Design and construction of a prototype for acidity level control in coal mining liquid effluents

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Abstract

It is a challenge of modern industry to develop processes that do not pollute the environment, most importantly water. The mining industry is no exception, and in turn must minimise environmental impact on water sources in or around areas of exploitation (Garner et al. 2012). The management of drainage in the depth of the mine is a problem due to high costs, and it is important to understand that the cost of the consumption of electric energy rises according to the size of the mine and the quantity of drainage.

This paper describes the design and implementation of a prototype to neutralise the acid water of mining in the didactic coal mine located in Morcá (Sogamoso, Colombia), which belongs to the Centro Nacional Minero (National Mining Centre), Servicio Nacional de Aprendizaje (SENA, Sogamoso, Colombia). The neutralisation of these acidic waters aims to minimise the environmental impact produced by these liquids, when they are discharged into nearby water sources. The neutralisation method is 'additives base', which comprises mixing a basic agent; in this case, caustic soda (NaOH) at a concentration of 1 Normal (1N) was used. In order to carry out this process, the system model is estimated and proportional plus integral (PI), algebraic, fuzzy logic and sliding mode controllers were applied to the prototype. A comparison of the performances of the different controllers showing the response time overshoot, steady state error and magnitude of the control signals are shown and analysed.

Keywords: *pH, acid water, caustic soda*

1   Introduction

The use of water in coal mining plays a very important role. This is because large amounts are used in the separation of the ore from its surroundings. Regardless of whether it is in underground or surface media, even in mineral processing water is used to separate the useful mineral from other useless minerals (Kemmer et al. 1989). The water used in the mining process is extracted from the mines, and in some cases it has to be pumped over considerable distances, from the bottom of the mine to the surface. When the ore extracted is coal or other minerals, a reaction occurs between the forms of iron pyrites with water and at that moment acid waters are generated (Russell et al. 2012). There is a very serious problem in the mining of coal when the acid waters generated in this operation are drained to healthy water sources without adequate treatment (Barettino & Pérez 2005). According to Kemmer et al. (1989), when acid waters are incorrectly disposed of, they alter the oxygen levels of the rivers or lagoons close to the area where mineral exploitation takes place. At the moment the basic composition of the water is altered, certain abnormal events in the biology and the ecology of the environment occur. This leads to a decrease in biota in the ecosystem. In some cases, the colour of the affected water is black and it can even take on a foul odour (Barettino & Pérez 2005). The hydrogen potential (pH) serves as a basis for the measurement of acidity levels present in liquid mining effluents. The pH is an indicator of the acidity of a substance and is determined by the number of free hydrogen ions (H^+). The pH of the water may vary between zero and 14. When the pH of a substance is greater than seven, it is a basic substance, and if it is below seven, it is an acidic substance.

Taking into account the water studies carried out by the National Mining Centre, SENA (Monguí-Galvis et al. 2015), the iron content of the mining effluents is 123 ppm with a permissible value of 0.3 ppm as established by Betancourt & Ramírez (2007). The colour of water before and after treatment is orange and the pH level of the water is 3.5. According to the resolution previously mentioned, the pH level must be between 6.5 and 9. The ideal pH value of water is seven. One method for neutralising the acidity present in the water is that of the base additives, which consists of the addition of compounds such as sodium hydroxide, limestone, lime or sodium carbonate, which neutralises the acid. In this case caustic soda (NaOH) is used with a concentration of 1 Normal (1N).

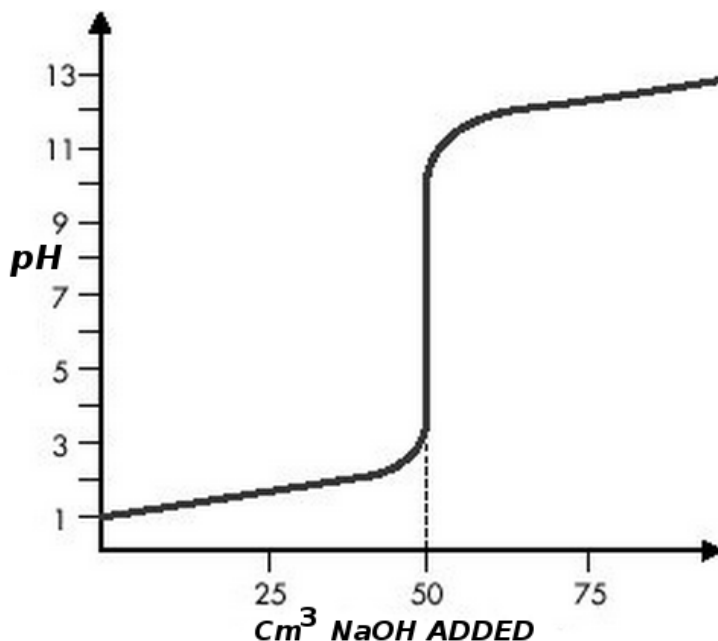The titration curve between an acid and a base (NaOH) is shown in Figure 1.

Figure 1   Base acid titration curve

In this paper, a prototype is considered which has four tanks to perform the neutralisation of the waters. For this system, traditional controller with proportional plus integral plus derivative action (PID) and modern control strategies such as fuzzy logic, algebraic and sliding modes are implemented and tested as a solution to control the acidity levels of the acidity liquid mining effluents. The performance of these control strategies is evaluated considering aspects such as:

- Response time.

- Setting time.

- Steady state error with respect to the reference.

