Design and Implementation of Fuzzy Controller on Embedded Computer for Water Level Control

Senka Krivić, Muhidin Hujdur, Aida Mrzić and Samim Konjicija
Faculty of Electrical Engineering, Department of Automatic Control and Electronics, Sarajevo, Bosnia and Herzegovina
krivic.senka@gmail.com, hujdur.muhidin@gmail.com, amrzic@gmail.com, skonjicija@gmail.com

Abstract - The paper deals with one of frequently encountered tasks in process industry - water level control. Proportional Integral Derivative (PID) control is often used for this purpose. Since control parameters of PID controller are fixed and tank system is inherently nonlinear, PID controller should not be used on wider level range. Therefore, this paper analyzes the effectiveness of water level control using fuzzy controller. The fuzzy controller is implemented based on mathematical model of tank and using MATLAB. The controller is implemented on Friendly ARM - embedded computer. Arduino board is used as an acquisition board for collecting sensor data from tank system Festo Didactic DD 3100 and as a PWM signal generator for water pump control. Experimental results confirm that the fuzzy control system has good adaptability in comparison with PID and provided satisfying results.

Keywords: fuzzy, Sugeno, PID, embedded system, microcontroller, tank, water level control, nonlinear system

I. Introduction

In certain industry branches (e.g. food, pharmaceutical, chemical etc.) the problem of water level control is very often encountered. The main objective of controller in this case is maintaining different setpoint water levels, mostly, in real time environment.

The traditional approach to this problem using PID controllers is not fully convenient when it comes to dealing with nonlinearity of tank systems and their complexity in industry [1][2]. These problems can be successfully dealt with using fuzzy control [3-5]. Based on expert knowledge and experience, control implementation is therefore simplified, and it can be achieved without complex mathematical modeling [6][7]. Since the water level controller is often a part of complex control system, the controller should have a communication interface which allows it to be incorporated and integrated with centralized control system. Different communication interfaces makes it suitable for use in already existing control systems, without changing communication protocols and interfaces.

Taking all this into account, this paper deals with implementation of PID and fuzzy water level controller using embedded computer and comparison of these controllers on laboratory tank model Festo DD3100.

The paper is organized in six sections. Section II describes implemented control system. In subsection A of section III, mathematical model of tank system is given. Subsection B of section III deals with system identification, while Section IV describes the PID and fuzzy controller implementation. The experimental results are shown in Section V, and conclusion is given in Section VI.

II. System Description

Figure 1 shows the block scheme of implemented control system.

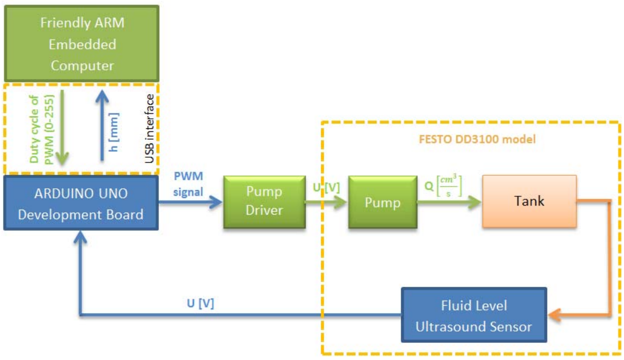

Figure 1. System structure

The PID and fuzzy controllers are implemented in application developed for Friendly ARM [10], which allows user to set desired water level and to select the type of controller (PID, or fuzzy). It also displays measured water level. Regardless of controller type, controller input (or one of the inputs) is measured water level expressed in millimeters, and its output is duty cycle of pulse width modulatied signal, expressed in 8 bits digital form proportional to percentage of duty cycle. The Figure 2 shows the implemented system.

