ppi 201502ZU4659
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ISSN 0254-0770 / Depósito legal pp 197802ZU38

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DE LA FACULTAD DE INGENIERIA
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VOL.41 ENERO - ABRIL 2018 No.1

Rev. Téc. Ing. Univ. Zulia. Vol. 41, No. 1, 15-24, 2018

Application of a Sliding Mode Controller to a Cooling Tower

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Abstract

In this work a real implementation of a Sliding Mode Controller based on a FOPDT model of the system is established, the Sliding Mode Controller uses a PID algorithm as the sliding surface. The Sliding Mode Controller is implemented in an Arduino Mega microcontroller. The implementation allows controlling an exothermic process, cooling tower, for research and teaching purposes. The Sliding Mode Controller is programmed and then applied to the actual process. The proposed scheme is compared with a PI controller; and the IAE performance index is used to compare the results of both the computational simulations, made with Matlab®, as well as the implementation work. Under the experiments, the sliding mode controller showed an improvement of up 25.85% with respect to the classical PI.

Keywords: Sliding Mode Control; PID controller; Cooling Tower.

Aplicación de un Controlador por Modos Deslizantes a una Torre de Enfriamiento

Resumen

En este trabajo se establece una implementación real de un controlador de modo deslizante basado en un modelo FOPDT del sistema, el controlador de modo deslizante utiliza un algoritmo PID como superficie deslizante. El controlador de modo deslizante se implementa en un microcontrolador Arduino Mega. La implementación permite controlar un proceso exotérmico, torre de enfriamiento, con fines de investigación y docencia. El controlador de modo deslizante se programa y luego se aplica al proceso real. El esquema propuesto se compara con un controlador PI, y el índice de desempeño IAE se utiliza para comparar los resultados tanto de las simulaciones computacionales hechas en Matlab®, así como los de la implementación. Bajo los experimentos, el controlador de modo deslizante mostró una mejora de hasta el 25,85% con respecto al IP clásico.

Palabras clave: Control por Modos Deslizantes; Controlador PID; Torre de Enfriamiento.

1. Introduction

In the processes industry, cooling processes are very important for any system that involves energy flow such as nuclear or chemical reactors, petroleum refining systems or any kind of process where to keep a convenient temperature be necessary. Most of these processes are difficult to model from phenomenological principles. Industrial processes are higher order with nonlinear behavior, resulting in a difficult mathematical representation, therefore the synthesis or designing procedure to get controllers for these kind of systems is a challenging task. For that reason, reduced order models represent a good system´s approximation that can been used for controller designing purposes. A First Order Plus Dead time (FOPDT) model is a good representation of the process and represents close to 90 % of chemical processes [1], thus, if the controller design comes from this model a general controller can be achieved, [2]

Nonlinear exothermic systems such as cooling towers are widely used in the industrial field and normally their operation is guaranteed by PID controllers. PID controllers produce acceptable results for industrial standards, with an affordable price and a lack of complexity from operator point of view, but sometimes do not guarantee an adequate performance against disturbances, aging system, systems with elevated time delay, and so on.

Sliding Mode Control (SMC) is a robust control [2] with a simple design that can be used and implemented both in linear and non-linear processes. The greatest benefit obtained in this kind of control is its robustness against uncertainties and external disturbances that may appear. This controller has been studied for different kind of processes [3-8]

There are some other papers where SMC have been focused on practical applications. Eker [9] presented a sliding mode control system with PID sliding surface to control the speed of an electromechanical plant. A robust sliding mode controller is derived so that the actual trajectory tracks the desired trajectory despite uncertainty, nonlinear dynamics, and external disturbances. Experimental results that are compared with the results of conventional PID verify that the proposed sliding mode controller can achieve favorable tracking performance, and it is robust with regard to uncertainties and disturbances.

In [10], is shown the application of sliding mode control for process control. Reaching phase and sliding phase are designed by using Lyapunov stability criteria. The FOPDT model parameters are used to calculate the tuning parameters. The approach has been demonstrated with an example of water tank level control system with disturbances.

