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Decentralized Fuzzy-PID Based Control Model for a Multivariable Liquid Level System

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Abstract: *Multivariable liquid level control is necessary in process industries to ensure quality of the product and safety of the equipment. However, the significant problems of the control system include excessive time consumption and percentage overshoot, which result from ineffective performance of the tuning methods of the PID controllers used for the system. In this paper, fuzzy logic was used to tune the PID parameters to control a four-coupled-tank system in which liquid level in tanks 1 and 2 were controlled. Mass Balance equation was employed to generate the transfer function matrix for the system, while a Fuzzy Inference System (FIS) file is created and embedded in fuzzy logic controller blocks, making tuning rules for the PID. Matlab R2009b simulation of the system model shows that the rise time (RT), settling time (ST), peak value (PV) and percentage overshoot (PO) for the developed DF-PID controller were 1.48 s, 4.75 s, 15 cm and 0% respectively for tank-1; and 0.86 s, 2.62 s, 10 cm and 0% respectively for tank-2, which are the smallest and best values when compared with other PID tuning methods namely: Ziegler-Nichols, Cohen-Coon and Chien-Hrones-Reswick PID tuning methods.*

Keywords: *Decentralized PID Combination, Fuzzy Logic, MIMO, Multivariable, Overshoot*

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I. INTRODUCTION

Among the paramount steps in chemical process industries is liquid level control. On many occasions the liquids are processed and treated in the tanks. Meanwhile, the level of the fluid in the tanks must be controlled, and the flow between tanks must be regulated [1]. Often the tanks, generally referred to as coupled-tanks system, are so coupled that the content levels interact and this must also be controlled; this is because the quality of control directly affects the quality of products and safety of equipment. However, despite its importance, liquid level control remains a complex task due to its time-varying and nonlinear characteristics.

PID controller is one of the earliest industrial controllers, it is economical, easy to be tuned and robust [2]. Also, a major practical solution to linear processes is conventional PID controller, but a considerable degradation is noticed when it is used in nonlinear processes; meanwhile, the incorporation of fuzzy control provides a worthwhile improvement in the response due to its nonlinear nature [3]. Therefore in this paper, Fuzzy Logic (FL), whose working principle is according to if-then rules based on expert knowledge, is incorporated into the conventional Decentralized-PID (D-PID) controller and used to control a four-coupled tank system. The rules designed are based on the characteristic of the four-coupled-tank system and properties of the PID controller. With this, the fuzzy reasoning is obtained by aggregating all the fuzzy set inputs and the designed rules. The resulting Decentralized Fuzzy-PID (DF-PID) controller is a kind of intelligent auto-tuning PID controller, which has yielded better performance in many non linear plants. It provides reliable industrial control system that maintains a desired liquid level; free of overshoot, instability, excessive rise time and settling time. This was established by comparing the Matlab simulation response from DF-PID with those from CHR, CC, and ZN PID tuning methods; the results are compared in Section V. The rest of this paper organized as follows: Section II gives the literature review, Section III is modeling of a four-coupled-tank system, Section IV explains fuzzy-PID technique; Section V gives the model simulation result, while Section VI is the conclusion.

II. LITERATURE REVIEW

The four-coupled-tank apparatus is one of the most commonly available systems representing a Multiple Input Multiple Output (MIMO) process, in which the liquid level control is challenging due to the interaction between the subsidiary tanks [4]. Hence, the liquid flow between the tanks depends upon the liquid level in the tanks as well as the voltage supply to the pumps. Proportional-Integral-Derivative (PID) controller, on the other hand, is a kind of controller that is favoured in most commercial process control applications, because of its satisfactory performance along with its simple, failure tolerant, and easy to understand structure [5], [6].

Due to the process interactions in MIMO systems, the conventional PID controller approaches cannot guarantee stability when all of the loops are closed simultaneously [7]. These conventional approaches include Ziegler-Nichols (ZN), Cohen-Coon (CC), Goodgain, Skogestad and Chien-Hrones-Reswick (CHR) tuning methods. The reason for this is not far-fetched: the closing of one loop affects the dynamics of the other loops and can make them worse or even unstable. Also, the level of overshoot and undershoot obtained as well as the settling time taken using these controllers are significant. Meanwhile, all these shortcomings have negative effects on the dynamic response, regulation, precision and robustness of the closed-loop system [8]. For those reasons, despite the wide popularity of PID controllers in many process industries, effective tuning method is eagerly required in liquid level control systems.