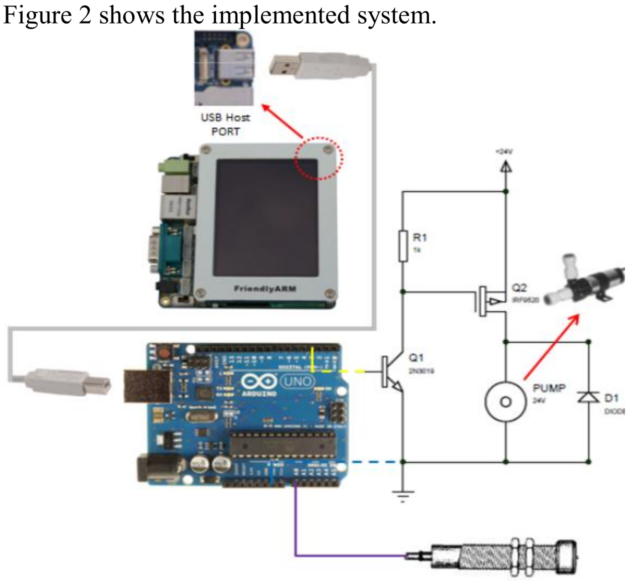

Figure 2. Implemented system

Both, controller input and output are exchanged with Arduino Uno Development Board [11]. Arduino is used as an acquisition input/output card for Friendly ARM. Arduino and Friendly ARM are connected using USB interface.
The PWM signal is used for triggering of pump driver [8] which generates a voltage signal used for pump control. Measurement of water level is done using ultrasound sensor and analog to digital and voltage to water level conversion on Arduino.

III. System Identification and Modelling

A. Mathematical modeling

The structure of the liquid volume in horizontal tank and its geometrical parameters are shown in Figure 3.

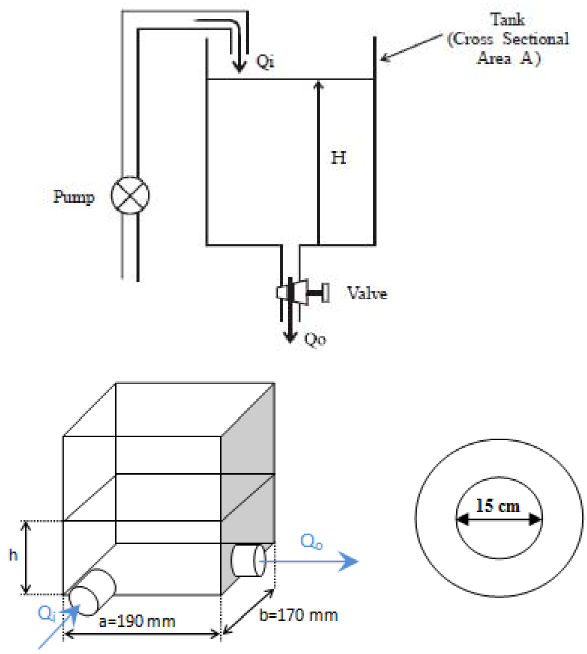

Figure 3. Single tank water level system

The system model is determined by relating the flow Q_i into the tank to the flow Q_o leaving through the valve at the tank bottom. Using a balance of flows equation on the tank, it is possible to write:

$$Q_i(t) - Q_o(t) = A\frac{dh(t)}{dt} \quad (1)$$

Where A is the cross sectional area of the tank and h is the height of the water in the tank.
The Bernoulli's equation can be adapted to a streamline from the surface to the orifice as:

$$gz_1 + \frac{p_1}{\rho} + \frac{v_1^2}{2} = gz_2 + \frac{p_2}{\rho} + \frac{v_2^2}{2} \quad (2)$$

Equations (1) and (2) refer to two different points in the flow, first being upstream of second point. v is the local velocity of the water, g represents the local acceleration of gravity, p the pressure and z the vertical height of the point.
If Bernoulli's equation including loss is applied to single tank system shown on Figure 3, h is calculated as:

$$h = \frac{v^2}{2g} + \Delta h \quad (3)$$

Where, h represents height of the water in the tank, $h = z1 - z2$. Loss to the system Δh can be written as

$$\Delta h = \frac{v^2}{2g}\left(\xi_t + 2\xi_k + \xi_i\frac{1}{d}\right) \quad (4)$$

