 1232 AQ1, module provides an analogue output that will be used to apply the control signal to the servomotor.

The servomotor corresponds to the Servo Fundamentals Trainer (33-001) by Feedback (Figure 1). On the one hand, it comprises a mechanical unit (33-100) which contains the DC motor, an analogue tachogenerator, encoders, potentiometers, magnetic brake and other supporting electronics. On the other hand, an analogue unit (33-110) and a power supply (01-100) provide the power supplies and signals. Connection between both units is by way of a ribbon cable for signal transmission.



a)

Figure 1: Servo Fundamentals Trainer (33-001).

This equipment allows open and closed loop speed and position control. It can be linked with a PC through USB connection. In our case, these possibilities are not used because both the control and data acquisition are carried out by the PLC.

2.1 System Integration

The PLC is responsible of operations such as sensors data acquisition, fuzzy control algorithm execution and driving of actuators according to the control signal generated. Furthermore, the PLC communicates with the system for monitoring

(HMI) through the Ethernet network where both devices are integrated. Figure 2 illustrates the scheme of connections between the components of the system. The HMI application runs in the computer connected to the PLC via Ethernet by using the PROFINET interface. This application accesses to data blocks in the PLC memory to be stored and displayed.

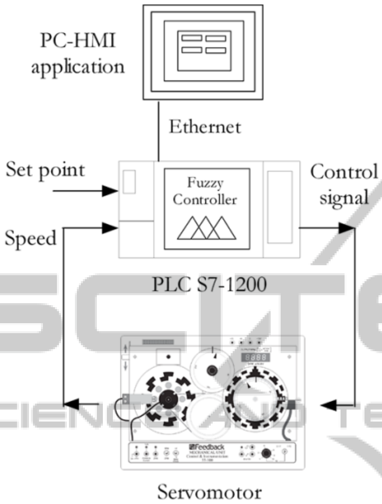


Figure 2: Connections between PLC, HMI and Servo.

3 FUZZY CONTROL MODULE

Fuzzy logic allows using the common language to describe problems; this is, to process inaccurate and qualitative information in terms of fuzzy sets. Because of this, fuzzy logic is better than classical logic to represent the human knowledge and reasoning. Fuzzy control consists on leading the process output to a desired value with control actions calculated according to a fuzzy description of such process. Fuzzy control is the main field of application of fuzzy logic and uses the experience in manual operation over a plant to design the control system.

The general structure of a fuzzy controller is depicted in the block diagram of Figure 3. The fuzzification of each natural value of the inputs consists in determining the degree of membership to each defined fuzzy set. The inference engine uses the fuzzy rules to process the input information and to generate the controller output. The defuzzification process converts the result of the fuzzy rules into a numeric or crisp value, non-fuzzy, which acts as the controller output signal.

In the module here presented each one of those parts has been solved by means of a subroutine, called function or FC, in the PLC.

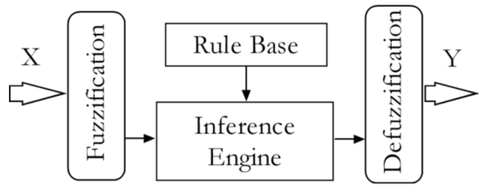


Figure 3: Block diagram of a fuzzy controller.

Mamdani type fuzzy controllers can be implemented with the developed module. This kind is more intuitive and adapted to the human language with respect to Sugeno type.

Ladder Diagram language has been used to develop the required code to perform the operations of the fuzzy algorithm.

The maximum number of variables is 6, for each one of them can be defined up to 5 subsets. Each subset is determined by means of 4 points. The available fuzzy logic operations are AND and OR. The first one can be applied by the Product or the Minimum procedure, whereas the OR operation is solved by the Maximum method. The rule base can be composed of up to 9 rules. The implication method is Min. The aggregation method is Max. Only one output variable is considered, so the controllers developed are of MISO (Multiple Inputs Single Output) type.

The design of the controller and its parameters must be performed in a stage before the configuration of the PLC. Hence, the developed module does not serve to design the fuzzy controller, but the implementation of such controller. Once the engineer or designer has established the controller parameters (I/O, rules, etc.); these ones will be programmed in the PLC via the TIA Portal software.

3.1 Fuzzy Module Structure

The fuzzy module has been developed to be versatile and user friendly. Furthermore, the use of Ladder diagram with a modular design provides a flexible very useful for future improvements structure.

The user has to specify and configure in the PLC the following parameters of the fuzzy controller:

- Input variables: number, points defining fuzzy subsets.
- Output variable: points defining fuzzy subsets.
- Rules: number, premises and conclusions.
- Fuzzy logic operation: AND or OR, with Minimum or Product options for AND.

