ISBN: 978-628-95207-4-3. ISSN: 2414-6390. Digital Object Identifier: 10.18687/LACCEI2023.1.1.319

Position Control Algorithms of Photovoltaic Panels with Respect to the Incidence of Sunlight

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Abstract*– This paper shows the design and operation of a one-axis sun position tracker prototype for use in energy harvesting systems with photovoltaic panels. The prototype design is characterized by using low-cost control elements that allow applying the control algorithms in a simple way using Matlab/Simulink for the development and execution of the PID, FUZZY and PREDICTIVE control algorithms, to evaluate their operation independently in the sun position follower prototype. The control parameters to be considered for the evaluation are the percentage over level, the time and the error in steady state. An external light is used to simulate sunlight, making it possible to show that the predictive controller obtains the best results compared to the other two controllers used.

***Keywords*-- Control, Fuzzy, PID, Predictive, Solar tracker.**

I. Introduction

Currently, thanks to the numerous studies carried out on climate change, it is known that the main sources of energy come from fossil fuels and that these are limited and polluting. Some countries have decided to promote and acquire the use of non-traditional energy sources intended to replace polluting sources as a guarantee of energy security, with the purpose of reducing environmental problems and reducing greenhouse gas emissions. For this reason, different investigations have been carried out based on the use of renewable energy sources, which can contribute to the reduction of current environmental pollution. For this reason, countries like Korea and China have established that by 2030 renewable energy will cover 15 to 20% of electricity generation [1],[2]. Several investigations on the use of solar energy are observed oriented to the use of photovoltaic systems with the purpose of generating electrical energy, the same ones that satisfy agricultural needs, water heating for cities, etc. [3],[4]. Although these investigations on the application of photovoltaic systems can be implemented in all areas of some countries, such as Ecuador, however, the use of photovoltaic systems would have a greater impact for sectors far from the urban area, where it can serve as backup power in the event of unforeseen power outages and in many cases as the main power source, which makes it extremely important to expand the field of study in this area, using scale prototypes, simulation software and applications in power systems that allow evaluating and capturing photovoltaic energy in an increasingly efficient way [5]. According to the different studies carried out on the capture of energy from the sun using static photovoltaic panels, it has been verified that the capture of energy is maximized when the panel is positioned in such a way that it is perpendicular to the sun, which is why it is have raised numerous investigations regarding the use of tracking systems of the position of the sun with the aim of improving the capture of energy by means of photovoltaic panels [6], in some cases the tracking of the trajectory of the sun is used in one axis and in others two-axis tracking, using different controllers in order to improve energy capture and maximize system efficiency [7],[8]. In most of the research on sun position tracking systems, automatic control has a main role, since classical, intelligent or advanced techniques can be applied to improve the efficiency of energy capture. The PID control is one of the controllers that is commonly used, thanks to its ease at the moment of implementing and performing its parameterization [9], due to this, it is of interest to study its operation on the systems that follow the position of the sun, as well as evaluate its performance against other controllers and observe its advantages and disadvantages that are presented [10],[11]. The Fuzzy controller is characterized by making use of mathematical logic and through inference rules that go according to what is required in the process, it is possible to control a system. One of the great applications of the fuzzy controller in photovoltaic systems is based on maximum power point tracking (MPPT), and in this way maximize the energy harvesting of the system. The goal of this fuzzy controller in such studies is to reach maximum power point (MPP) in a short period of time and quickly adapt to changing environmental conditions [12],[13],[14]. The MPC or model-based predictive control is a controller that bases its control technique on the process model to predict the value of the output variables in a period. Among the multiple applications of photovoltaic systems using predictive control, several investigations of maximum power point trackers are presented, whose purpose is to evaluate the performance of the controller applied with improved techniques or in comparison with other control techniques, such investigations show an important contribution in minimizing module current transients, resulting in better performance when using the MPC algorithm [15],[16],[17]. The objective of this work is to design and implement a prototype solar light tracker on one axis, using an Arduino Mega 2560 as a means of communication with Matlab/Simulink, we proceed to design the PID, Fuzzy and Predictive controllers in Simulink to obtain the parameters. that should be used in the prototype, finally the responses of each are evaluated.

Digital Object Identifier: (only for full papers, inserted by LACCEI).
ISSN, ISBN: (to be inserted by LACCEI).
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II. Design And Implementation Of Control Algorithms

For the implementation of the control algorithms, a prototype plant with easy transport and low cost elements has been designed, using Matlab Simulink to implement the PID, Fuzzy and Predictive control algorithms.