The paper is organised as follows: in Section 1, an introduction explaining generalities about the generation of acid waters as well as the solution and objectives of the control system is given. In Section 2, the prototype design and implementation procedure for the neutralisation of acid waters is presented. In Section 3, the modelling of the plant is presented in order to obtain a model serving to design the controllers. In Section 4, the design of the different control strategies that are applied to the prototype is presented. In Section 5, the analysis of the results of the implemented control strategies and their performance according to the evaluation parameters is outlined. Finally, in Section 6, the conclusions are presented.

2   Design and implementation of the prototype for analysis and control of the acidity level in liquid mineral effluents

The design and elaboration of the prototype structure was considered by taking into account the objective of neutralising the acidity present in the mine effluents of the didactic mine from the National Mining Centre, SENA.

The prototype consists of four tanks:

- The first tank stores the acid waters to be treated.

- The second tank is used to contain the neutralising agent; in this case caustic soda (NaOH) is used.

- The third tank fulfils the function of the reactor tank where the neutralisation takes place.

- The fourth tank stores the neutralised effluents.

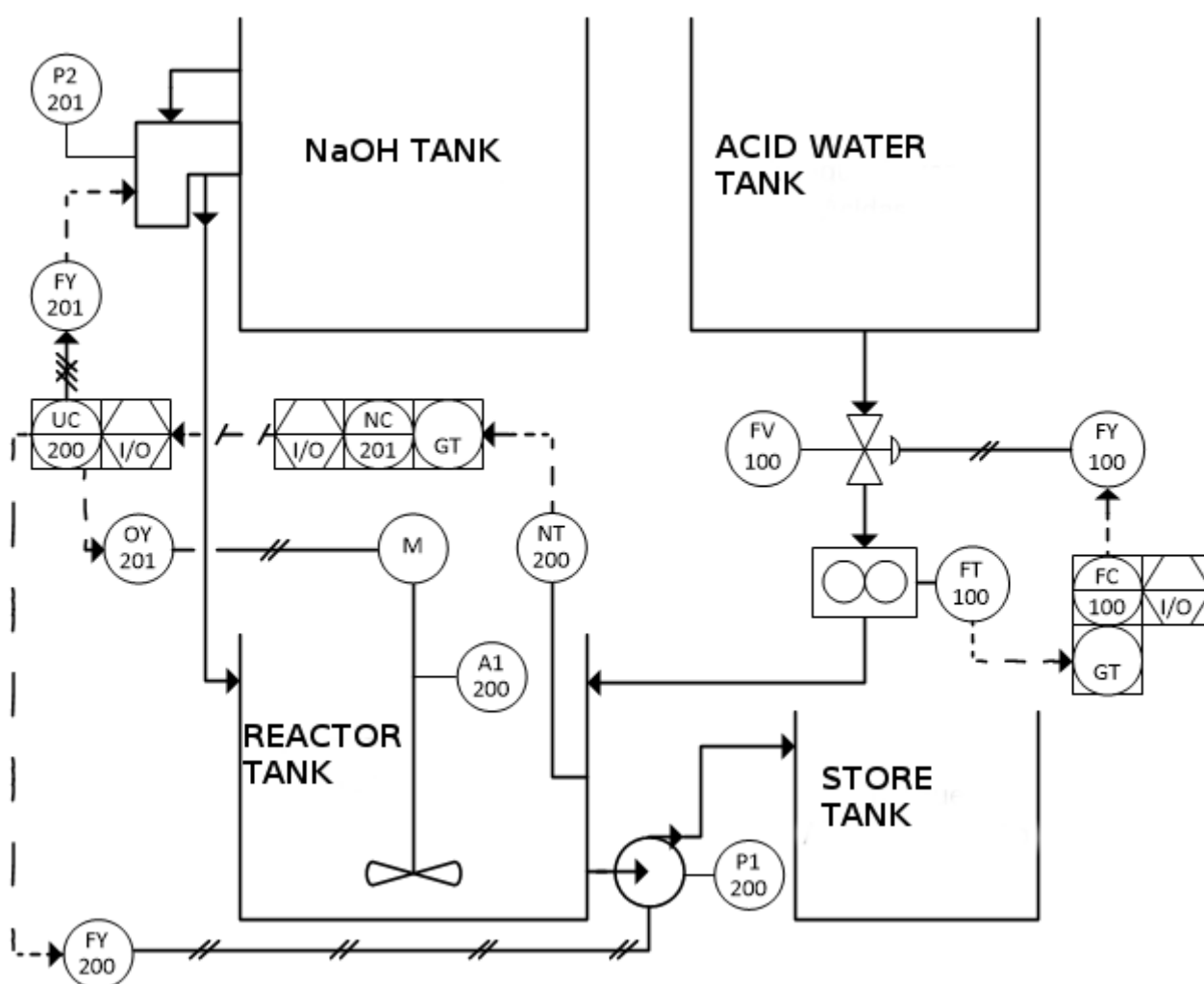Figure 2 shows the implemented prototype diagram, and Figure 3 shows the real prototype.

Figure 2   Implemented prototype diagram

The pH sensor in the reactor tank is located far from the mixer and the source of NaOH to prevent them from producing abrupt variations in sensor measurements and inhibiting control strategies.

