Full Paper

CONSTRUCTION, MODELING AND FUZZY LOGIC CONTROL OF A LABORATORY SCALE pH NEUTRALIZATION SYSTEM

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ABSTRACT

Control of the pH neutralization process plays an important role in different chemical plants, such as biological, wastewater treatment, electrochemistry and precipitation plants. However, it is difficult to control a pH process with adequate performance due to its nonlinearities, time-varying properties and sensitivity to small disturbances when working near the equivalence point. For this purpose, modern process industries are increasingly relying on intelligent and adaptive control strategies such as fuzzy logic control. This research project deals with studies on the control of pH neutralization processes using fuzzy logic controllers. The fuzzy logic controller with a feedback control approach was implemented and a wide range of tests and experiments were conducted. Simulations results obtained revealed that fuzzy logic controller displays better closed-loop performance, in terms of set-point tracking and disturbance rejection.

Keywords: process control, Neutralization process, Nonlinear process control, Fuzzy control, PID, pH

1. INTRODUCTION

There has been an increased interest by researchers on pH neutralization process control in process engineering over the past thirty years (Ibrahim and Murray-Smith, 2007). The control of pH at the neutralization point has often been used as a benchmark to test nonlinear control schemes in process control literature.

The control of pH arises in a wide range of industries, including wastewater treatment, biotechnology, pharmaceuticals and chemical processing. The control of pH is also important in compliance with environmental and quality standards therefore the control of pH at a certain region or set point is highly important. The general purpose of a pH neutralization plant is to neutralize the waste product solution before discharging it to the environment. The requirement in terms of pH value to be discharged from a wastewater treatment plant is in the range of 6 to 8. The main reason is to protect rivers and aquatic life and to avoid damage due to corrosion (Ibrahim and Murray-Smith, 2007). Furthermore, the main aims of pH neutralization are also to protect the population from the impact of less conservation in rivers. In addition, pH neutralization is also part of the preliminary treatment in bio processes as well as providing neutral pH water for water recycling process with the pH value 7 (Sasi and Saji M., 2011).

The Proportional, Integral and Derivative control (PID) and Proportional plus Integral control (PI) are widely used in this type of application. In some cases, feedback control is combined with feed forward control. Feedback control is basically corrective in action while feed forward provides predictive or preventive control. Much interest has been shown in the works of (Henson and Seborg, 1994), (Hu and Rangaiah, 1999) and (Gustafsson and Waller, 1983) in which they studied adaptive nonlinear control of a pH Neutralization process.

Rosdiazli Ibrahim carried out studies on the practical modelling and control implementations studies on a pH neutralization process pilot plant in this work (Ibrahim R. , 2008). In his work he used a fuzzy logic controller with a feedback/feed forward control approach was implemented. The results from this feedback/feedforward control structure are extremely encouraging and the controlled responses of the plant with the fuzzy logic controller show interesting characteristics.

Fuente, et al. (2006) also studied the control of pH neutralization processes using fuzzy controllers. As the fuzzy controller was designed using auxiliary variable as input and it gave adequate performance in all regions. This controller was tested real-time on a laboratory plant. The results showed that the controller provided good performance at the desired working points.

The rest of the paper is structured as follows: in section 2, the general presentation of the constructed laboratory scale pH-neutralization system. The process definition is presented in section 3, to show the development of the proposed model to be used in controlling. In section 4, the development of the fuzzy logic controller is presented. Section 5 displays the results obtained and Section 6 conclusions are drawn for this paper.

2. THE LABORATORY SCALE PH NEUTRALIZATION SYSTEM

The laboratory scale pH system used is specifically designed for process control studies and has several features of an industrial control system. The system will have three inputs and a single output with significant interactions and non-linearities.

2.1. Overall System Architecture

The pH neutralization system constructed is based on the UCSB bench-scale neutralization system used by (Henson and Seborg, 1994).

Figure 1 shows a simplified schematic diagram of the laboratory scale pH neutralization system. As shown in Figure 2 there are three different functional levels for this pilot plant, a similar construction was that seen in a previous paper, (Bamimore, Adebayo and Aladekomo). The first level is known as the Plant and Field Instrument Layer, the second level is the Data Acquisition System Layer and the third level (shown at the top) is the Supervisory Computer System Layer. The overall system architecture of the pilot plant is shown in Figure 3.