A. Prototype Implementation

For the design of the plant, a block diagram is made to know how the system should operate in general and what elements are necessary for the operation of the system. The block diagram is shown in Figure 1.

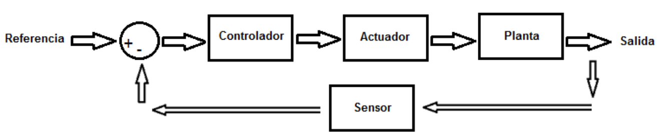


Fig. 1 Block diagram of the control system for the solar tracker on one axis.

The selection of the elements for the implementation of the prototype begins considering that the control algorithms will be developed and executed in Simulink, therefore, maintaining the idea of using low-cost elements, an Arduino Mega 2560 is chosen, the same one that will be used. for communication between Matlab/Simulink and the prototype plant. As actuating element, a servo motor is selected, which will oversee moving the solar panel, to determine the position of the sun, three photoresistors (LDR's) are used. Using three-dimensional printing, we proceed to assemble the prototype, adding an arm at the top, at the end of which a 5-volt bulb is placed, as shown in figure 2, since it is very important to carry out the tests in the same conditions for each controller.

Fig. 2 Prototype for the application of control algorithms.

B. Plant Identification.

The plant model is obtained through an algorithm developed in Matlab that generates a PRBS signal that is used as input or test signal that makes the solar panel move around the operating point, which in this case should be 90 degrees, and measure the position of the panel, that is, the output resulting from the LDR's, whose results are used to perform the identification of the plant using Matlab system identification. An algorithm is also designed to read the data from the LDR's sensors using Matlab/Simulink, the sensors are connected to the analog inputs of the Arduino Mega 2560 through a voltage divider circuit formed between the LDR's and three 10(kΩ) resistors, 1/4 (W). The resistance that is read in each LDR is inverse to the amount of light that is being collected. Therefore, due to the voltage divider, the higher the intensity of sunlight, there is more voltage at the output of the divider. The LDR's have been connected to the analog inputs A0, A1 and A2, to then obtain the voltage difference (A0 - A1) and (A2 - A1), considering that the LDR connected to input A1 is the one that it is in the center of the photovoltaic panel, as shown in figure 3. In the end, a resulting voltage value is obtained according to the values obtained in each LDR given by, Vin = (A0 – A1) – (A2 – A1), the value of Vin must be zero when the photovoltaic panel is perpendicular to the sun. It should be noted that for the design of the controllers, Vin is taken as the signal to be controlled.

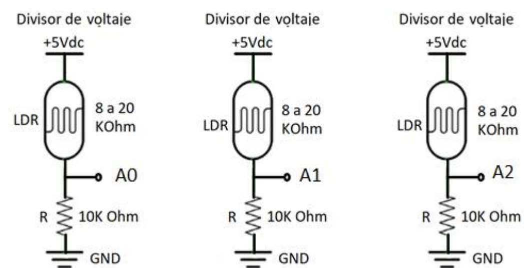


Fig. 3 Connection of LDR's sensors through a voltage divider.

After running the identification algorithm using the data from the PRBS signal and the output signal Vin, the model obtained by system identification is shown in (1).

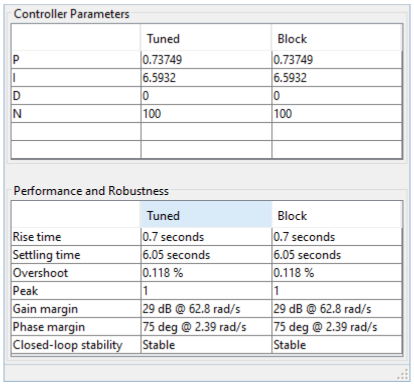
$$(4.419\ s + 0.5403) / (s^2 + 15.58\ s + 0.6298) \quad (1)$$

This model obtained an approximation percentage of 84%.

C. PID Control Algorithm.

For the application of the designed control algorithms, we proceed to create an algorithm to move an arm that contains a focus at its upper end, this focus represents the sun, in this way the designed plant can be operated in a simple way and thus demonstrate its operation at any time. It should be noted that by applying the same sequence of movements that simulate the sun, the response of each controller can be evaluated under identical conditions. With the model obtained using systems identification, we proceed to determine the values of parameters Kp, Ki and Kd that will be applied in the

PID controller of the real plant, using the Matlab/Simulink PID Tuner Toolbox, the values obtained are shown in the figure 4.