Garcia et. al. [11] presented a control approach using Sliding Mode Control concepts to the air feed of a fuel cell. Fuel cells are electrochemical devices that generate electrical energy from chemical reactants and are good candidates for a clean energy generation, since the waste product is water. An efficient operation of fuel cells depends on a good control strategy for the air supply system.

Furat and Eker [12] presented an experimental evaluation and practical applicability of conventional (first-order) sliding-mode control techniques are investigated. Experimental applications are performed using an electromechanical system for speed tracking control and disturbance regulation problems. The graphical results are illustrated and the performance measurements are tabulated based on time-domain analysis. The experimental results indicate the fact that the sliding-mode control is applicable to practical control systems with the cost of some disadvantages.

In this work a real implementation of a Sliding Mode Controller based on a FOPDT model of the system [13] is established. The implemented SMC is a simple algorithm which can be executed in any commercial board and can be presented as a simple and easy Human-Machine Interface (HMI) for the operator. The controller can be applied on any process that can be approximated by a FOPDT model. The purpose of the HMI is to make it look as a commercial PID controller such a way that it be familiar for operators. The controller is utilized in a cooling tower of the Mechanical Engineering Department at Escuela Politécnica Nacional, Quito, Ecuador. The SMC is simulated firstly and then it is implemented in real time. In both tests, simulation and real time, the proposed implementation is compared against a PI controller.

This work is divided as follows: firstly, the SMC controller based on an FOPDT system is shown. After these topics process considerations are presented. In the next section several tests are done, the obtained results of the SMC and the PI controller are compared. Finally, some conclusions are obtained.

2. Sliding Mode Controller Based on a FOPDT model.

This section is divided in two parts. A first one where a brief presentation of SMC concepts. The concepts presents come from [2,8]. The second one shows the proposal implementation in an Arduino board.

2.1 Basic design concepts.

The design of the SMC controller was developed by [13]. In [14] is presented a proposal to implement this controller.

The FOPDT model is represented as follows:

$$G(s) = \frac{K_0}{\tau s + 1} e^{-t_0 s} \tag{1}$$

Where K_0, t_0 and τ represents the characteristics parameters of the model [1] and [14]

The SMC equation contains two terms:

$$U(t) = U_l(t) + U_r(t) \tag{2}$$

An equivalent or sliding mode controller part called $U_l(t)$ and the reaching component named $U_r(t)$. The meaning and the methodology followed to get the SMC, are presented in [13]. The results for each controller component are:

For the sliding part of the controller is:

$$U_l(t) = \frac{t_0\tau}{K_0}\left(\frac{X(t)}{t_0\tau} + \lambda_0 e(t)\right) \quad (3)$$

And for the reaching or discontinuous part is defined as follows:

$$U_r = K_d\left(\frac{S(t)}{|S(t)| + \delta}\right) \quad (4)$$

Where the tuning parameters are defined by (5) and (6) as:

$$K_d = \frac{0.51}{|K_0|}\left(\frac{\tau}{t_0}\right)^{0.76} \quad [Fraction\ CO] \quad (5)$$

$$\delta = 0.68 + 0.12|K_0|K_d\lambda_1 \left[\frac{Fraction\ TO}{s}\right] \quad (6)$$

The sliding surface is defined as:

$$S(t) = sign(K_0)\left(\frac{de(t)}{dt} + \lambda_1\, e(t) + \lambda_0 \int_0^t e(t)dt\right) \quad (7)$$

$sign(K_0)$ is used to select the appropriated controller action: direct or reverse. The controller action depends on the sign of the static gain (K_0).

With:

$$\lambda_1 = \frac{t_0 + \tau}{t_0\tau} \quad [s]^{-1} \quad (8)$$

$$\lambda_0 \le \frac{(\lambda_1)^2}{4} \quad [s]^{-2} \quad (9)$$

Equation (7) represents a PID algorithm, thus this algorithm (PID) is used as the sliding surface, and adding some algebra it is possible to obtain the SMC, that can be called a robust PID controller.

2.2. Implementation

In this part a general scheme, Figure 1, can be used to implement the proposed controller, the approach is implemented in the Arduino Mega Board.