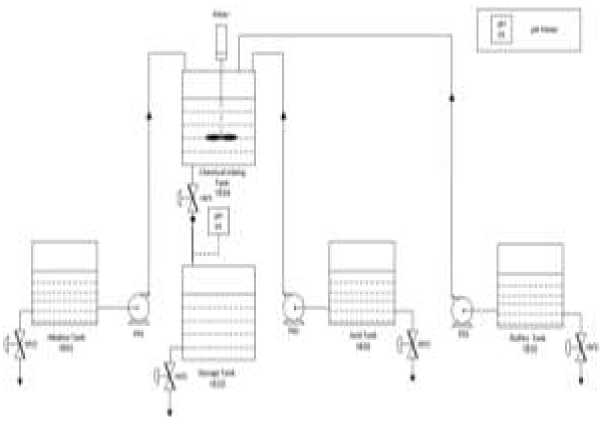

Figure 1: Schematic Diagram of the Laboratory Scale pH Neutralization System

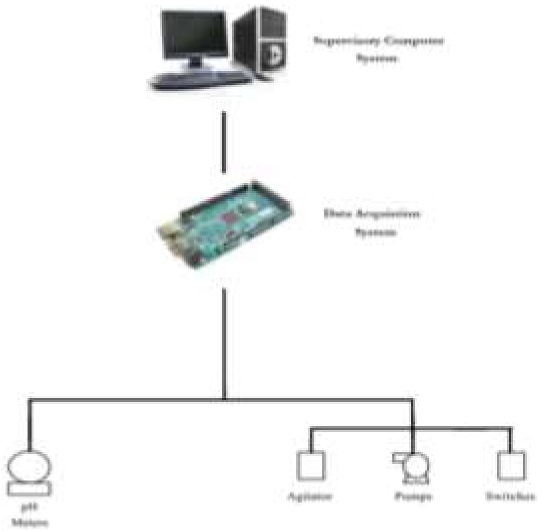

Figure 2: Overall System Architecture

Figure 3: Laboratory scale pH neutralization system

3. PROCESS DEFINITION AND MODELING

The dynamic model for the pH neutralization process is developed based on the conservations equations and equilibrium relations. The modeling assumptions are as follows:

- Perfect mixing
- Constant density
- Complete solubility of the ions involved
- No substance enters or leaves the system except through the flow streams

A reaction invariant is a linear combination of concentrations of chemical species, with the property that, in a reactor, it behaves as an inert species. Based on methods proposed by researchers (Gustafsson and Waller, 1983) two reaction invariants are defined by the following equations:

$$W_{ai} = [H^+]_i - [OH^-] - [HCO^-]_i - 2[CO_3^{2-}]_i \quad (1)$$

$$W_{bi} = [H_2CO_3]_i + [HCO_3^-] + [CO_3^{2-}]_i \quad (2)$$

The process model consists of three nonlinear ordinary differential equations (Henson and Seborg, 1994):

$$\dot{W_{a4}} = \frac{1}{Ah}[(W_{a1} - W_{a4})q_1 + (W_{a2} - W_{a4})q_2 + (W_{a3} - W_{a4})q_3] \quad (3)$$

$$\dot{W_{b4}} = \frac{1}{Ah}[(W_{b1} - W_{b4})q_1 + (W_{b2} - W_{b4})q_2 + (W_{b3} - W_{b4})q_3] \quad (4)$$

The state variables, inputs and outputs are defined as follows:

$$x = \begin{bmatrix} W_{a4} \\ W_{b4} \end{bmatrix} \quad (5)$$

$$u = [q_3] \quad (6)$$

$$y = [pH] \quad (7)$$

$$x_2 + 10^{y_2-14} + x_3 \frac{1+2*10^{y_2-pK_2}}{1+10^{pK_1-y_2}+10^{y_2-pK_2}} - 10 = 0 \quad (8)$$