Figure 3   Real prototype implemented

3   System modelling

In order to obtain the model of the system, a substance that flows through a pipe with a known delay is considered. Its purpose is to reach the reactor tank with a perfect mixture (Bequette 1998; Smith & Corripio 2006). Accordingly, Equations 1 and 2 describe the process:

$$V_m(t)\,\dot{C}_0(t) = q(t)[C_{in}(t-\theta) - C_0(t)] \tag{1}$$

$$\theta(t) = \frac{V_d}{q(t)} \tag{2}$$

where:

$C_o(t)$ =   concentration in the outflow tank.

$C_{in}(t)$ =   concentration in the inlet mixing tank.

$V_m(t)$ =   volume of the substance in the tank in litres (L).

$q(t)$ =   inlet flow to the tank (L/s).

V_d =   volume in the pipe (m³).

$\theta(t)$ =   delay of the substance (NaOH) to reach the reactor tank.

Assuming $V_m(t) = V_{m0.}$

The equation of the system is expressed by Equation 3

$$\dot{C}_0 = \frac{q_0}{V_{mo}} C_0(t) + \frac{q_0}{V_{mo}} C_{in}(t-\theta) \tag{3}$$

where:

$\theta = V_d/q$ y $q(t) = q_0$ (constant) and applying the Laplace transform we obtain the transfer function of the process given by Equation 4.

$$\frac{C_0(S)}{C_{in}(S)} = \frac{K_p e^{-\theta S}}{\tau_o S + 1} \; ; \; K_p = 1 \; ; \; \tau_0 = \frac{V_{m0}}{q_0} \tag{4}$$

Considering the parameters determined in the prototype construction, it is assumed that $V_m(t)$ has a value of 1 (L), $q(t)$ with a measure of 6 (ml/s) and θ(t) with a delay of 10 (s). With the aforementioned values, the model of the plant is represented by Equation 5.

$$G_p(s) = \frac{1e^{-10\,s}}{166.67\,s+1} \tag{5}$$

In order to carry out the validation of the design model, the Ziegler and Nichols method or open-loop response curve is used as shown in Figure 4. This method (Kiam Heong et al. 2005) consists of applying a step to the control signal, and the changes in the measured or controlled variable are recorded. By applying this method, the characteristics of the system to be controlled are obtained.
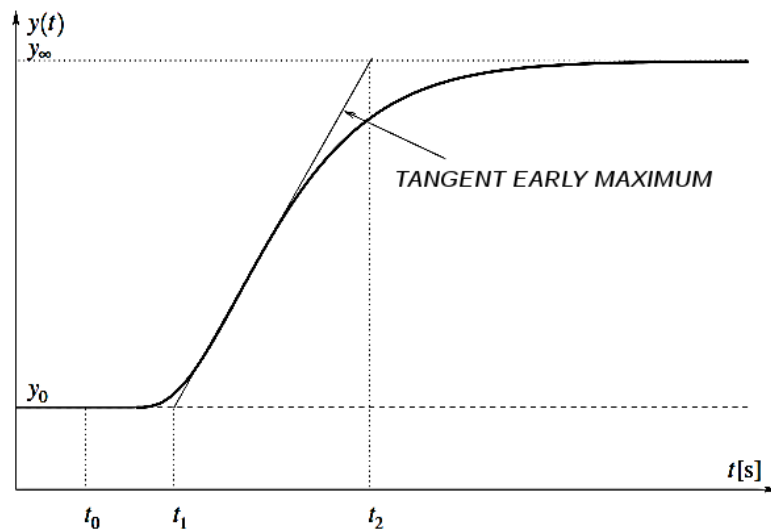

Figure 4   Open-loop response

From the response curve, Equation 6 is obtained:

$$K_0 = \frac{y_\infty - y_0}{u_\infty - u_0} \;;\; \tau_0 = t_1 - t_0 \;;\; \gamma_0 = t_2 - t_1 \tag{6}$$

With these parameters, the transfer function (Equation 7) of the system is:

$$G_p(s) = \frac{K_0\,e^{-\tau_0 s}}{\gamma_0 s+1} \tag{7}$$

In order to obtain the system model a step is applied to the control signal of the peristaltic pump. Thus, the pH variation in the water to be treated with respect to the sodium hydroxide dosage (NaOH) in the reactor tank is derived. Figure 5 shows the response curve obtained.
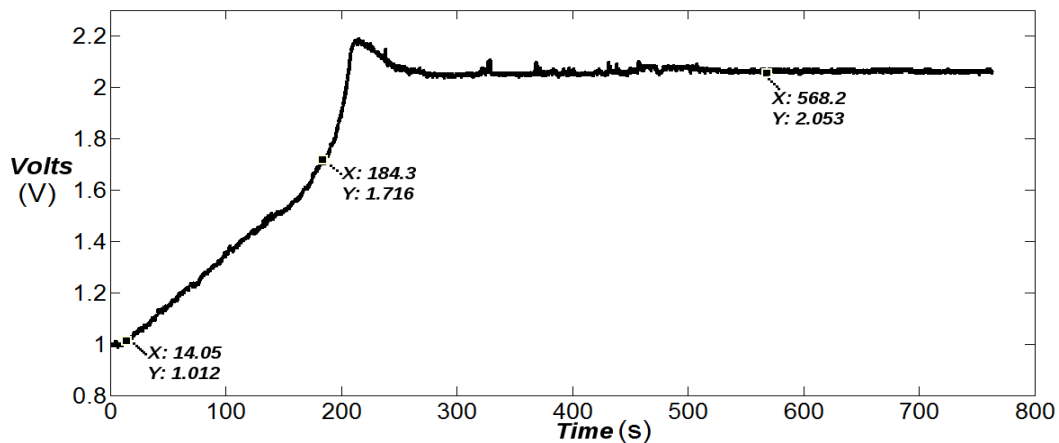

Figure 5   System response curve

From the response curve given in Figure 5, an overshoot before the signal stabilises can be observed. This response is similar to a second order system, but this overshoot is given by the measurements in the pH sensor while stabilising the concentration in the reactor tank. It is known that the prototype corresponds to a system of first order with dead time. From this view point, to obtain the transfer function, the required data was acquired from the response curve (Figure 5) and, for their validation, were compared with the results obtained by Kang et al. (2009) and Rivero Ochoa and Chávez Cuadros (2010).