Where, ξ_k is the local loss coefficient of the curved tube, ξ_i is the local loss coefficient at the entrance of the tube, ξ_t is the resistance coefficient, l is the length of the discharge pipe and d is the diameter of the discharge pipe. Combining (3) and (4) h becomes:

$$h = \frac{v^2}{2g}\left(1 + \xi_t + 2\xi_k + \xi_i\frac{1}{d}\right) \quad (5)$$

The flow Q_o leaving through the valve at the tank bottom is given by

$$Q_0 = \frac{d^2\pi}{4}v \quad (6)$$

Using (6) and (5), the flow Q_o can be expressed as

$$Q_0 = C\sqrt{2gh} \quad (7)$$

where

$$C = \frac{d^2\pi}{4}\frac{1}{\sqrt{1 + \xi_t + 2\xi_k + \xi_i\frac{1}{d}}} \quad (8)$$

Combining equations (7) and (1), gives

$$A\frac{dh(t)}{dt} + C\sqrt{2gh} = Q_i(t) \quad (9)$$

C is called the discharge coefficient of the valve. This coefficient takes into account all water characteristics, losses and irregularities in the system.
Equation (9) represents mathematical model of system.

B. System identification

In this section, nonlinear system model described with (9), will be approximated by the integrator and time delay model. The tank model, Festo Didactic DD3100 is shown on Figure 4.

Figure 4. Festo Didactic DD3100 tank model

In order to identify the tank model, step of maximum pump voltage was applied until the water level reached 12,5 cm, starting from water level of 9,5 cm. System response is shown in Figure 5.

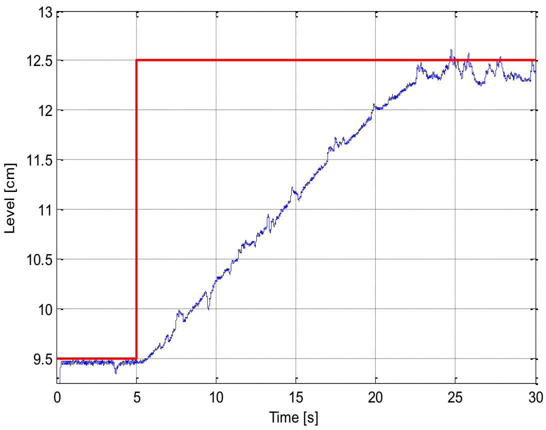

Figure 5. System response

Identification process provided following transfer function.

$$G_{ob}(s) = \frac{0,1553}{s} \cdot e^{-0.19s} \qquad (10)$$

The transfer function of approximated system was used for simulation and tuning of PID and fuzzy controller inside Matlab/Simulink program package. [9]

IV. Controller Implementation

A. PID controller implementation

The design of PID controller based on approximate model was done using Matlab/Simulink. Control parameters (gain/proportional band, integral gain/reset, derivative gain/rate) were adjusted to their optimum values for the desired control response (reaching the operating point of 12.5 cm) using Ziegler-Nichols Method. Following values of PID controller parameters were obtained: Kp = 2, Kd = 0.001, Ki = 0.005. The system discretization was conducted with sample time of Ts = 10ms.

B. FUZZY controller implementation

Two Sugeno fuzzy controllers were designed based on mathematical model and also using Matlab/Simulink. Simulink model shown on Fig. 6 was used for testing fuzzy controller performance.

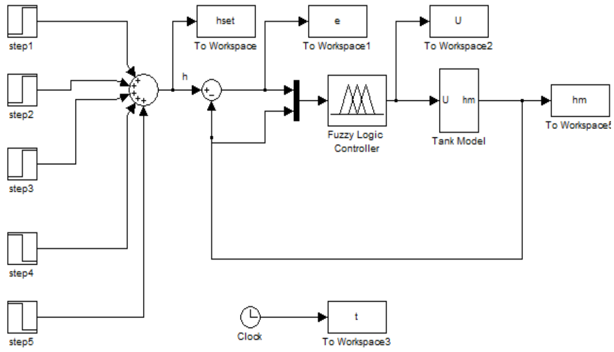

Figure 6. Simulink model used for fuzzy controller testing

Since the tank system is nonlinear and water drainage is correlated with water level, two possible inputs for fuzzy controller can be taken into account – error and current water height. In order to analyze the influence of using measured water level as controller input, two types of fuzzy controller were implemented

1. one input fuzzy controller with error as input
2. two inputs fuzzy controller with error and current water height as inputs

The Sugeno model was used, since it is computationally efficient and works well with optimization and adaptive techniques. This makes it popular for control problems, in particular for dynamic nonlinear systems [7]. Properties of Sugeno type for both controllers are given in Table I.