Some other tuning techniques were reviewed and were used for the sake of comparison. They are discussed as follows:

1. Ziegler-Nichols Method

Being a closed-loop system, Ziegler-Nichols closed-loop method is chosen, in which a steady oscillation is desired with only a proportional gain (K_P) involved. Ultimate gain (K_U) refers to the proportional value at which the oscillations become constant. Ultimate period (T_U) is period of oscillations at the ultimate gain. The ultimate gain and ultimate period are applied to the ZN formulae as noted in Table I. From there, parameters K_P , K_I , K_D needed for the PID controllers were obtained. This method works provided the closed loop transfer function is known and there is an ultimate gain [9].

TABLE I
THE ZIEGLER-NICHOLS CLOSE-LOOP RULES [10]

Controller	K_P	$T_I = \frac{K_P}{K_I}$	$T_D = \frac{K_D}{K_P}$
PID	$0.6K_U$	$T_U/2$	$T_U/8$

2. Chien-Hrones-Reswick Method

The Chien, Hrones, and Reswick method of tuning was derived from the original Ziegler-Nichols Open Loop method with the intention of obtaining the quickest response with 20% overshoot [11]. The PID parameters of the Chien-Hrones-Rreswick step response method are then determined as given in Table II, where L = apparenttime delay, T = apparent time constant and a is the intercept on time axis of the ZN open-loop step response curve. [12].

TABLE II
CONTROLLER PARAMETERS OF CHR TUNING METHOD [12]

Controller	K_P	$T_I = \frac{K_P}{K_I}$	$T_D = \frac{K_D}{K_P}$
PID	0.95/*a*	1.4T	0.47L

3. Cohen-Coon Method

Cohen-Coon method is another version of the Ziegler-Nichols PID tuning method. This method is also based on a delayed first order rise, and the method of tuning the PID gains to achieve good response more sensitive than the Ziegler-Nichols method. The controller parameters with this method is designed by the direct use of Table III where $a = bL/T$ and $\tau = L/(L+T)$ [13]. This method differs from Ziegler-Nichols'on the fact that it requires rise time [9].

TABLE III
CONTROLLER PARAMETERS OF COHEN-COON METHOD [14]

Controller	PID
K_P	$\frac{1.35}{a}(1 + \frac{0.18\tau}{1-\tau})$
$T_I = \frac{K_P}{K_I}$	$\frac{2.5 - 2\tau}{1 - 0.39\tau}L$
$T_D = \frac{K_D}{K_P}$	$\frac{0.37 - 0.37\tau}{1 - 0.81\tau}L$

III. MODELING OF A FOUR-COUPLED-TANK SYSTEM

The four-coupled-tank laboratory apparatus is a good representative of chemical plant; in which the tanks are coupled in groups with little interactions between groups. The four-coupled-tank laboratory apparatus (Fig. 1.) has four translucent tanks each of specific height, H, with a capacitive measuring device to measure the liquid level [15]. Liquid is delivered to the tanks by two independently controlled pumps. The apparatus inputs are the voltage supplies v_1 and $v2$ (0 - 5V) to the pumps. The outputs are the water levels in the bottom two tanks, which are the voltages from capacitive level measurement devices, which are converted to heights y_1 and y_2 in cm. The target is to control the liquid level in lower two tanks (Tank 1 and Tank 2) with two pumps as shown in Fig. 1.

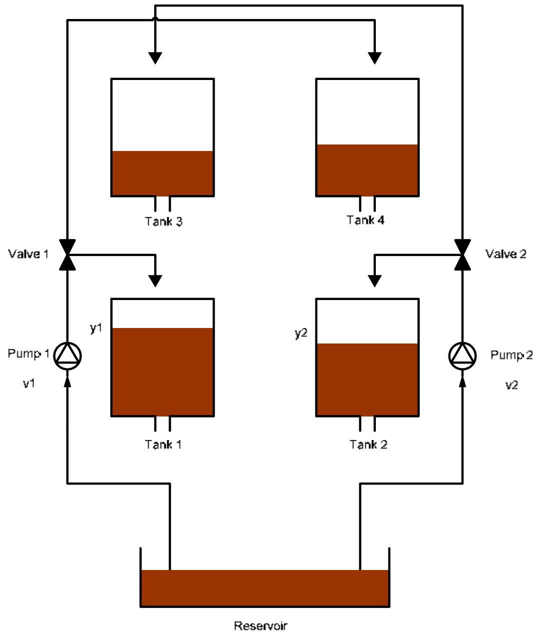

Fig. 1. Four-coupled-tank laboratory apparatus [15]

