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Intelligent Automatic pH Control System Based on Microcontrollers

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Abstract

In this paper it is presented the development of an intelligent pH-monitoring and control system for residual water, which has its functionality based on the artificial neuro-fuzzy systems theory. Using one of the latest state of the art microcontroller technologies, our system is capable to maintain a neutral pH level by releasing acid or alkaline compounds. Our fuzzy inference system developed in MATLAB is implemented at hardware level. The results are also discussed along this paper.

Key words: *pH, fuzzy inference, ANFIS, microcontroller.*

Introduction

A disadvantage of fuzzy systems is represented by the developing of the rule base that is time consuming and needs to be permanently updated and adapted to obtain more consisted rules. In the last years a great interest was shown regarding to the usage of fuzzy logic combined with neural networks, due to the transparency of fuzzy systems and the capacity of neural networks to adapt, in this way being obtained the so called adaptive neuro-fuzzy inference systems (ANFIS) [10].

The control of parameters that describe certain processes can be achieved using conventional or advanced methods. Some of the advanced methods belong to the artificial intelligence (AI) domain, such as: fuzzy logic, neuro-fuzzy, artificial neural networks, expert systems or genetic algorithms. Also, model predictive control (MPC) systems, based on the previously mentioned methods, are spread today in many industrial areas [5]. According to [11, 2, 9], some of the advantages that recommend the usage of fuzzy logic or fuzzy logic combined with neural artificial networks, are as following:

- Successful application for non-linear processes;
- Usage of the “know-how” from the process operator;
- Allows the development of fuzzy or neuro-fuzzy robust controllers for complex and high non-linear processes ;
- Capability to adapt through a learning process (the membership functions of the fuzzy sets can be adapted using a certain minimization criterion such as the mean squared error between the current and desired neuro-fuzzy system output);

- Possibility to develop robust controllers using the human expert knowledge without a previously-known mathematical model of the process, which eliminates any complications such as a complex or an unknown mathematical model;
- Improvement of controller performance by using training algorithms for the neuro-fuzzy techniques.

In [3] the ANFIS are defined as a “class of adaptive networks that are functionally equivalent to fuzzy inference systems“. The ANFIS uses a hybrid training algorithm (consisting in two steps: feed forward propagation and back propagation) to generate a fuzzy inference system (FIS) capable to auto-adjust by using input-output training data sets [4]. The ANFIS functionality is equivalent to the Takagi-Sugeno-type fuzzy rule base theory [6, 8]. Nowadays, the ANFIS are used in many domains such as automated control, where the main purpose is a robust controller development for different types of applications in areas such as: aeronautics, facial features recognition ([7]) or the control of various processes parameters (wastewater pH control [10]). This paper presents the development and implementation of an ANFIS at microcontroller level.

Experimental Set-up

The process of pH neutralization takes place in the chemical step of a wastewater treatment plant. Through the dosage of different neutralization agents (like H_2SO_4, NaOH) the pH value must be brought to the limits imposed by the legislation in domain.

The system presented in this paper is based on the BSD Unix-based Data Logger (BSDLog) developed at the Petroleum-Gas University of Ploiesti in Romania [1]. The conceptual block of the proposed system is shown in Figure 1.