3.1. Process Description

The laboratory scale pH neutralization consists of a continuously stirred tank reactor (CSTR) with three inlets and one outlet. The tank has a constant hold up height h. The acid, base and buffer solutions are pumped into the tank. The solutions pumped into the tank and stirred continuously while they react and exit the tank via the outlet. The pH from the solution in the outlet is measured continuously. The process is a SISO process, the base flow rate q_3 is the manipulated variable (The acid and buffer flow rates are held constant) while the pH is the controlled variable. The other flowrates acid flowrate q_1 and buffer flowrate q_2 are kept constant. A simplified schematic of the process is shown in Figure 4.1. The objective is to control the pH by manipulating the base flowrate q_3 in the presence of changes in buffer flow rate q_2 and acid flowrate q_1. Table 1 shows the nominal operating conditions of the neutralization system.

Table 1: Nominal operating conditions for the laboratory scale pH neutralization system

Variable	Nominal Value
A	$19.63 cm^2$
pK_1	6.35
pK_2	10.25
W_{a1}	$3x10^{-3}$ M
W_{a2}	$-3x10^{-2}$ M
W_{a3}	$-3.05x10^{-3}$ M
W_{a4}	$-4.32x10^{-4}$ M
W_{b1}	0
W_{b2}	$3x10^{-2}$ M
W_{b3}	$5x10^{-5}$ M
W_{b4}	$5.28x10^{-4}$ M
Q_1	2.00 ml/s
Q_2	1.00 ml/s
Q_3	3.00 ml/s
h	5 cm
pH	7.1

3.2. Stream Compositions

The nominal inlet stream compositions are: acid stream (q_1), 0.003 M HNO3; buffer stream (q_2), 0.03 M $NaHCO_3$; and base stream (q_3), a mixture of 0.003M NaOH and 0.00005 M $NaHCO_3$.

4. FUZZY LOGIC CONTROLLER DESIGN

The Mamdani methodology is used for the development of the fuzzy logic controller. It combines physical understanding of the process with the practical experience gathered from work on the plant on which the controller is to be installed. The principal requirement for the control is to maintain the pH value in the reactor tank at a chosen set-point level between 6 and 10. In addition there must also be able to accurately tracking set point changes and maintaining the pH at a given step point value regardless of changes of flow rate or concentration of the buffer flow.

Eleven groups of membership functions are used to represent the input set. Figure 3 shows that the setting of input range is between −20 ml/s and 20ml/s. The input set represents the error and this is simply defined as:

$$Error = Setpoint - Process\ Variable \quad (9)$$

Eleven groups of membership functions are used to represent the output as shown in Figure 4. The setting for output is between −30 and 30. This output is used to control the flow rate of the base. A fuzzy logic controller is paired with the base flow rate to control the pH while one of the PID controllers used in section 5.1 is paired with the acid flow rate to control the height in the reactor tank. Table 2 gives the relationship between the input set and output set of the pH Fuzzy Logic controller.

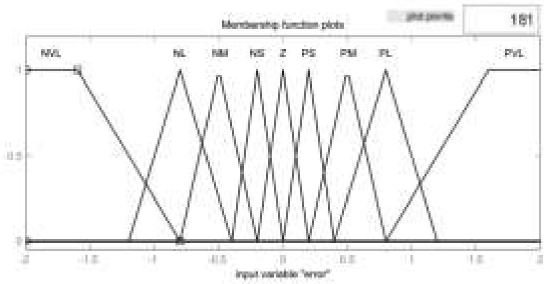

Figure 4: Membership functions used to represent input membership set (error)

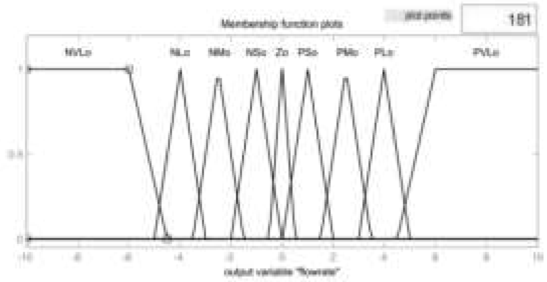

Figure 5: Membership functions used to represent output membership set (output)