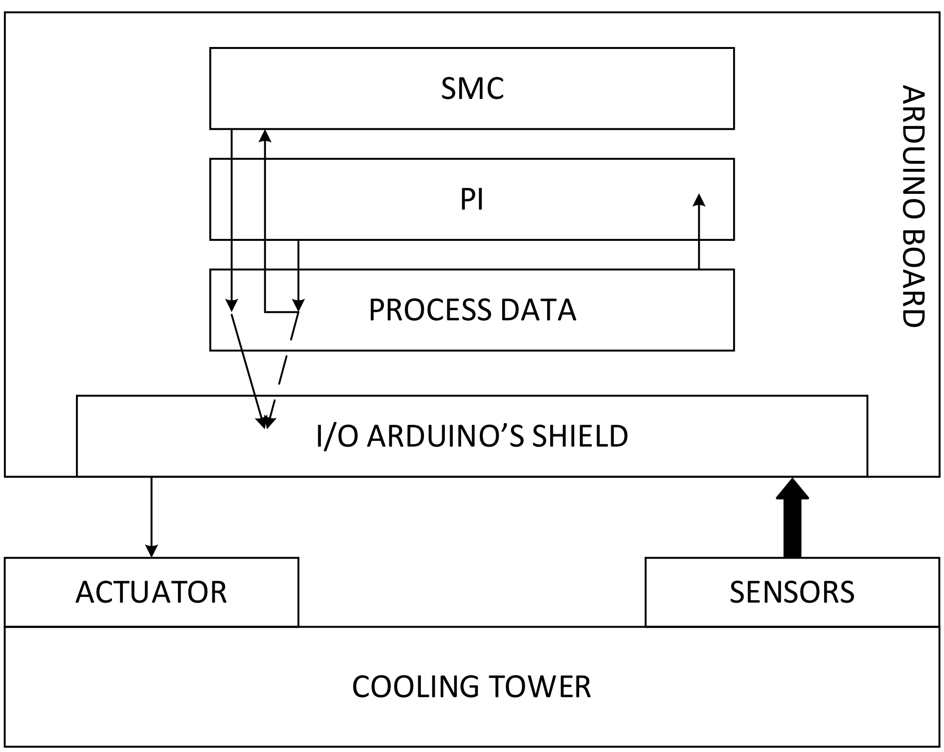


Figure 1. Implementation of SMC.

The next figures show how the controller is built. In Fig. 2 is shown the internal control panel connections. Figures 3 and 4 show the connections and the box. Fig. 5 depicts the selector screen. The selector lets to choose between a PI controller or a Sliding Mode Control, finally Fig. 6 presents a screen to introduce the tunings parameters for the controller. The HMI was done by the authors. The purpose of the HMI is to make it look as a commercial PID controller such a way that it be familiar for operators.

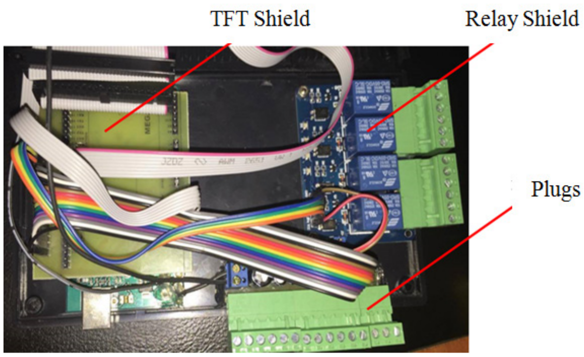


Figure 2. Control panel connections.