Table I. FIS (Fuzzy Inference System) Parameters

FIS type	Sugeno
AND method	prod
OR method	max
Defuzzyfication	wtaver

In case of one input fuzzy controller, the error is calculated by taking the difference between referent and current water level. Chosen error memberships functions are shown on Fig. 7.

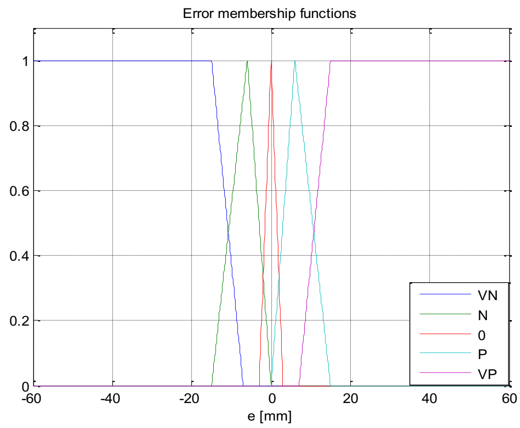

Figure 7. Membership functions of one input fuzzy controller

Output Membership functions represent voltage value. Output values are: 0, 4, 6, 12 and 24. Output MFs are shown on Fig. 8.

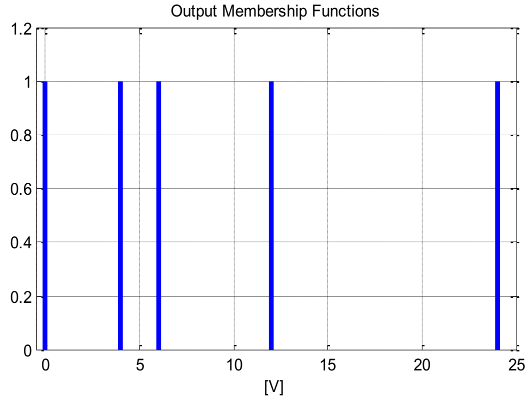

Figure 8. Output membership functions of one input fuzzy controller

The final output of the system is the weighted average of all rule outputs, computed as

$$FINAL\ OUTPUT = \frac{\sum_{i=1}^{N} w_i z_i}{\sum_{i=1}^{N} w_i} \quad (11)$$

where N is the number of rules [7]. In this case the number of rules N is 5. These rules are shown in Table II.

TABLE II. RULE BASE FOR ONE INPUT FUZZY CONTROLLER

If e is VN	Output voltage is 0V
If e is N	Output voltage is 4V
If e is 0	Output voltage is 6V
If e is P	Output voltage is 12V
If e is VP	Output voltage is 24V

Labels in Table II and Figure 7 are as follows: VN=Very Negative; N=Negative; 0=Small; P=Positive; VP=Very Positive.

Inputs for two inputs fuzzy controller are current water level and error, calculated as a difference between referent and current water level. Chosen memberships functions are shown on Fig. 9.

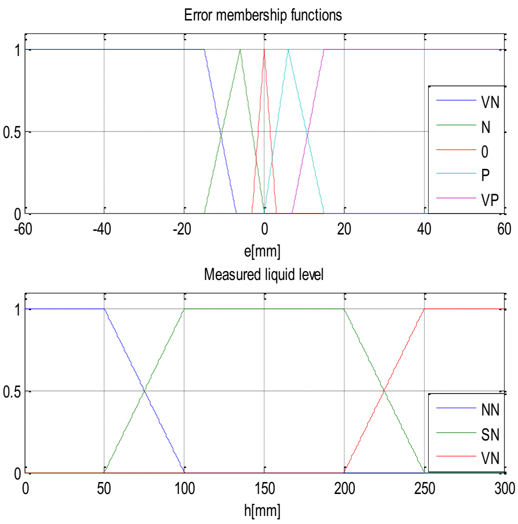

Figure 9. Membership functions of two inputs fuzzy controller

Output membership functions represent voltage value and they are shown on Fig. 10. Output values are: 0, 3, 4, 5, 6, 7, 10, 12, 13 and 24.