Table 2: If-then-rules statements for the fuzzy logic controller

No	Statement	Error	Statement	Flowrate (ml/s)
1	IF	NVL	THEN	NVLo
2	IF	NL	THEN	NLo
3	IF	NM	THEN	NMo
4	IF	NS	THEN	NSo
5	IF	NVS	THEN	NVSo
6	IF	Z	THEN	Zo
7	IF	PVS	THEN	PVSo
8	IF	PS	THEN	PSo
9	IF	PM	THEN	PMo
10	IF	PL	THEN	PLo
11	IF	PVL	THEN	PVL

4.1. PID Controller Design

A single SISO controller is used to control the process. The pH is paired with the base flow rate. The PID controller settings were:

$$K_c = 2.5, \quad \frac{1}{\tau_I} = 0.015\, min, \quad \tau_D = -27\, min$$

5. SIMULATION RESULTS AND DISCUSSIONS

This section presents some of the simulations carried out. All simulations were carried out in the MATLAB/Simulink environment.

The first simulation considered involves the set point change testing. The objective of this simulation is to observe the control performance of the fuzzy logic controllers and PID controller when a set point change has been introduced. Two step-changes were made for the pH value in the reactor tank. The first change was made from pH value 7 to pH value 8 and the second set-point change was a change in the negative direction from pH value 8 to pH value 7.

Both FLC and PID controllers were used in simulating the first experiment. The simulation was successfully performed and the results are as shown in Figure 6. The set point response indicates that the FLC controller provides better pH set point tracking than the PID controller.

The next test or simulation involved a set point tracking test. This simulation was performed to test the robustness of the fuzzy logic controller for a series of a random set point changes. Although the target pH value for the specific neutralization process considered in the current application is always 7 some other processes might involve control with other solutions at different pH values. Thus, this test will determine whether the fuzzy logic controller can provide good responses at different set points.

The simulation was successfully performed and the results are as shown in Figure 7. The set point response indicates that the FLC controller provides better pH set point tracking than the PID controller.

The third simulation involved "Load Change" tests. In these tests the flow rate for the acid stream acts as a load or demand for the entire system. The aim of this experiment is to observe the response of the fuzzy logic pH control system when a load disturbance occurs in the buffer flow rate, q_2. The expected response from the fuzzy logic pH controller is an immediate and appropriate control action to maintain the pH value at the desired set point (i.e. the pH value of 7) regardless of the changes in the acid stream. The experiment was carried out successfully and the results suggest that the system performed very well, as shown in Figure 8.

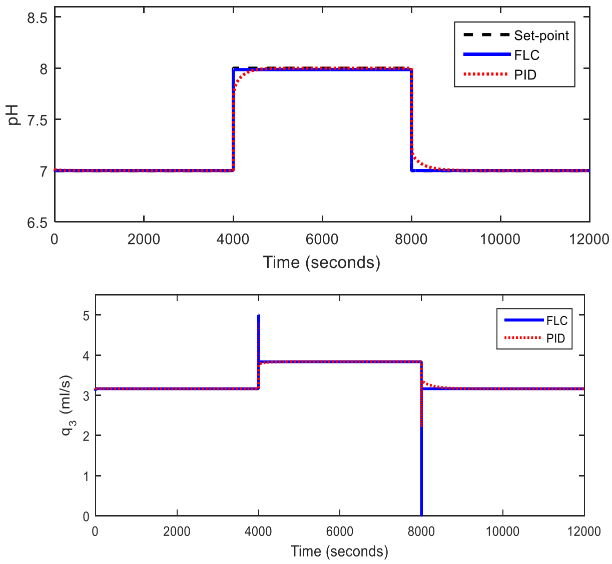

Figure 6: Performance of PID controller and FLC for set point changes in the pH: (a) controlled variables, and (b) manipulated variables