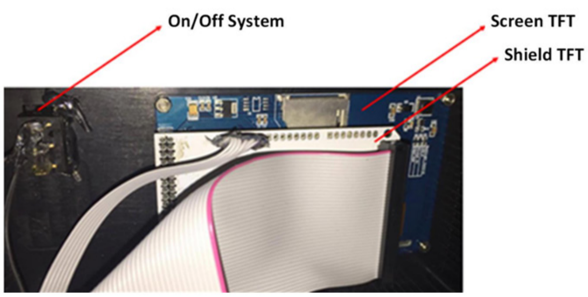


Figure 3. Screen TFT connections

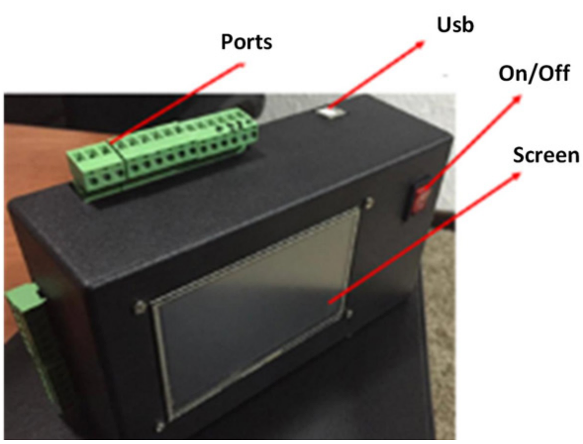


Figure 4. SMC box

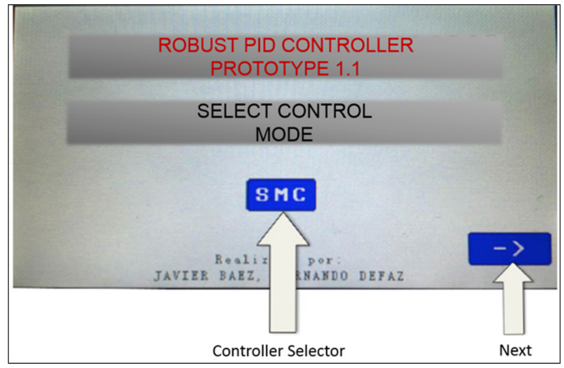


Figure 5. Controller selector screen

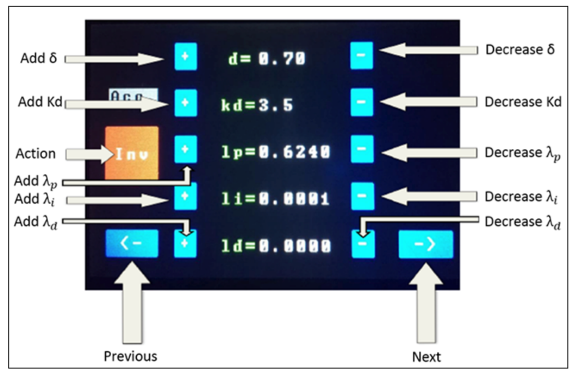


Figure 6. SMC tunings parameters screen.

In section 4, the control algorithm is examined in simulations first and secondly experimentally implementing it in real time to the cooling tower. Therefore, the proposed approach can be analyzed totally in the process.

3. Cooling tower process.

The Cooling Tower is presented in a P&ID diagram (Figure 7), as it is shown in figure 5 where all the sensors and transmitters can be appreciated.

A brief description of the process is as follows: the heating tank emulates an exothermic process where the temperature of the water raises at a maximum of 50°C and it is controlled by an ON/OFF controller.

After the water has reached the maximum temperature, a transmission pump sends it to the top tank of the tower. In this tank, there are two sensors one for the temperature input and another for the humidity, as it is shown in the P&ID diagram.

The water goes down through the tower lowing its temperature while doing so, and it is accumulated at the water collector where it is found the output temperature sensor.