Controller Parameters

	Tuned	Block
P	0.73749	0.73749
I	6.5932	6.5932
D	0	0
N	100	100

Performance and Robustness

	Tuned	Block
Rise time	0.7 seconds	0.7 seconds
Settling time	6.05 seconds	6.05 seconds
Overshoot	0.118 %	0.118 %
Peak	1	1
Gain margin	29 dB @ 62.8 rad/s	29 dB @ 62.8 rad/s
Phase margin	75 deg @ 2.39 rad/s	75 deg @ 2.39 rad/s
Closed-loop stability	Stable	Stable

Fig. 4 Design of the PID controller using the TUNE tool of Simulink.

Once the PID controller has been designed using the plant model, we proceed with the implementation of the controller in the real system. The value of 0V is established as the input or reference signal, since the values in the voltage dividers formed by the LDR's must be at zero volts (Vin) and thus keep the panel perpendicular to the sun. Figure X0 shows the algorithm designed in Simulink using the PID controller adjusted to operate in the real plant.

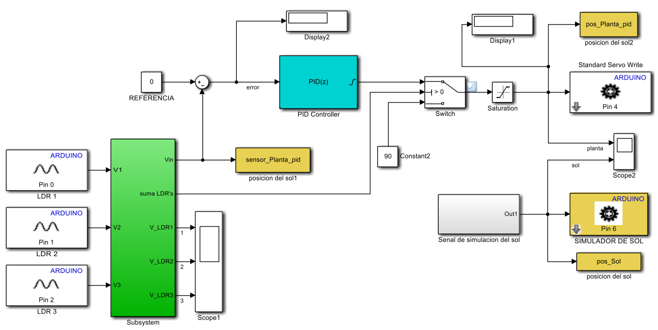


Fig. 5 PID Control Algorithm.

D. FUZZY Control Algorithm.

In the design of a Fuzzy controller it is very important to understand the operation of the system and to elaborate the membership and correspondence rules in an adequate way, for this case the algorithm is developed using the Matlab/Simulink Fuzzy Toolbox. The input variables are ERROR, which represents the system feedback error, and D-ERROR, which is the derivative of the ERROR variable. The output called CONTROL is established as the output variable, that is, the output signal of the Fuzzy controller, such as shown in figure 6.

For this work, 3 Gaussian type membership functions are established for the ERROR and D-ERROR variables. For the CONTROL variable, 5 Gaussian-type membership functions are established. The correspondence rules are established according to TABLE I, allowing the system to operate satisfactorily.

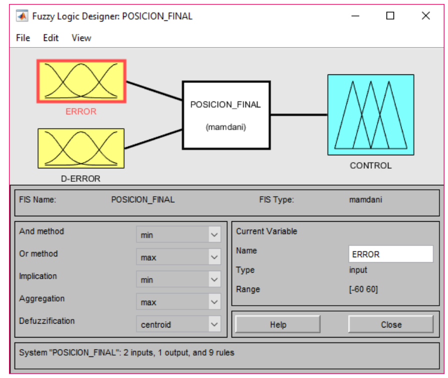


Fig. 6 FUZZY Control Algorithm.

TABLE I
MATCHING RULES FOR THE FUZZY CONTROLLER

CONTROL		D-ERROR		
		NEG	CERO	POS
ERROR	NEG	NG	N	N
	CERO	N	Z	P
	POS	P	P	PG

The input variables ERROR and D-ERROR operate between -60 and 60, so the membership functions have been set in this range. For the output variable named CONTROL, it varies from -1 to 1, taking into account that the photovoltaic panel varies from 0 to 180 degrees, the output integrator is limited between 0 and 1 and the result is multiplied by a gain of 180. degrees, as shown in Figure 7.

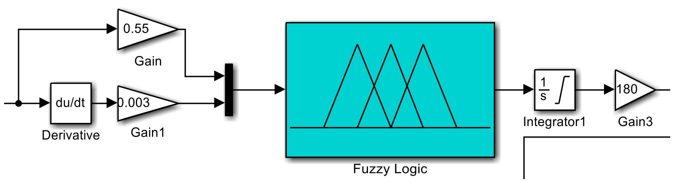


Fig. 7 FUZZY Control.