In order to optimize the CPU performance according to the available resources, several functions, FC, have been included. Each FC is designed to carry out a determined processing of information. These blocks have input and output data, but do not require associated data block which would occupy memory and would slow down the calculations. The required data (variables, points of membership functions, etc.) are stored in Data Blocks, DB, which are available for the FCs.

Figure 4 shows the flowchart of the module for fuzzy control in the s7-1200 PLC. From the main program, OB1, the FCs that implement the different parts of the fuzzy control algorithm are called sequentially. Reading of input data and writing of the output signal are made directly in the OB1. The control signal is applied to the servomotor by means of the voltage analogue output obtained through the Signal Board.

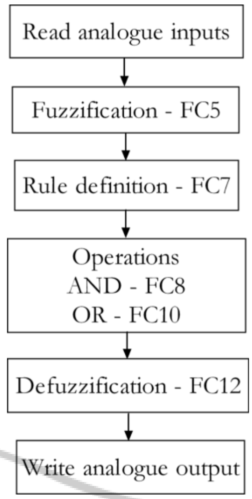


Figure 4: Flowchart of the module for fuzzy control in PLC.

3.1.1 Fuzzification

The Trapezoidal function acts as basis to define the membership functions, so there are 5 available functions: Trapezoidal, S, Z, Triangular and Singleton. In the case of functions S and Z type, due to their configuration as particular cases of the Trapezoidal one, they are not soft, simplifying this way their codification.

The maximum number of subsets is 5 and the linguistic labels are S1, S2, S3, S4 and S5 for all the variables. To define these functions the user has to introduce the values of 4 points signalled as A, B, C and D in Figure 5, for all subsets of each variable. It is not required to specify the range of input variables due to the fact that it is implicitly expressed with the points that define the subsets as said before.

The calculation of membership degrees begins with a comparison between the actual value of the variable and the points that define the functions.

If the input is located in an interval which corresponds to a membership degree of 0 or 1, such value is directly assigned (no more operation is needed). In another case, the equation that defines the straight line is determined and used to calculate the membership degree. Figure 6 shows the described sequence as flow diagram, where MD means membership degree.

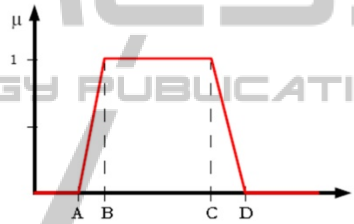


Figure 5: Points required to define the Trapezoidal membership function.

3.1.2 Rules

A maximum of 9 rules can be formulated, all of them of Mamdani type. This number of rules has been considered adequate for the application here exposed, but a higher number can be programmed.

Each one of these rules can incorporate all of the input variables that have been defined. In addition, each rule has a weight factor associated, which can vary between 0 and 1.

A FC, called "Rule definition", carries out the selection of the fuzzy subsets of the inputs according to the user specifications to constitute the antecedents or premises. To this aim, the user indicates if an input must be included in each rule using a 1 bit memory position.

Later, for each variable an integer number defines the subset associated to such variable. Based on this information, a multiplexer selects the membership degree that corresponds to the defined subset, generating the premises. The same procedure is followed for the subsets associated to the output variable to define the consequents. Figure 7 illustrates the multiplexation process for the rule 1, were, μS1(V1) is the membership degree to the first subset of the first variable.

3.1.3 Operations

The fuzzy logic operations can be chosen between the intersection (AND) and the union (OR).

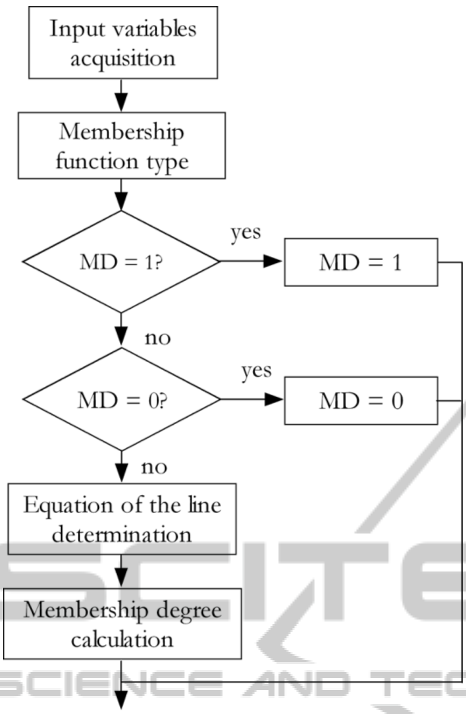


Figure 6: Flowchart for fuzzification of input variables.