Equation 8 is used to find the parameters where $K_p = 1.051$; $\tau_0 = 14.05$ and y $\gamma_0 = 170.25$. With the parameters found, the system transfer function was of the form in Equation 7.

$$G_p(s) = \frac{1.051 e^{-14.065s}}{170.25\,s + 1} \tag{8}$$

When comparing Equation 5, which represents the equation of the ideal model, with Equation 8, representing the experimental model, it can be seen that the parameters do not differ much; therefore, we chose Equation 8 for the design of the controllers. For more information about the behaviour of this model, see Distefano III et al. (1992).

4   Control strategies applied to the system

Taking the model of the plant, the next step is to study the implementation of the controllers. The implementation of the drivers utilised MATLAB Simulink (The MathWorks, Inc. 2017) together with the Arduino UNO and MEGA 2560 cards. For more information see Banzi (2011), Goilav and Loi (2016) and Pedrera (2017).

As mentioned in the introduction, the implemented drivers were:

- PID controller.

- Algebraic method controller.

- Fuzzy logic-based controller.

- Sliding mode controller.

4.1   Proportional plus integral controller

The general expression of the proportional plus integral (PI) control signal (Åström & Hägglund 2006; Kiam Heong et al. 2005) is given by Equation 9.

$$u(t) = K_p \left[e(t) + \frac{1}{T_i} \int_{-\infty}^{t} e(\tau)d\tau \right] \tag{9}$$

From the process model, the controller parameters are calculated using the integral minimum error criteria; the integral of the error square (ICE) (Åström & Hägglund 2006) represented by $\int_0^\infty e(t)^2 dt$ and the integral of the absolute value of the time-weighted error (ITAE) (Åström & Wittenmark 2011) determined by $\int_0^\infty t|e(t)|dt$. Table 1 shows the equations for finding the parameters of the controllers P and PI depending on the implemented criterion. On the other hand, a PID controller by location of poles in a closed loop without using the previous criteria was also designed. The obtained parameters, in this case, were $K_P = \frac{0.9\gamma_0}{K_0\tau_0}$ and $T_i = 3\tau_0$.

From the system model given by Equation 4, a PI controller is chosen due to the system time constant. The parameters of the PI controller with the criterion (ICE) are $K_p = 13.5831$; $T_i = 54.7623$, and with the criterion (ITAE) the parameters are $K_p = 9.3515$ and $T_i = 46.3135$. For the location of poles in a closed loop without using the previous criteria, the parameters of the controller are $K_p = 10.3765$ and $T_i = 42.15$.

Table 1   Criteria of minimum integral of the error

Controller	P		PI			
	$K_P = \dfrac{a}{K}\left(\dfrac{t_0}{t}\right)^b$		$K_P = \dfrac{a_1}{K}\left(\dfrac{t_0}{t}\right)^{b_2}$		$\tau_i = \dfrac{t}{a_2}\left(\dfrac{t_0}{t}\right)^{b_2}$	
Criteria	a	b	a_1	b_1	a_2	b_2
ICE	1.411	-0.917	1.305	-0.959	0.492	0.739
IAE	0.902	-0.985	0.984	-0.986	0.608	0.707
ITAE	0.490	-1,084	0.859	-0.977	0.674	0.680

4.2   Algebraic controller

For the design of the controller by algebraic methods, the continuous time model (Equation 4) is discretised assuming the input generated by a zero order hold. A discrete time reference model is generated in accordance with the proposed objectives and the comparison between the discretised model of the plant and the reference model yields the equations of the controller. The controller is then implemented in MATLAB Simulink (The MathWorks, Inc. 2017), with which it is intended that the system will behave as the desired reference model (Figure 6). In the reference model, desired specifications such as response time, peak, and steady state error are incorporated for the closed-loop system. For more details see Salamanca (2009).
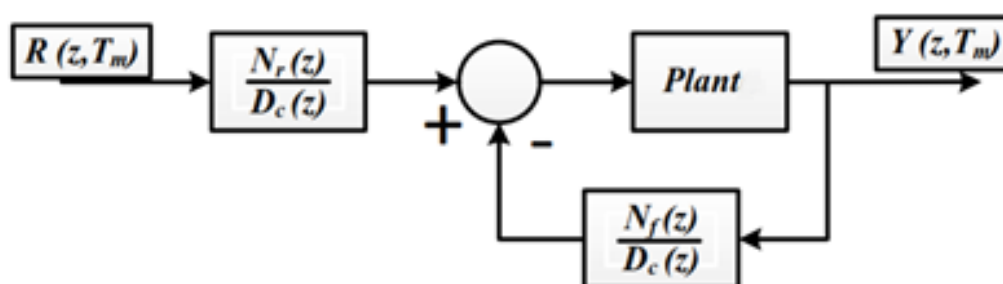

Figure 6   Schematic of discrete algebraic controller

The plant model used was obtained by discretisation with input generated by a zero order hold with a sample time of two seconds of the model given by Equation 8.