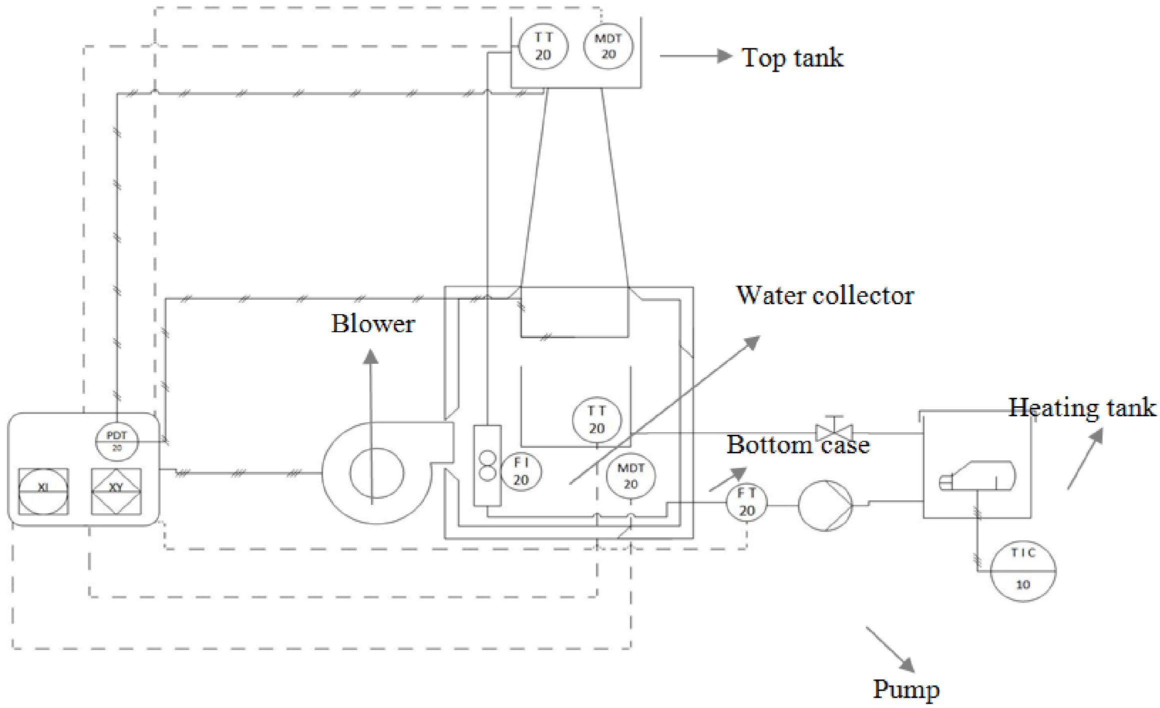


Figure 7. Cooling tower diagram

The process needs humidity and airflow control for desired performance so inside the bottom casing there is a humidity sensor plus a flow indicator so the user can manually adjust the amount of water that flows inside the tower.

Since the tower is a mechanical draft type, made for counter flow, the actuator is a blower and the SMC controller sends a voltage signal to control the speed of the internal motor.

As the SMC is designed from a reduced order model, FOPDT, and its tuning parameters depends on the characteristic parameters of the process (K_0, t_0, τ), thus, it is necessary to apply the reaction curve procedure [1,15]. Once the plant stabilizes at 47.5 ° C (data obtained experimentally by feeding the heating and distribution system with nominal voltages), a positive step change of around 80% is applied to the cooling system. Since the ambient conditions in the laboratory changed a lot, we wanted to consider the broader linear model in this sense in such a way that the controller could have a more extensive information about the process to be controlled. Data were taken, until the system reached stability at 27.5 °C. Therefore, the reaction curve is obtained and showed in Figure 8:

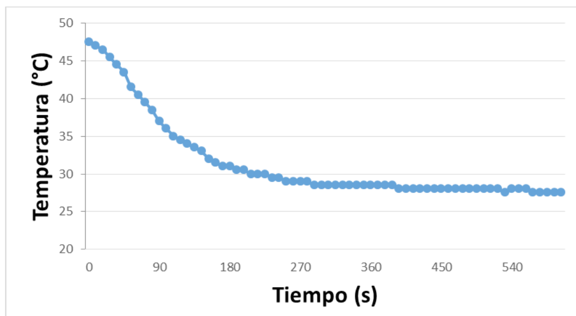


Figure 8. Reaction curve

From the data obtained and using the Ident toolbox of Matlab®, the characteristic parameters (K_0, t_0, τ) of the FOPDT model are obtained, In table 1 the results are shown:

Table 1. FOPDT model parameters.