Furthermore, there are two options to select the method for the AND operation: Minimum and Product. In the event of OR operation, the applied method is Maximum. These selections are defined using a bit position.

The procedures for performing these operations are briefly described. In the case of AND operation using minimum criterion, successive comparisons between the membership degrees are performed until obtaining the minimum value. When the product method is chosen, the membership degrees are multiplied (Figure 8). For the OR operation, the maximum criterion is performed by means of successive comparisons until reaching the maximum membership degree.

3.1.4 Defuzzification

The programmed defuzzification method is the centroid, also called center of gravity.

The defuzzified output signal is obtained applying the following equation:

$$y = \frac{\sum_i^R p_i * A_{(Ri)}}{\sum_i^R A_{(Ri)}} \quad (1)$$

where p_i is the centre of the membership function of the consequent of each rule, and $A_{(Ri)}$ is the surface of such subset truncated by the membership degree result of the premises of such rule. This last procedure corresponds to the implication method Minimum. This area is calculated as the surface of a trapezoid, resulting very simple from the point of view of computational resources. Figure 9 shows the flow diagram of the defuzzification process.

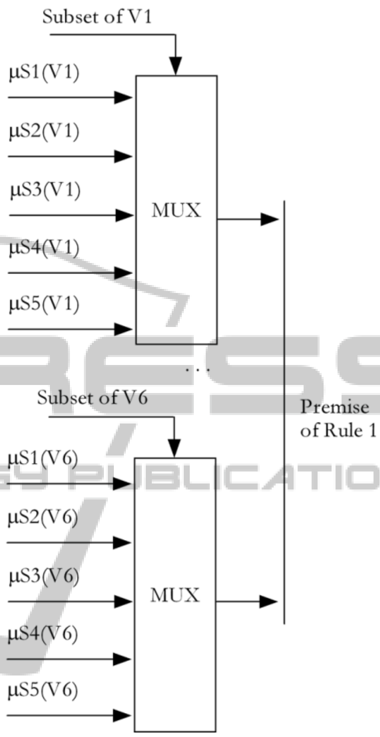


Figure 7: Multiplexation for premises configuration.

4 FUZZY CONTROLLER FOR SERVO SPEED CONTROL

The servomotor is a well-known first order system so its speed control is considered an illustrative process to test and validate the developed fuzzy module.

It is necessary to clarify that the aim of this work is not to design or optimize a controller for the servomotor, but test and validate the FLC.

The membership functions and rules were adjusted during trials with different input signals. Simulink and Fuzzy Logic Toolbox of Matlab were used at this stage. Once the FLC was tuned, it was coded in the PLC program language.

The input signals are the voltages of reference or set point speed and the error of the actual speed. The output signal is generated by the FLC for the servomotor to reach the desired speed.

The structure of the FLC has been made as simple as possible. The fuzzy controller is of Mamdani type, the And method is Min, the implication operator is Min, the Aggregation is Max and the defuzzification strategy is the Centroid of area. Triangular membership functions are adequate for this application, so they have been used for input and output variables. Membership functions for speed set point, error signal and output variable are presented in Figure 10. These variables have been defined by means of 3 fuzzy subsets despite the fact that the module is able to manage 5 subsets.

Input ranges goes from 0 to 8 V for the speed set point. Although the interval where the servomotor behaviour is lineal goes from 3 to 8 V. In the case of the error signal, the input range is -8 to 8 V. The range of output signal is 3.5 to 9 V. The fuzzy rules that define the FLC behaviour are represented by means of a matrix as can be seen in Table 1.

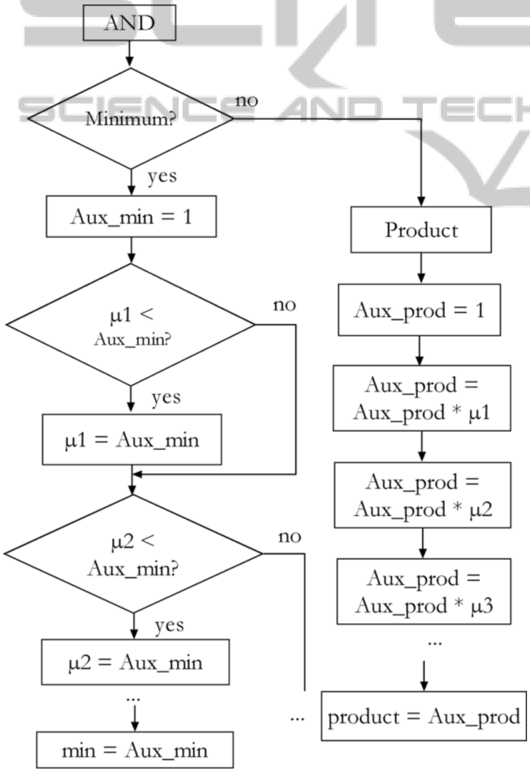


Figure 8: Flowchart of AND operation.