The discrete transfer function $\frac{Nr(z)}{Dc(z)}$, which is a component of this controller, is defined by Equation 10.

$$\frac{\text{Nr(z)}}{\text{Dc(z)}} = \frac{81.47\,z^7}{z^7 + 0.9883\,z^6 + 0.9768\,z^5 + 0.9654\,z^4 + 0.9541\,z^3 + 0.943\,z^2 + 0.9319\,z + 0.9211} \tag{10}$$

The discrete transfer function $\frac{Nf(z)}{Dc(z)}$, the other component of the controller, is defined in Equation 11.

$$\frac{Nf(z)}{Dc(z)} = \frac{74.16\,z^7}{z^7 + 0.9883\,z^6 + 0.9768\,z^5 + 0.9654\,z^4 + 0.9541\,z^3 + 0.943\,z^2 + 0.9319\,z + 0.9211} \tag{11}$$

4.3   Fuzzy logic controller

Fuzzy logic control provides a formal methodology for representing, manipulating and implementing a human's heuristic knowledge about how to control a system (Passino & Yurkovich 1998). A fuzzy logic controller with its basic components is shown in Figure 7. The fuzzy logic controller can be considered an artificial decision-maker that operates in a closed-loop system in real time.
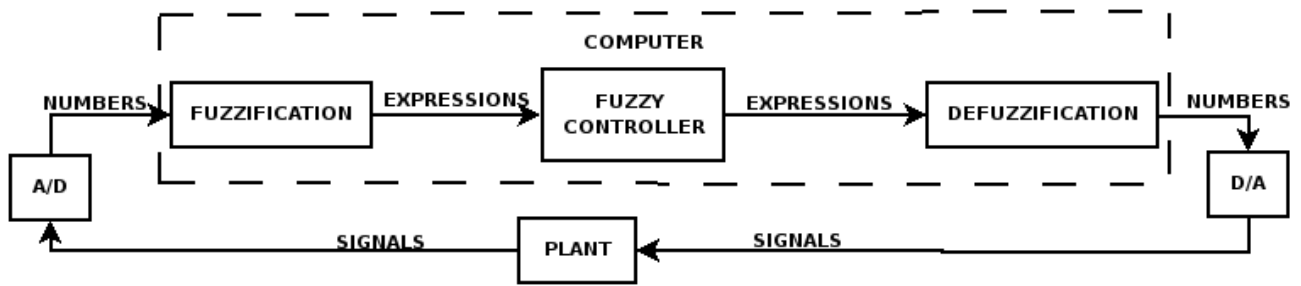
Figure 7   Controller schemes using fuzzy logic

The fuzzy logic controller is composed of the following elements (Figure 7):

- A rule base (a set of the rules), which contains a fuzzy logic quantification of the expert's linguistic description of how to achieve good control.

- An inference mechanism (also called an 'inference engine' or 'fuzzy inference' module), which emulates the expert's decision-making in interpreting and applying knowledge about how best to control the plant.

- A fuzzification interface, which converts controller inputs into information that the inference mechanism can easily use to activate and apply rules.

- A defuzzification interface, which converts the conclusions of the inference mechanism into actual inputs for the process.

The variables in a fuzzy controller (Figure 8) are represented by the degree of membership to fuzzy sets that represent the possible values that the variables can take in the actual process. The fuzzy sets, in this process, are represented by trapezoidal and triangular-type membership functions. The operations between the subsets of the controller are given by Bojadziev and Bojadziev (1996); and Passino and Yurkovich (1998). The logical conjunction 'AND', where the controller rules, considers the following notation: High: High, Med: Medium, Low: Low, Zero: Zero, TClosed: Completely closed, 1Q: 25%, 2Q: 50% of the pump and TOpen: Totally open.

The fuzzy set for the system entry is called 'Error'; it contains four subsets called 'High', 'Med', 'Low', and 'Zero'. The universe of this set is comprised between -9 and 9 since they are the maximum errors that exist in the pH measurements of the prototype. In this case, we used trapezoidal and triangular functions as shown in Figure 8. At the output of the controller, a discourse universe between 0.5 is selected. For the output, a fuzzy set called 'Peristaltic' is chosen. This choice was made because this variable will be entered into the peristaltic pump. The 'Peristaltic' set is divided into four subsets named 'TClosed', '1Q', '2Q' and 'TOpen'. Triangular functions are used as shown in Figure 9.
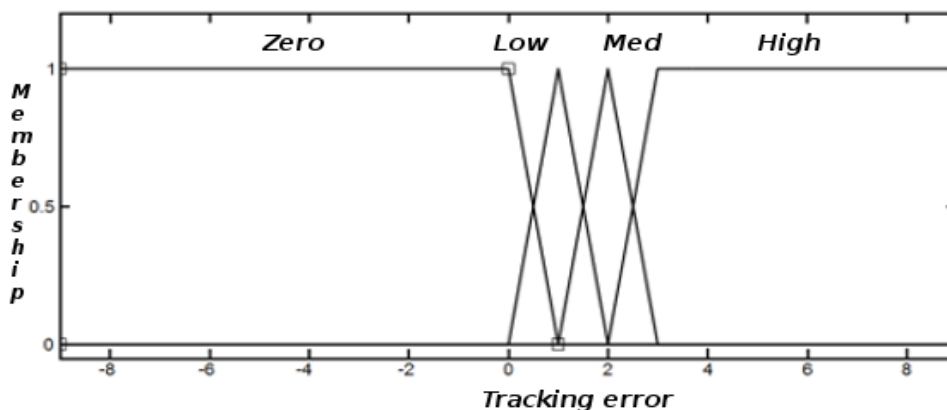