Parameters	Value
K_0	-26.083
τ	43.925 [s]
t_0	20.124 [s]

The units of the constant K_0 are fraction of the transmitter output $[TO]$ divided by fraction of the controller output $[CO]$. By other side, since K_0 is negative the term $sign\ (K_0)$ is negative, therefore the controller has a reverse action.

The sensors, the actioner (blower) and the control panel are shown in figure 9, which corresponds to the schematic diagram of the cooling tower where the connections and positions of every element can be appreciated.

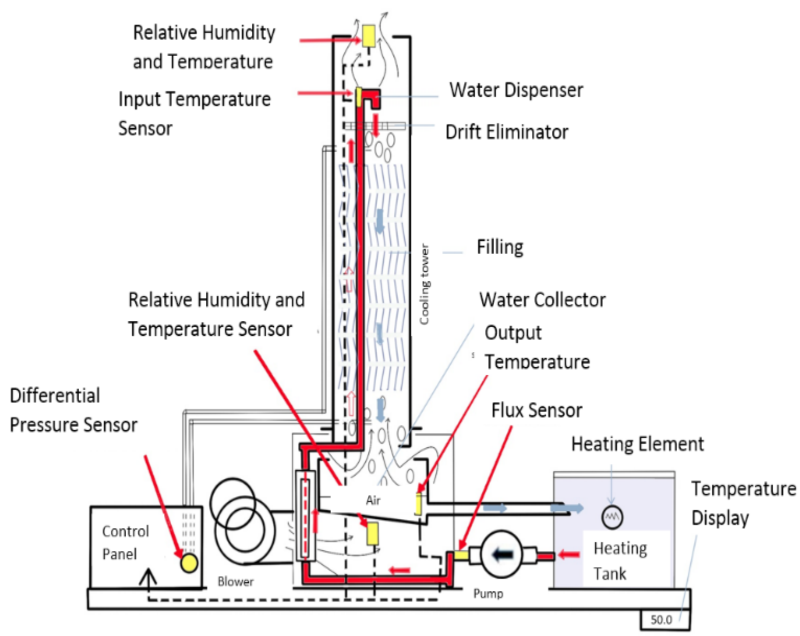


Figure 9. Schematic diagram of the cooling tower

4. Results and comparisons

The controller presented in section 2 will be used for two tests. The first one corresponds to simulations of the SMC and PI controllers and the second test corresponds to implementations of the SMC and PI controllers in the real process itself. A performance index is used to compare the controllers.

The parameters are determined and presented on table 2.

Table 2
Values of the tuning parameters

Parameter	Value
$\lambda_0 [s]^{-2}$	0.0013
$\lambda_1 [s]^{-1}$	0.0724
$K_d\ [Fraction\ CO]$	0.0354
$\delta \left[\frac{Fraction\ TO}{s}\right]$	0.689

These parameters are introduced to the controller, as was shown in fig. 6, and the controller can be tuned.

4.1 Simulation Results

4.1.1 SMC and PI controllers' comparison for set point changes.

In this experiment, the simulation of both controllers are done. The SMC controller and the actual PI controller using Matlab® are simulated for several set point changes, as its shown in figure 10. These changes were carried out to cover the broadest working range for the process in order to test if the controller is able to respond properly to each change.

The currently implemented PI is tuned by Ziegler and Nichols using previous work [16], shown in figure 8.