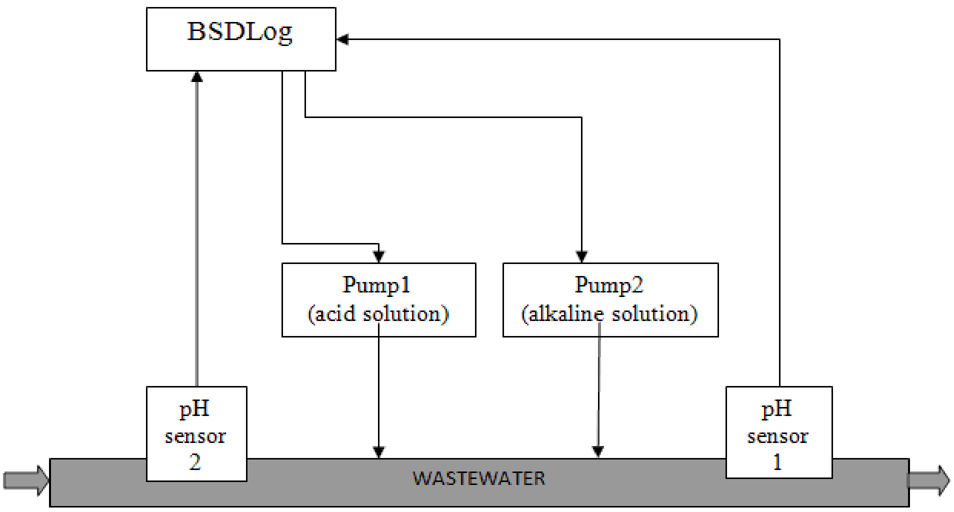

Fig. 1. The architecture of the proposed system

The process consists of injecting the appropriate quantity of neutralizing agent inside a residual water pipe. As shown in Figure 1, the central processing unit (BSDLog) measures the input values provided by the first pH sensor. The data is passed at the input of the ANFIS controller component of the BSDLog software level (as shown in fig. 2). The measured pH value from the second sensor is stored in a remote SQL database and is used for information purpose, to compare the resulting value with the calculated (desired) pH value. Figure 2 shows the architecture of the experimental system. Our BSDLog controller interfaces with the environment through a monitoring interface (IFMON) and a warning interface (IFW), both also based on microcontroller technology.

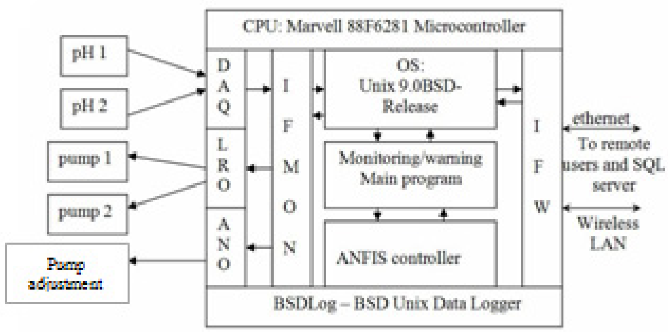

Fig. 2. The architecture of the proposed system

IFMON consists of the following three microcontroller technology-based units:

- Data Acquisition Unit (DAQ), which measures the pH levels before and after the adjusting process;
- Logical Relay Output Unit (LRO), which activates two pumps for applying the necessary pH level corrections;
- Analog Output Unit (ANO), which adjusts the pump flow.

The data measured from the pH sensors is passed through the IFMON to the internal operating system. The main program has permanent bidirectional access to IFMON by means of a previously built BSD-Unix hardware driver and passes the data from first pH sensor to the ANFIS software controller [1]. The data is processed via the already trained ANFIS, which outputs the proper reactive quantities back to ANO via the same path through IFMON, as the main purpose of the described system is to keep a neutral pH value.

IFW consists of several slave microcontrollers corresponding to the standard local area networks (cable Ethernet and wireless LAN). Through this interface, the process can be monitored by local or remote users and all the data is recorded on a remote SQL server for further analysis.

The BSDLog system is based on the Marvell OpenRD development platform and has a large variety of interfaces, as shown in Figure 3 [16]. The master microcontroller is built under the System on a Chip technology and its main destination is the mobile multimedia equipments market, such as telephones and tablets.

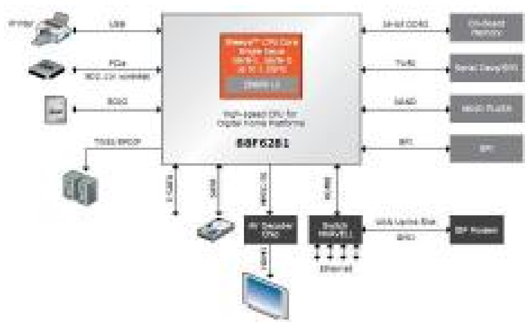

Fig. 3. Marvell openRD microcontroller interfacing options

For this experimental system, the latest BSD Unix 9.0-Release [12] operating system was modified and compiled. It was chosen due to its stability, simple programming ([13]), and the support offered for ARM microcontroller architecture.