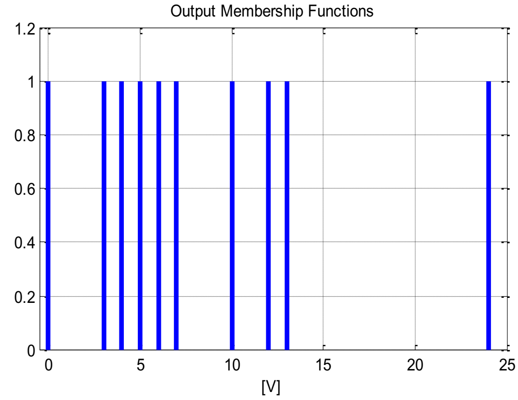

Figure 10. Output membership functions of two inputs fuzzy controller

The final output of the system is represented with weighted average of outputs of all rules, computed as in equation (11). In this case the number of rules N is 11. Rule mapping is shown in Table III.

TABLE III. RULE MAPPING FOR TWO INPUTS FUZZY CONTROLLER

		Error				
		VN	**N**	**0**	**P**	**VP**
Height	**NN**	0	4	5	10	24
	SN	0	3	6	13	24
	VN	0	0	7	24	24

Labels in Table III. and Figure 9 are as follows: VN=Very Negative; N=Negative; 0=Small; P=Positive; VP=Very Positive, NN=Low Height, SN=Medium Height, VN=High Height.

V. EXPERIMENTAL RESULTS

Controllers were first designed using Matlab and tested using Simulink model, based on mathematical model of tank. Functions that represent controllers were then created in programming language C. For more user-friendly usage of these functions, GUI application was created. Simple GUI is designed using QT Designer for Friendly ARM mini 2440. The GUI application is shown on Figure 11.

Figure 11. GUI application for ARM mini 2440

All control and measured data is collected and placed into files. Change of controllers type and set level is possible during control. For demonstration of controllers effectiveness and their comparison, same step sequence for each controller is used. Collected data and control errors for controllers are shown on Figures 12 - 15.

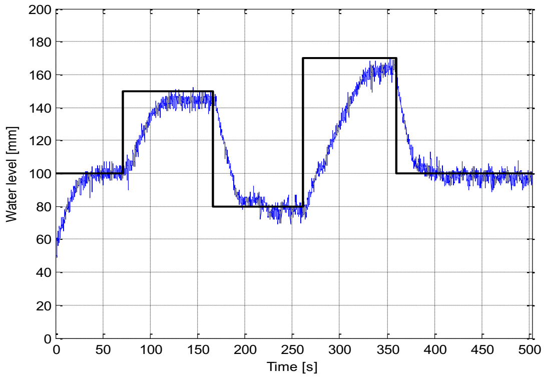

Figure 12. System response on step sequence (PID controller)

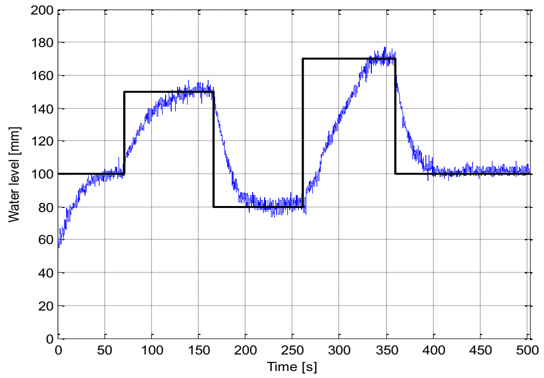

Figure 13. System response on step sequence (one input fuzzy controller)