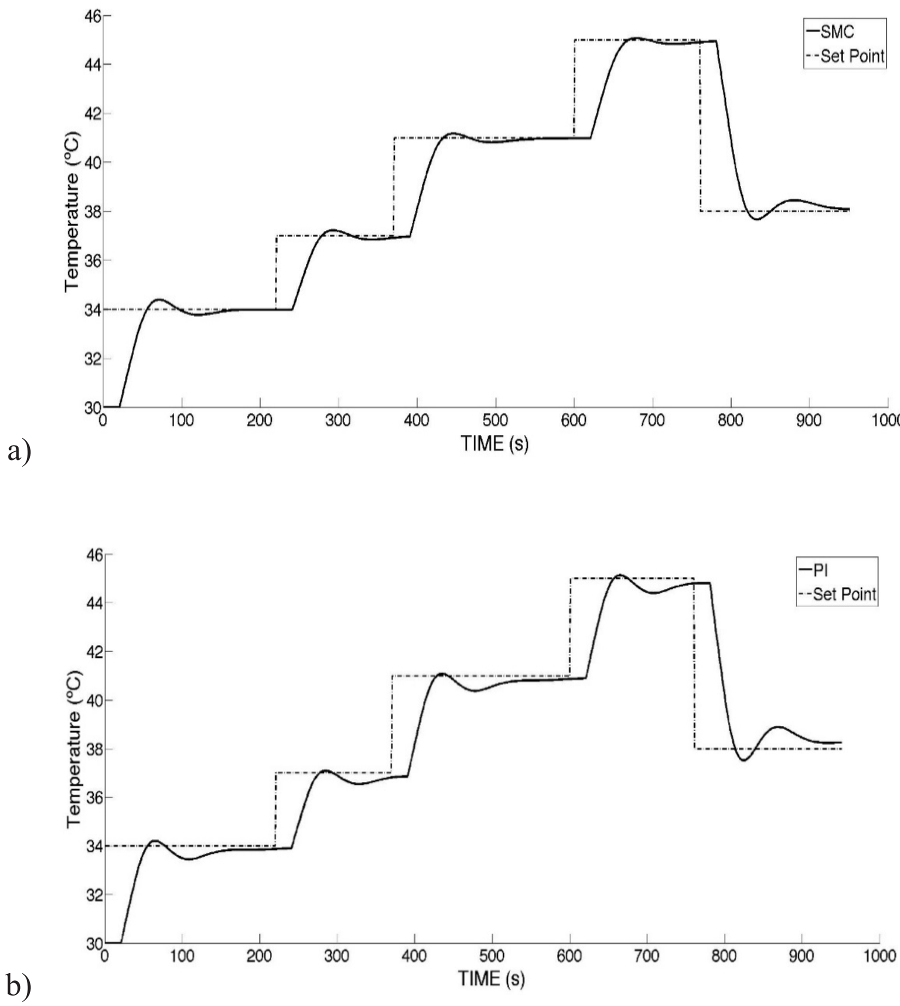


Figure 10. Simulation responses for set point changes

4.1.2 Performance comparisons.

To quantitatively measure the performance of each controller the IAE (Integral of Absolute Error) index is used. The IAE performance index is defined by:

$$IAE = \int |e(t)|dt \tag{10}$$

This performance index is calculated in the simulation for all controllers considering similar conditions. Performance results appear in table 3.

Table 3
Performance analysis

Controller	IAE	Δ%
SMC	24.59	15.84
PI	28.82	

The SMC controller overcomes the PI controller close to 16%.

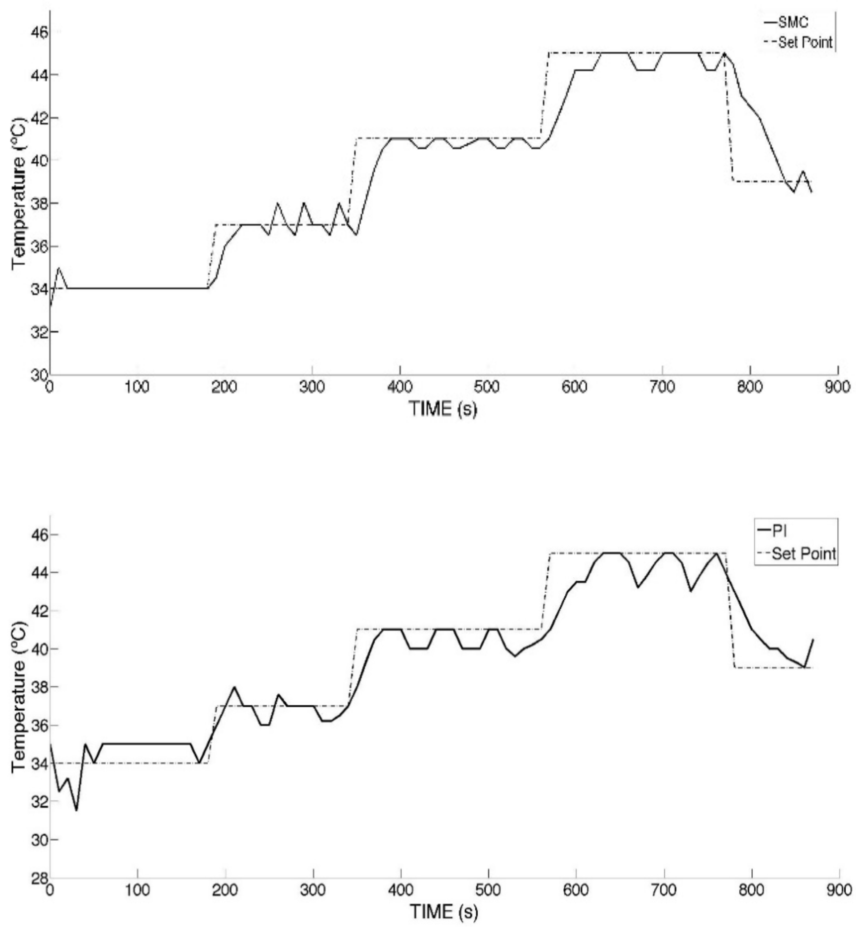
4.2 Experimental results.