ANFIS Controller Architecture

As shown in Figure 4, the ANFIS software controller receives an error value, defined in the main program as the difference between the pH reference value (ref_{pH}=7) and the measured pH value (m_{pH}), acquired from pH sensor 1. The output data (*dosing_pump*) represents the control command for the adjustable pump, which sets the appropriate flow for the neutralizing agents (H_2SO_4 and NaOH).

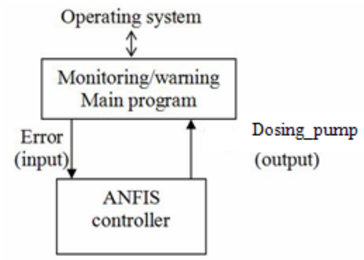

Fig. 4. ANFIS controller input/output

MATLAB design of the ANFIS controller

The ANFIS controller was designed in MATLAB as a Takagi-Sugeno type fuzzy system with a single input and also a single output - the pump adjustment for the chosen neutralizing agents. As shown in both Figure 4 and Figure 5, the error value is passed to the controller input. The fuzzy system calculates and passes out the pump adjustment percentage.

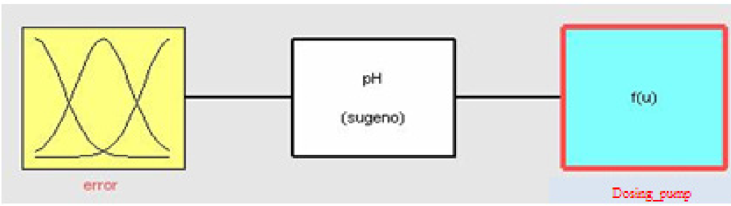

Fig. 5. MATLAB architecture of the ANFIS controller.

As shown in Table 1, the rule base consists of 10 components automatically generated by the generate FIS MATLAB function which is based on the training data, a selection of it being shown in Table 2. As a result, this function generates the entire fuzzy inference system (shown in fig. 5).

Table 1. Controller rule base

	Error		**Dosing_pump_adjustment**
if	in1mf1	**then**	out1mf1
	in1mf2		out1mf2
	in1mf3		out1mf3
	in1mf4		out1mf4
	in1mf5		out1mf5
	in1mf6		out1mf6
	in1mf7		out1mf7
	in1mf8		out1mf8
	in1mf9		out1mf9
	in1mf10		out1mf10

Table 2. Selection of training data

Error	Pump_adjustment (%)	Error	Pump_adjustment (%)
4.91	86.84	4.67	82.60
4.90	86.69	4.66	82.44
4.89	86.53	4.65	82.28
4.88	86.37	4.64	82.12
4.83	85.43	4.63	81.97
4.82	85.27	4.58	81.02
4.81	85.11	4.57	80.86
4.80	84.95	4.56	80.71
4.79	84.80	4.55	80.55
4.76	84.17	4.54	80.24
4.70	83.07	4.53	80.08

The training data was obtained by manually preparing a large number of acid and alkaline solutions sets in different percentages, and releasing the proper neutralizing agents at different dosages (set by pump adjustment) for obtaining a neutral pH measured value. The MATLAB hybrid training optimization method was used together with a large selection from the training data.

As specified before, only a selection from the entire data was used for training. As validation data, the entire set was used. As shown in Figure 6, MATLAB validated the supplied model, as the validation data follows the FIS output.

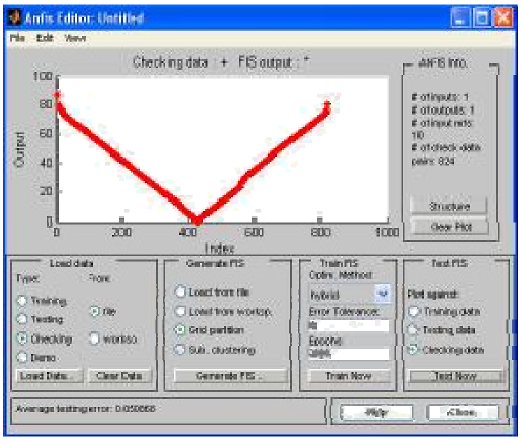

Fig. 6. ANFIS validation

The rule viewer showing a map of the entire fuzzy inference process is shown in Figure 7, covering all the situations between a strong acid and strong alkaline measurements.