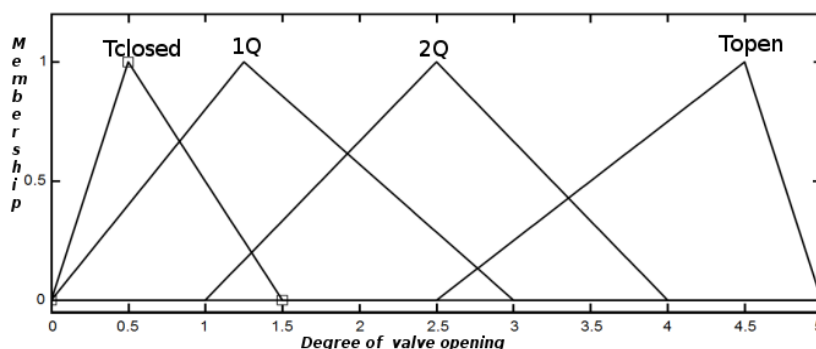**Figure 8   Subsets belonging to the error set**

Figure 9   Subsets belonging to the peristaltic assembly

To establish the operations between the input and output subsets, the AND logic connector is used as follows:

- If (error is zero) then (Peristaltic is TClosed).

- If (error is low) then (Peristaltic is 1Q).

- If (error is half) then (Peristaltic is 2Q).

- If (error is high) then (Peristaltic is TOpen).

Figure 10 shows the control signal applied by the controller to the peristaltic pump as a function of the pH concentration error.
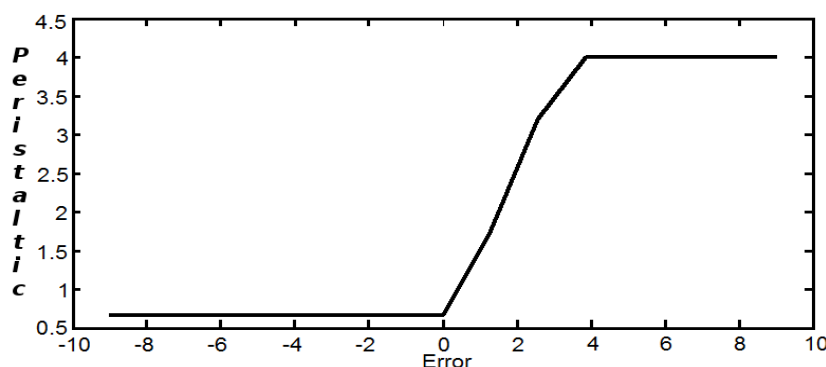

Figure 10 Fuzzy logic controller graphs (peristaltic versus error)

4.4   Controller by sliding modes

For the design of this type of controllers (Evangelista 2012; Salamanca et al. 2010) Equation 12 is taken into account.

$$e\,(t) = y\,(t) - y_d \tag{12}$$

where:

$e(t)$ = the error in the system.

y_d = the reference and $y(t)$ is the measured variable.

From the surface represented by Equation 13, the parameters K_p and K_i are selected which are constants defined in the system.

$$z\,(t) = K_p\,e\,(t) + K_i \int_0^t e(\tau)d\tau \tag{13}$$

In this way, Equation 14 defines the control signal of the system, where its purpose is to make the sliding surface $z\,(t) \rightarrow 0$.

$$u\,(t) = \Gamma_0\,sig\,[z(t)] \tag{14}$$

Equation 15 is obtained from Equation 13.

$$K_p\, e\,(t) + \ K_i \ \int_0^t e(\tau)d\tau = 0 \tag{15}$$

Therefore, the solution is interpreted by Equation 16.

$$K_p \ \dot{e}\,(t) + \ K_i \ e\,(t) = 0 \tag{16}$$

Solving $\dot{e}\,(t)$ from Equation 15, Equation 17 is obtained.

$$\dot{e}\,(t) = \ -\frac{K_i}{K_p}\,e(t) \tag{17}$$

Equation 17 represents the objective of the controller to achieve that $e\,(t) \rightarrow 0$.

$$e\,(t) = \ e\,(t_0)\ e^{-\frac{K_i}{K_p}*(t-t_0)} \tag{18}$$

$$z\,(t) = K_p\, e\,(t) + \ K_i \ \int_0^t e(\tau)d\tau \tag{19}$$

Equation 19 is used where $K_p\ K_i$ are constants defined in the objective sliding surface. The values of these constants are assumed with $K_p = 100$ and $K_i = 0.01$. The chosen values are intended to make the system respond in a more agile way to minimise the error as quickly as possible.

5 Analysis of results

Figure 11 shows the response signals of the PI controller with criteria and without criterion. From Figure 11 it can be seen that the criterion that has a better response in the system is the ICE criterion, because it has a better response time and establishment compared to the other criteria. Figure 12 shows the output signals of the different controllers implemented. The reference for controller responses is the ideal pH value for water (seven).