For the implementation of the Fuzzy controller in the prototype, the same algorithm designed in figure 4 is used, but the PID controller has been exchanged for the designed Fuzzy controller, as shown in figure 8.

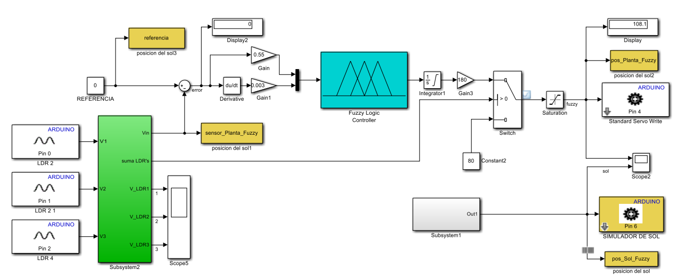


Fig. 8 FUZZY control algorithm applied to the prototype

E. Predictive Control Algorithm

The predictive controller based on the MPC model is based on the plant model, therefore, it is of vital importance to obtain a model that represents the plant with a high degree of approximation. The MPC controller is designed, using the Matlab MPC Designer Toolbox, in the TUNING menu a sampling time of 0.1s, a prediction horizon of 10s and a control horizon of 2s are established. Using Review Design, it is checked if the design parameters are correct. The results obtained are shown in Figure 9.

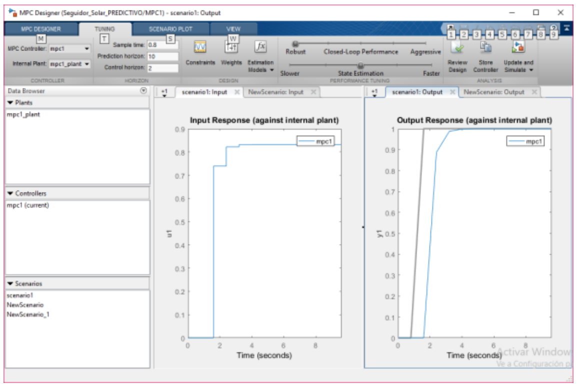


Fig. 9 MPC controller design using MATLAB's MPC Designer Toolbox

With the best simulation scenario obtained, the controller is applied in the plant as it was done for the PID and Fuzzy controllers, as shown in figure 10.

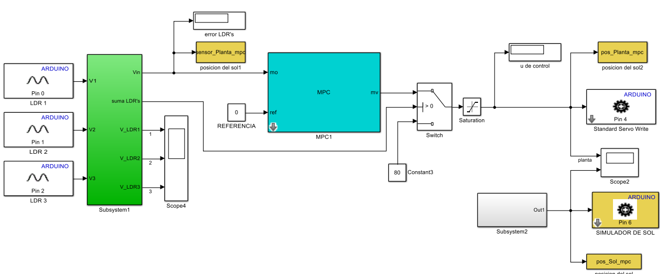


Fig. 10 Control algorithm applied to the prototype using an MPC.

III. Results and Discussion

A. Obtaining results through simulation and experimentation.

To operate the prototype, there is an arm placed at the top to simulate the position of the sun with a spotlight. This arm that simulates the sun is made to move with a servomotor independently of the algorithm that controls the position of the photovoltaic panel. The designed signal is used to perform angular movements of the arm and to evaluate the designed algorithms in identical situations. The designed algorithm generates step type signals as shown in figure 6, this algorithm determines the changes in the angular position of the arm that supports the focus.

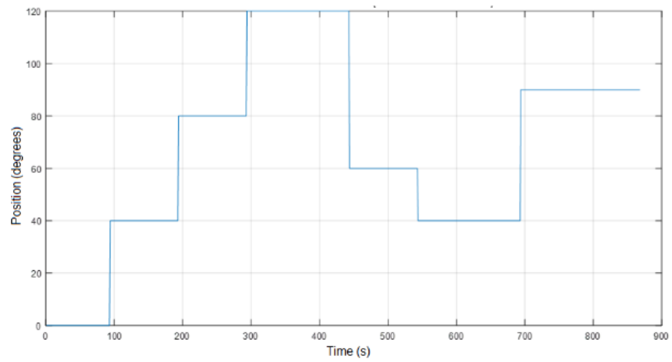


Fig. 11 Signal generated to simulate changes in the external signal that simulates the position of the sun.