Table 1: Rules of the FLC.

Set point/Error	S1	S2	S3
S1	S1	S1	S2
S2	S1	S2	S3
S3	S2	S3	S3

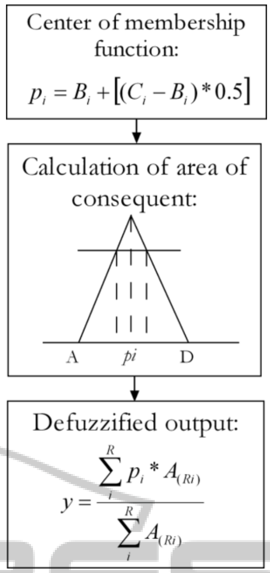


Figure 9: Flowchart of defuzzification process.

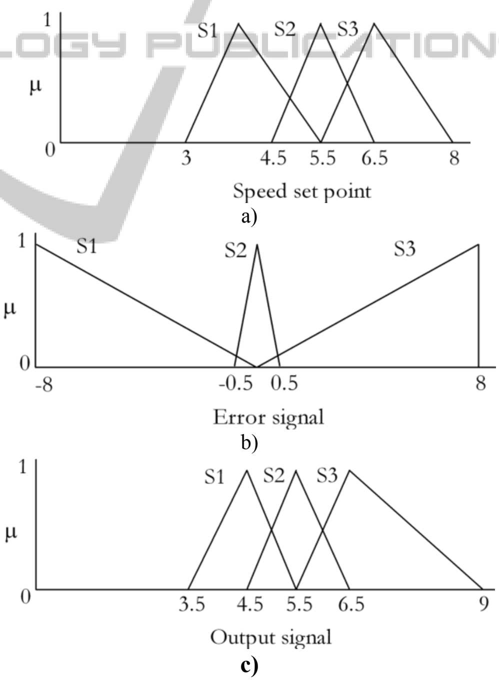


Figure 10: Membership functions for: a) Speed set point, b) Error signal, c) Output signal.

5 EXPERIMENTAL RESULTS

With the aim of evaluating fuzzy module behaviour, a comparison with the FLC designed using the Fuzzy Logic Toolbox of Matlab is carried out. This way, a set of simulations has been developed in Simulink using the scheme shown in Figure 11. The transfer function for the servomotor (Equation 2) was experimentally obtained.

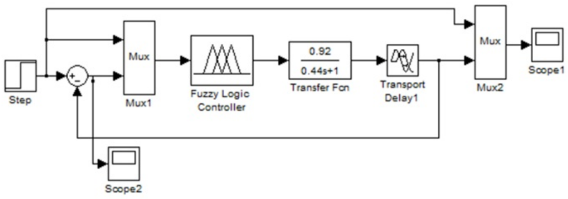
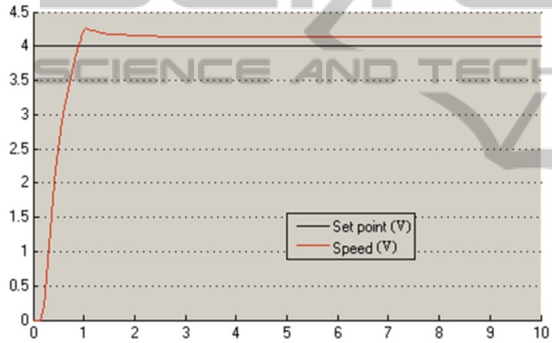


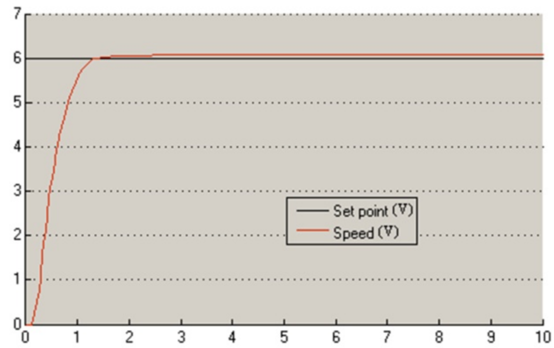
Figure 11: Simulink scheme to simulate a fuzzy controller applied to the servomotor.

$$FDT=\frac{0.92}{0.44s+1} \quad (2)$$

Figure 12 shows the servomotor response for three steps with amplitudes of 4 and 6 V. In this figure the set point speed is in black, while the servomotor speed corresponds to the red line.



a)



b)

Figure 12: Servomotor speed response simulation applying step input with amplitude: a) 4 V, b) 6 V.