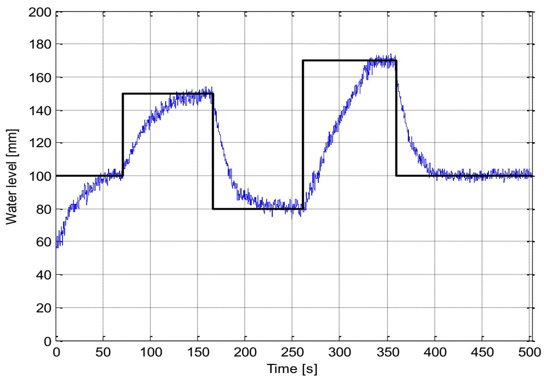

Figure 14. System response on step sequence (two input fuzzy controller)

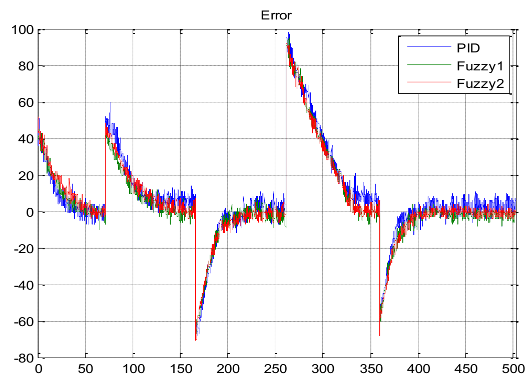

Figure 15. Control errors for different controllers

Based on experimental results, the control error and oscillations around stationary states for both fuzzy controllers were smaller, compared to PID controller. The fuzzy controllers provide better results on wider ranges of water level setpoints. The two input fuzzy controller did not provide significant improvements compared to one input fuzzy controller, although some improvements were achieved in terms of amplitude of oscillations around stationary states.

VI. Conclusion

By implementing fuzzy and PID controllers for water level control, in form of application for Friendly ARM embedded Computer, user-friendly solution was offered. This solution can be used separately or as a part of already existing control system. The use of fuzzy controller is fully justified by experimental results due to nonlinearity of tank model.

This paper can be used as a base for future work involving different fuzzy controller structures and control techniques for water level control. Future work may also include development of centralized control system for process industry, using on-board controllers and integrating them into one system.

References

[1] Isa, I.S., Meng, B.C.C., Saad, Z., Fauzi, N.A., "Comparative study of PID controlled modes on automatic water level measurement system", 7th International Colloquium on Signal Processing and its Applications, Penang, 2011.

[2] Maziyah Mat Noh, Muhammad Sharfi Najib, Nurhanim Saadah Abdullah, "Simulator of Water Tank Level Control System Using PID-Controller", 3rd IASME/WSEAS Int. Conference on Water Resources, Hydraulics and Hydrology, University of Cambridge, 2008.

[3] Maruthai Suresh, Gunna Jeersamy Srinivasan and Ranganathan Rani Hemamalini, "Integrated Fuzzy Logic Based Intelligent Control of Three Tank System," vol. VI, Serbian Journal of Electrical Engineering, 2009, pp. 1–14.

[4] Daniel Wu, Fakhreddine Karray and Insop Song, "Water Level Control by Fuzzy Logic and Neural Networks," Unpublished.

[5] Qi Li, Yanjun Fang, Jizhong Song, Ji Wang, "The Application of Fuzzy Control in Liquid Level System", International Conference on Measuring Technology and Mechatronics Automation (ICMTMA), Changsha, 2010.

[6] Jang, J.S., Sun, C.T. & Mizutani, E. "Neuro-Fuzzy and Soft Computing", Prentice Hall, New Jersey, 1997.

[7] Passino, K.M. & Yurkovich, S., "Fuzzy Control", Addison Wesley, Menlo Park, 1998.

[8] Jacob, J.Michael, "Industrial Control Electronics", Prentice-Hall, New Jersey, 1988.

[9] "MATLAB documentation," Mathworks (www.mathworks.com)

[10] "FriendlyARM mini2440 Manual", FriendlyArm (www.friendlyarm.net)

[11] "Arduino Reference," (www.arduino.cc)