The system reference signal is zero volts, that is, the photovoltaic panel must remain perpendicular to the position of sunlight, that is, at 90 degrees. Figure 12 shows the test signal that simulates the position of the sun and the control signal delivered by the PID to move the servo of the photovoltaic panel.

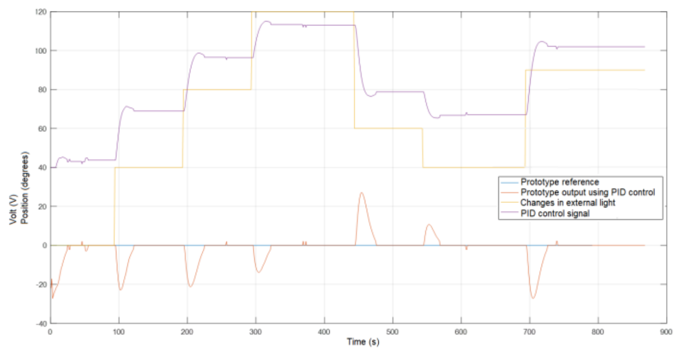


Fig.12 Control signal applied to the prototype before a variation in the position of the sun measured in degrees and response of the system measured in Volts applying PID control.

In the case of the Fuzzy controller, the procedure is similar to what was done for the PID control, using the same test signal. Figure 13 shows the control signal of the Fuzzy controller with respect to the reference signal.

Fig.13 Control signal applied to the prototype before a variation in the position of the sun measured in degrees and response of the system measured in Volts applying Fuzzy control.

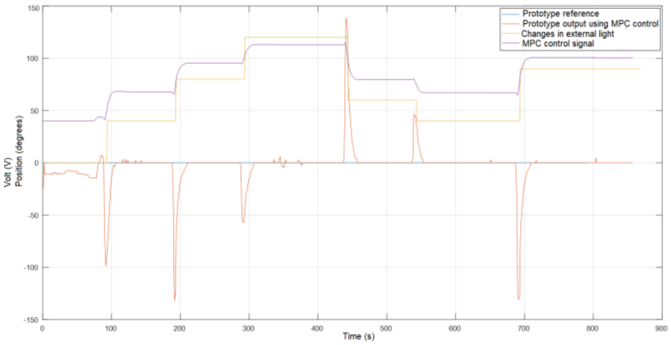


Fig.14 Control signal applied to the prototype before a variation in the position of the sun measured in degrees and response of the system measured in Volts applying MPC control

B. Controller performance measurement index.

To analyze the response of each of the controllers, a reference signal is applied that changes from time to time. Figures 15, 16 and 17 show the responses of the controllers with their respective time and magnitude labels so that, based on this, we can know the stabilization time, the percentage over level and steady-state error that have been considered as more parameters. relevant to the present work.

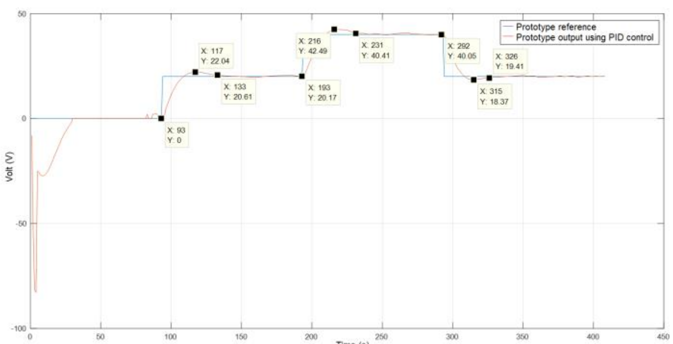


Fig.15 Response of the prototype using PID control.

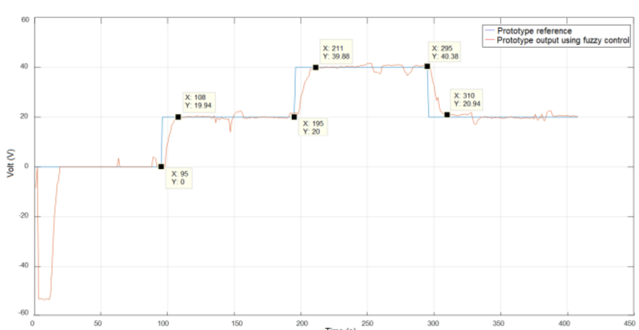


Fig.16 Response of the prototype using FUZZY control.