The control signals can be seen in Figure 13. It is observed that the control signal applied to the peristaltic pump ranges from zero to five volts. Table 2 presents a comparison of the control signals and closed-loop time response signals of the different types of controllers applied to the prototype.
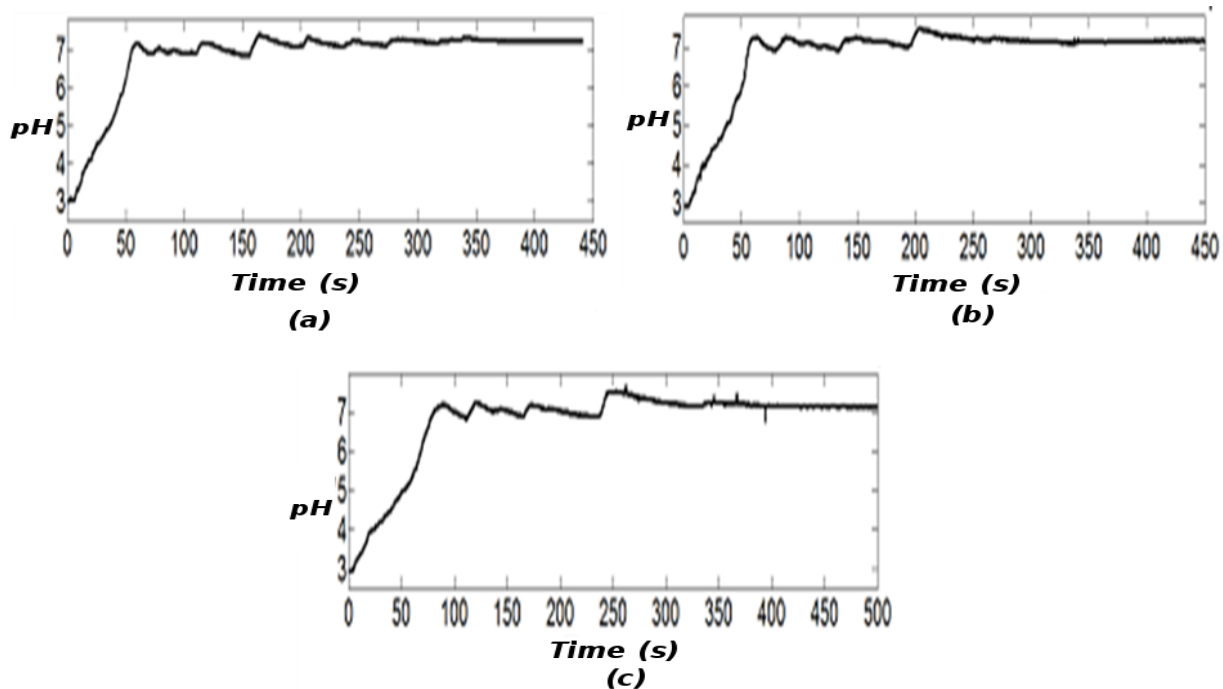

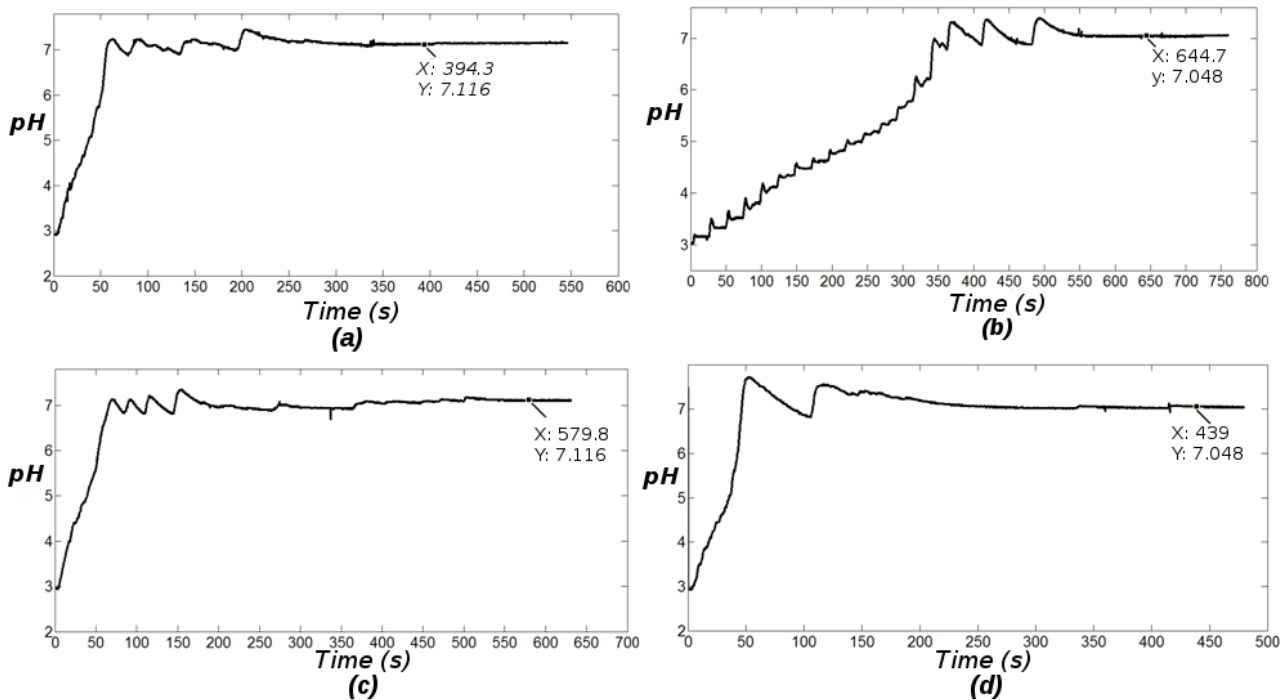Figure 11 PI controller response; (a) Single PI; (b) ICE PI; (c) ITAE PI