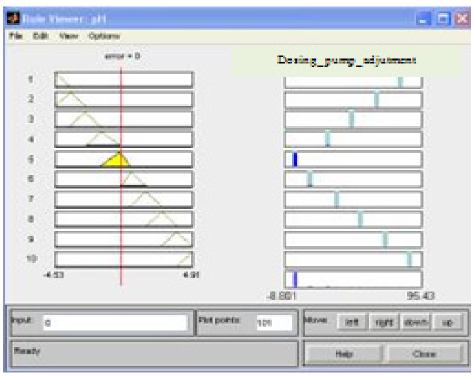

Fig. 7. ANFIS controller rule viewer

The graphic shown in Figure 8 varies between acid and alkaline situations (on the x axis), and indicates the pump adjustment in percentage. When the calculated error is close to -5, it can be interpreted as a far-from-reference acid measurement situation, so a greater percentage of adjustment must be performed. When the calculated error closes to zero a gradual reduction of percentage adjustment must be performed. The same situation is present on the alkaline side of the graphic–a gradual increase of the adjustment is performed, based on the increase of calculated error value.

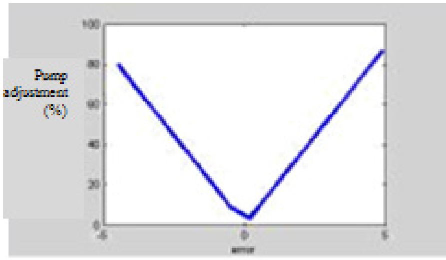

Fig. 8. ANFIS controller surface viewer

The results presented in Figure 9 can be interpreted as follows:

- The error equals 0, which means the pH=7 (neutral pH) and no action is performed on the dosing pumps (for H_2SO_4 and NaOH), dosing_pump_adjustment=0%;
- error = -5, which means the pH=12 (strong alkaline solution) and the degree of acid agent dosing pump is set to 80%;
- error = 5, meaning the pH=2 (strong acid solution) and the degree of alkaline agent dosing pump is again set to 80%.

The main program selects the corresponding dosing pump (acid or alkaline neutralizing agent) according to the positive or negative error value.

A method for exporting the designed ANFIS software controller from MATLAB to UNIX BSD

For the BSDLog-level implementation of the ANFIS controller designed in MATLAB, a special exporting method approach was used. During the execution of the ANFIS controller algorithm in testing mode, the entire physical random access memory content was dumped to a core file on the hard drive. This method is known as a core memory dump. The resulting data was transferred to three different debugging environment programs: SoftIce [17], OllyDbg [15] and Ida Pro Interactive Disassembler [14]. The memory area occupied by ANFIS program was later identified by comparing the live memory content to the dumped mirror. By using the Ida Pro Disassembler produce C file feature, a POSIX-compatible C source code was obtained, which was manually reviewed and modified as following:

- restriction apply for all variables in fixed memory-length areas by using the *malloc()* C function, to avoid any compiling and execution errors under the microcontroller ARM architecture;
- redirection of the input and output parameters of the code to the main program, which provides the communication to IFMON.

Results and Discussion

The previously described setup is based on two SBE-18 pH transducers, which, according to the datasheet [18], has a linear output from 0 to 5 volts corresponding to pH values between 0 and

14. As the transducers condition states were unknown, measurements of different, previously known acid and alkaline characteristics were performed to elaborate the sensor slope shown in Figure 9.