In a similar way as was presented for the simulation case, now the SMC and PI are compared when they are applied to the real process. The behavior of each controller is analyzed, beginning from the same temperature and then changing the set point. The controller was discretized using the trapezoidal method with a sampling time of 1 s.

4.2.1 SMC and PI controllers' comparison for set point changes

In Figure 11 can be seen the results of the experiment. Figure 9(a) shows the SMC results and 9(b) the PI results.

Figure 11, shows in the starting part the SMC presents a response without oscillations while the PI presents close to +1[°C] of position error. For the second set point change the settling time is almost the same in both controllers but the SMC has more oscillations than the PI controller. For the third set point change the oscillations of the PI controller are greater than those given by the SMC. Finally, for the last set point change the magnitude of the oscillations given by the PI are more important than those produced by the SMC.



a)

b)

Figure 11. Experimental results for set point changes

4.2.1. Performance Comparisons.

As it was made in simulation, the controllers are compared using the IAE performance index. The results of this analysis are found in the Table 4.

This experiment is important because there are aspects that are not considered in the simulations, such as: pressure, humidity, ambient temperature and even the amount of impurities inside the water, which represent disturbances not considered, in the design moment, that affect the process but at the same time serve as a robustness measure to compare both controllers.

Table 4. Real time performance analysis

Controller	IAE	Δ%
SMC	49.17	25.85
PI	63.77	

The IAE on both controllers is higher than the simulation case, the reasons were explained by the different weather conditions that the real process has to face, in this case the SMC overcomes the PI controller up 25.85%, showing a good performance.

5. Conclusions

The SMC controller uses a PID controller as the sliding surface and it was implemented successfully into the Arduino Board. It is important to mention that the controller can be implemented in any commercial board making syntaxes changes.

The operation conditions of the SMC are similar to PID controller, the implementation follows exactly figure 1, from an operator point of view, this controller can be presented as a robust PID controller. Both simulations and real experimental results indicate that the SMC controller has a better performance than the PI controller, the sliding mode controller showed an improvement of up 25.85% with respect to the classical PI.

Acknowledgments

Oscar Camacho thanks to PROMETEO Project of SENESCYT, Republic of Ecuador, for its support for the realization of this work. Authors thank to PIJ-15-17 Project of Escuela Politécnica Nacional, for its sponsorship for the realization of this work.

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Recibido el 12 de Enero de 2017
En forma revisada el 17 de Julio de 2017

UNIVERSIDAD DEL ZULIA

REVISTA TECNICA

DE LA FACULTAD DE INGENIERIA
UNIVERSIDAD DEL ZULIA

Vol. 41. N°1, Enero - Abril 2018

*Esta revista fue editada en formato digital y publicada en Diciembre de 2017, por el **Fondo Editorial Serbiluz, Universidad del Zulia. Maracaibo-Venezuela***

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