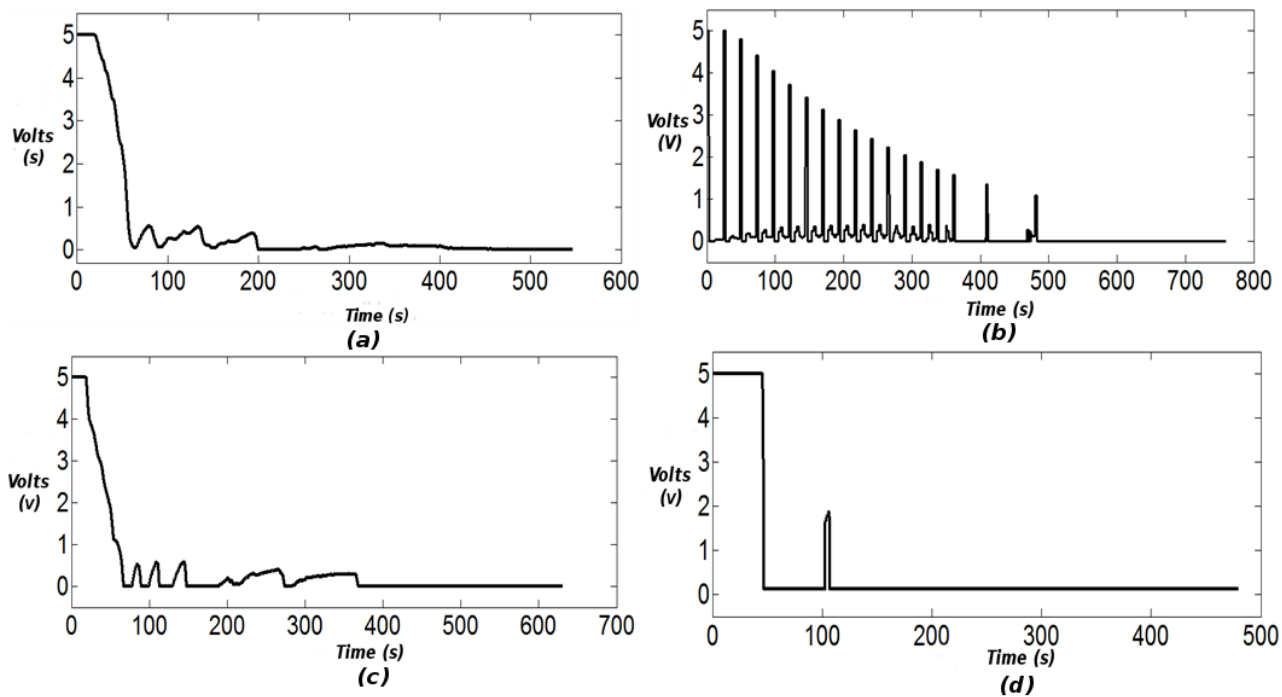**Figure 12 Comparison of the response of the implemented controllers; (a) PI; (b) Algebraic; (c) Fuzzy; (d) Sliding**

Figure 13 Control signal; (a) ICE PI; (b) Algebraic; (c) Fuzzy logic; (d) Sliding model

Table 2   Comparison of controller's performance with respect to control signal size and time response

Comparison of controller's performance		
Controller	**Control signal size**	**System response**
PI	The system requires a slight control signal, since it is decreasing from 5 to 0 V in 66 sec. It has a response time of 14.2 sec.	The system response has an establishment time, which occurs between 300 and 400 sec, a maximum overshoot of 6.54% and an error of 1.66% with respect to the reference value.
Algebraic controller	The control signal is quite demanding because it has abrupt changes of values between 0 and 5 V, with a time interval of 24 sec. It has a response time of 1.7 sec.	The system response has a set time between 550 and 650 sec, a maximum overlap of 5.57% and a rather low error (0.69%) with respect to the reference value
Fuzzy logic controller	The required control signal is slight, with a reduction of 5 V at 0 V in a time of 67.2 sec. The response time is 6.9 sec.	The system response has a settling time between 500 and 600 sec, a peak of 4.84% and an error of 1.66% with respect to the reference value.
Sliding mode controller	The control signal is required on average because it has a maximum voltage value of 5 V for 45.7 sec. It has a response time of 3 sec.	The system response has a set time between 250 and 350 sec, has a rather high maximum peak of 10.21%, although a rather low error (0.69%) with respect to the reference value.

6   Conclusions

The design of the prototype is simple and easy to assemble, which makes it a practical plant for the application of control techniques.

The system is unstable because large variations in pH are produced in response to small variations in the volume of NaOH that is added to adjust the pH to seven. This instability prevents the controllers from reaching an error equal to zero and causes oscillations around the pH value.

The applications of the different control strategies present a good response both in rise time and stability time. Moreover, the error is not great even though the reference is in an unstable zone.

The three criteria for the PI controller stabilise the pH by seven. However, the error squared integral criterion does not present the overshoots generated by the controller without criterion and its response time is smaller than that obtained with the criterion of the integral of time-weighted absolute error.

The algebraic controller response time is higher than the other controllers implemented and its error is the lowest despite the difficulty of adjusting pH 7 as a reference.

Comparing the controllers from the stability time and the error with respect to the pH setting of seven, the sliding mode control strategy has the lowest error and oscillations around the reference point.

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