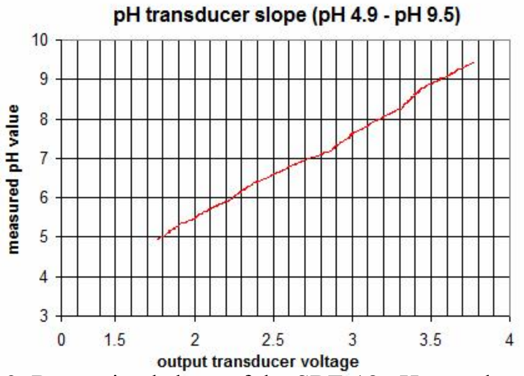

Fig. 9. Determined slope of the SBE-18 pH transducer

During the experiment, a large quantity of distilled water was used because of its neutral pH characteristic. A small quantity of sulphuric acid extracted from an old lead battery was injected in the water flow pipe. The experiment consisted in neutralizing the acid solution, and it is described graphically in Figure 10 and numerically with a selection of data shown in Table 3. By following the graphics characterizing both the pumps activities and the adjustable valve signals, it is noticed that during the decrease on pH value measured by pH sensor 1, the first pump releases alkaline neutralizing agent. As the measured pH slowly increases above the neutral value, the second pump is activated to release a small amount of acid neutralizing agent. At the end of the experiment, the pH falls back to the neutral area.

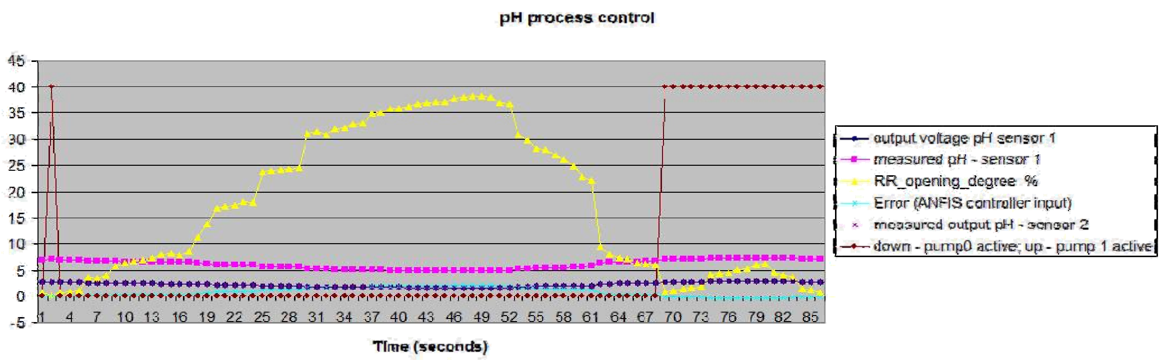

Fig. 10. pH control process evolution in time

Table 3. Selection of extracted data

pH sensor 0 voltage	pH sensor 0 (measured pH value)	Pump adjustment (%)	Error (ANFIS input)
1.95517	5.41	28.16	1.59
1.965222	5.42	28.01	1.58
2.000124	5.48	26.9	1.52
2.015075	5.52	26.12	1.48
2.037738	5.59	24.86	1.41
2.095007	5.71	22.81	1.29
2.112727	5.75	22.03	1.25
2.430234	6.46	9.44	0.54
2.485241	6.54	8.03	0.46
2.505192	6.59	7.24	0.41

Conclusions

This paper has presented a hardware application of the Takagi-Sugeno-type fuzzy rule base theory, implemented at microcontroller level and designated for intelligent pH monitoring and control inside residual water plants. Two major flaws were identified in the presented hardware setup, which need future attention. The first flaw consists of a common injection path for both the acid and alkaline neutralizing agents, which transfers small amounts of H_2SO_4 salts to the water flow pipe. The second flaw is characterized by the pH sensors in bad conditions, which were recovered from a discarded installation and their parameters had to be rediscovered by performing measurements and validating them using a calibrated pH meter.

However, the presented method of extracting a MATLAB ANFIS function in execution state from the computer RAM memory and transferring it to a microcontroller opens a path for more complex model design and implementation with minimal costs. The system presented in this paper is able to use any MATLAB exported .fis document as an updated algorithm.

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Sistem inteligent automat pentru reglarea pH-ului bazat pe microcontrolere

Rezumat

În cadrul acestei lucrări este prezentată dezvoltarea unui sistem inteligent pentru monitorizarea și reglarea pH-ului apei uzate, sistem a cărui funcționalitate are la bază teoria sistemelor artificiale neuro-fuzzy. Utilizând una dintre cele mai recente tehnologii asociate microcontrolerelor, sistemul dezvoltat este capabil să mențină un pH neutru prin adăugarea de agent bazic sau acid. Sistemul cu inferență fuzzy dezvoltat în MATLAB este implementat la nivel hardware. Rezultatele sunt de asemenea discutate în cadrul acestei lucrări.