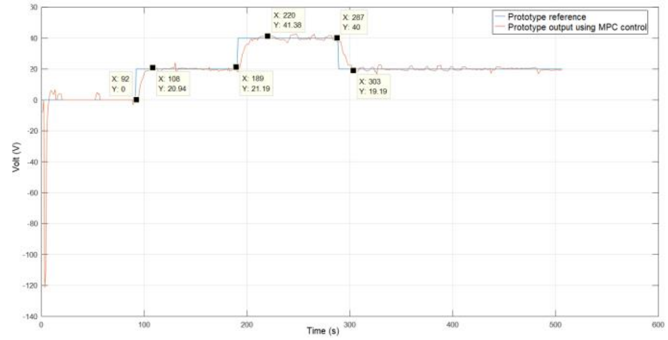


Fig.17 Response of the prototype using PREDICTIVE control.

C. Comparative analysis of the PID, Fuzzy and Predictive algorithms.

According to what was determined in section *B*, it can be observed that the three control algorithms designed present a similar response and can be used as a control of the prototype plant, however, according to their performance indexes, it is observed that the Predictive control (MPC) presents better results, since, despite presenting a higher percentage over level than the PID and similar to the FUZZY, it presents a much shorter stabilization time than the PID and FUZZY controllers, all maintaining a steady state error of 0 , as can be seen in TABLE II. Figure 18 shows the response of the system applying the three PID, FUZZY and PREDICTIVE controllers, upon changes in the reference.

TABLE II
PERFORMANCE INDEX OF PID, FUZZY AND PREDICTIVE CONTROLLERS.

	PID		Fuzzy		MPC	
	Tiempo [s]	Vi [V]	Tiempo [s]	Vi [V]	Tiempo [s]	Vi [V]
Overshoot [%]	0	0	13	10.7	6	9.9
Settling time [s]	33	0	16	0	8	0
Steady state error	95	0	43	0	95	0

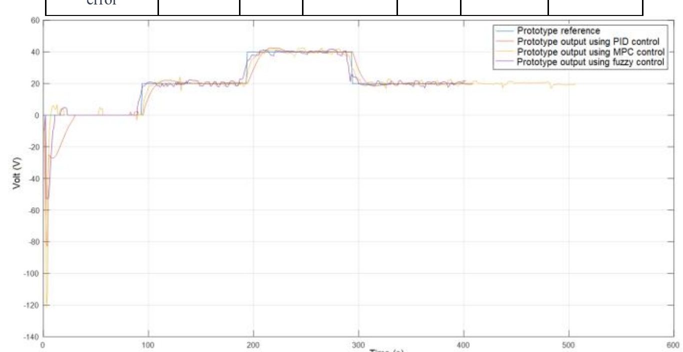


Fig.18 Responses of the prototype plant using PID, FUZZY and PREDICTIVE controllers.

IV. CONCLUSIONS

Once the PID control has been designed, it was observed that it is not necessary to use its derivative part, that is, the resulting control operates correctly using only the PI part.

For the design of the Fuzzy controller, it was necessary to add a PD to the input to achieve the desired results, leaving the control as PD + Fuzzy.

According to the analysis of the three controllers applied to the energy capture system, the MPC controller is selected as the one with the best performance, given that, despite presenting a higher percentage level than the PID, it is the one that reaches the stationary state in less time in relation to the other controllers used in this prototype, maintaining a steady state error of zero which, given that there is a positioning system, it is vitally important to achieve the objective in the shortest possible time.

The three controllers designed for this plant can be used satisfactorily, since, despite obtaining results that are slightly lower than Predictive, their response characteristics are within the acceptable parameters for the operation of a plant.

Once the different control algorithms have been designed and tested in the prototype plant, the good performance of the Arduino Mega 2560 can be observed, since it has allowed the linking of the PID, Fuzzy and Predictive controllers developed in Matlab/Simulink.

With the present work, it has been possible to obtain a didactic plant, at a low cost and easy to transport, in which the PID, Fuzzy and Predictive controllers can be easily executed from the same environment, such as Simulink from Matlab.

Given the didactic benefits of the prototype plant, it is possible in the future to design and test other controllers in a simple way.

Acknowledgment

This work was developed thanks to the contribution of the industrial processes research group (GIPI) of the Salesian Polytechnic University.

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