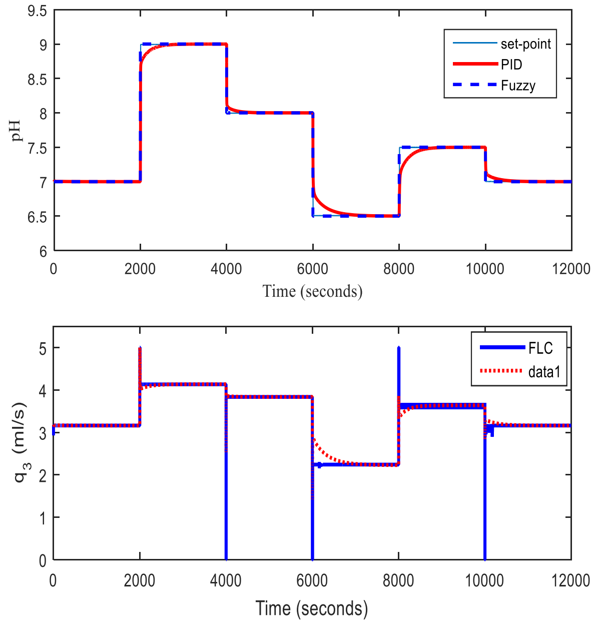

Figure 7: Performance of PID controller and FLC for set point tracking in the pH: (a) controlled variables, and (b) manipulated variables.

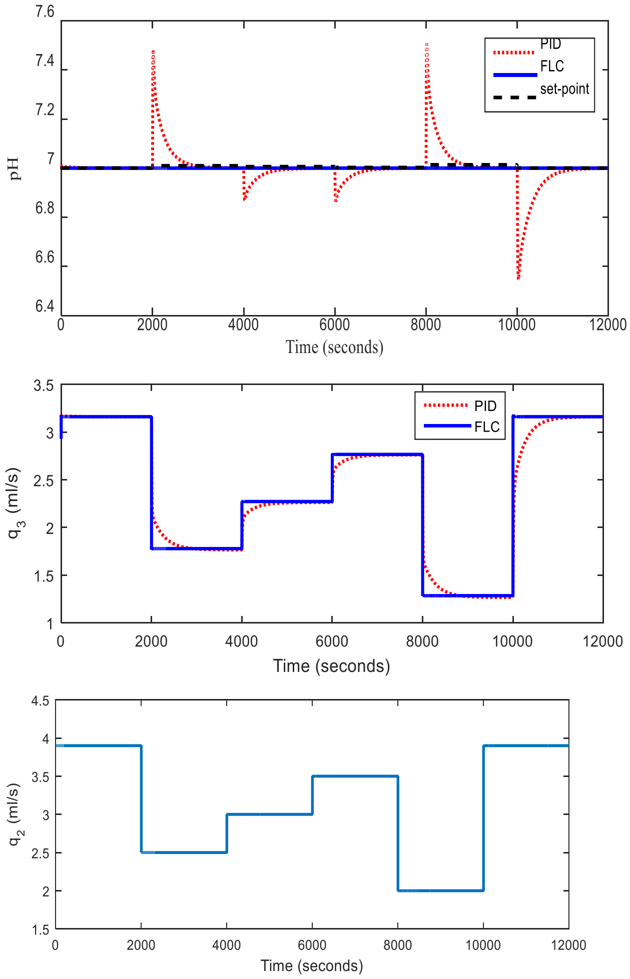

Figure 8: Performance of PID controller and FLC for Load changes in the q_2: (a) controlled variables, and (b) manipulated variables (c) Load changes in q2.

The results obtained for simulation of the system are shown below. The results show a better performance of the FLC as compared to the PID response in Figure 7.

The evaluation of the controller performances are presented with the IAE values provided for the simulation instances are presented in table 3.

Table 3: Integral Absolute Errors in simulation cases

	Integral of Absolute Error (IAE)	
Simulation Cases	PID	FLC
Figure 6	42.2416	6.4024
Figure 7	608.9515	518.0537
Figure 8	447.5938	337.2416

6. CONCLUSIONS

Construction, modeling and interfacing of a laboratory scale pH neutralization process with a Arduino micro-controller board for real-time fuzzy logic control has been successfully carried out. Work carried out involved simulations of the pH neutralization process in SISO configuration using PID controllers, design of the fuzzy logic controller, and preliminary real-time experimentation.

Comparison between conventional PID and FL controller reveals better closed-loop performance, in terms of set-point tracking and disturbance rejection by the FLC. The IAE computed and the preliminary real-time results also corroborate this.

It can be concluded that for the control of a nonlinear system, the Fuzzy Logic Controller gives much more satisfactory responses when compared to conventional controller. The developed approach will find applications in industrial processes where pH control is a challenge.

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