Once the proposed FLC for controlling the servomotor has been simulated, the next step consists in testing the fuzzy module under real conditions. To this aim, the FLC implemented in the PLC has been applied to the servomotor for several trials. Figure 13 contains a photograph of the whole system connected in the laboratory.

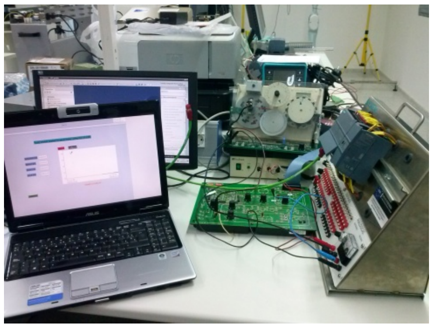
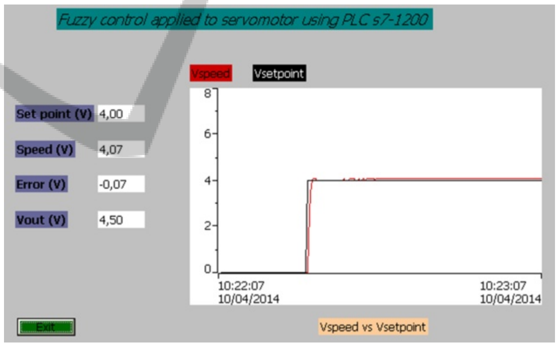


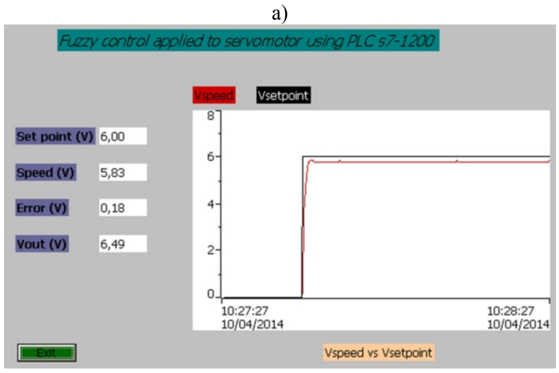
Figure 13: Components of the system in the laboratory.

The HMI allows visualizing in real-time the numerical and graphical evolution of the servomotor speed as can be seen in Figure 14. The corresponding colours to the variables are the same of Figure 12. The step amplitudes are the same as shown for the simulations, 4, 5.5 and 6 V.

Table 2 contains the steady-state error expressed as a percentage for the most representative trials in both of the situations, the simulation and the PLC implementation.



a)



b)

Figure 14: Screens of the HMI showing the servomotor speed response to step input with amplitude: a) 4 V, b) 6 V.

As can be appreciated, the output signal generated by the FLC leads the servo speed to the desired value with an acceptable steady-state error and high stability. In both of the cases the errors reached are small and the difference between them is slight. The main cause of such difference is the higher resolution and computational resources of Simulink.

Table 2: Steady-state error comparison.

Vsetpoint	Steady-state error (%)	
	Simulink	PLC
4	-3.5	-1.7
5	4.2	6.2
5.5	4.7	4.7
6	-1.1	2.8

On the view of these results we can conclude two facts. On the one hand, it has been demonstrated the ability of the developed controller to adjust the servomotor speed to the required set point. On the other hand, these data validate the module developed to implement fuzzy controllers in the PLC s7-1200.

6 CONCLUSIONS

A software module to implement fuzzy controllers in a Siemens PLC s7-1200 has been presented. A servomotor has been used as test platform to validate the developed PLC-Fuzzy Controller.

The results under real operating conditions constitute a proof-of-concept of the feasibility of the proposed system.

A positive feature of the developed work is the utilization of a PLC of recent market release and, hence, progressive introduction in industrial plants and research teams. This device belongs to Siemens low-end performance range, providing automation solutions with minor costs.

This work has contributed to a better understanding of the abilities and procedures to implement fuzzy controllers in PLC.

Future works focus on the application of the controller to more complex systems such as a hydrogen generator integrated in a hybrid renewable energy system. Also, its integration with software applications using OPC protocol and the programming of more options such as fuzzy PID structure are under study.

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