Using the Mass Balance Equation, (1) and Bernoulli's Law, (2), the relationship between volumes, liquid inflow and liquid outflow are explained as applied to the apparatus shown in Fig. 1.

$$A\frac{dh}{dt} = -q_{out} + q_{in} \tag{1}$$

where
A = cross section of the tank
h = liquid level
q_{in} = inflow to the tank
q_{out} = outflow of the tank

(h, q_{in}, and q_{out} are each greater than or equal to zero)

$$q_{out} = a\sqrt{2gh} \quad (2)$$

$$q_{in} = \gamma\beta v \quad (3)$$

where
a = cross section of the outlet hole;
g = acceleration due to gravity.
q_{in} = inflows to the tanks
γ = valve setting parameter, $\gamma \in (0,1)$;

β = parameter that relates pump to voltage;
v = voltage applied to the pump.

The liquid flow through pump-1 and 2 are each split so that parts of the total flow through each pump travels to each corresponding tank. This can be adjusted via one of the two valves shown in Fig. 1.

Combining (1) to (3), assuming that the flow generated is proportional to the voltage applied to each pump; the following nonlinear equations, which represent the physical system, are derived.

$$\frac{dh_1}{dt} = -\frac{a_1}{A_1}\sqrt{2gh_1} + \frac{a_3}{A_1}\sqrt{2gh_3} + \frac{\gamma_1}{A_1}\beta_1 v_1 \quad (4)$$

$$\frac{dh_2}{dt} = -\frac{a_2}{A_2}\sqrt{2gh_2} + \frac{a_4}{A_2}\sqrt{2gh_4} + \frac{\gamma_2}{A_2}\beta_2 v_2 \quad (5)$$

$$\frac{dh_3}{dt} = -\frac{a_3}{A_3}\sqrt{2gh_3} + \frac{1-\gamma_2}{A_3}\beta_2 v_2 \quad (6)$$

$$\frac{dh_4}{dt} = -\frac{a_4}{A_4}\sqrt{2gh_4} + \frac{1-\gamma_1}{A_4}\beta_1 v_1 \quad (7)$$

Substituting the process parameter values for the apparatus as given in Table IV, as well as the operating point parameters given in Table V, in (4) to (7), a transfer function matrix is derived as (8).

$$G(s) = \begin{bmatrix} g(11) & g(12) \\ g(21) & g(22) \end{bmatrix} = \begin{bmatrix} \frac{2.6195}{63s+1} & \frac{1.4056}{(90s+1)(30s+1)} \\ \frac{1.5071}{(62.89s+1)(23.87s+1)} & \frac{2.8288}{90s+1} \end{bmatrix} \quad (8)$$

IV. FUZZY PID TUNING TECHNIQUE

With this approach, K_P, K_I, K_D of PID controllers are tuned by using fuzzy logic. The structure of the auto-tuning fuzzy PID controller is shown in Fig. 2, where $e(t)$ is the error between desired set point $r(t)$ and the measured output $y(t)$,

TABLE IV
APPARATUS PARAMETER VALUES [15]

Parameter	Value
A_1, A_3	28cm^2
A_2, A_4	32cm^2
H_1, H_2, H_3, H_4	20cm
a_1, a_3	0.071cm^2
a_2, a_4	0.057cm^2
v	0 - 5V
g	981cm/s^2

TABLE V
OPERATING POINT PARAMETER VALUES OF THE PROCESS [4]

Parameter	Value
$h_1^0, h_2^0, h_3^0, h_4^0$	(12.4, 12.7, 1.8, 1.4) [cm]
v_1^0, v_2^0	(3.0, 3.0) [V]
β_1, β_2	(3.33, 3.35) [cm^3/V]
γ_1, γ_2	(0.70, 0.60)

$\frac{d}{dt}e(t)$ is the derivation of error. The PID parameters are tuned by using fuzzy inference derived from a set of rules based on expert knowledge, which provide a nonlinear mapping from the error and derivation of error to PID parameters.

The centroid defuzzification method used was chosen for use because of its simplicity and accuracy. The portion of Fig. 2 enclosed in broken lines explains what is referred to as DF-PID by having a kind of loop arrangement with little interaction between the two constituent loops as shown in Fig. 3.

Using the Fuzzy Inference System (FIS) editor window, in conjunction with the rule base, and triangular membership functions, a FIS file named coupled_4tank.fis was created and exported to a file on Matlab. This file was embedded in the fuzzy logic controller block of SIMULINK and serves as a link between fuzzy toolbox and SIMULINK, which lays the foundation for building the whole control system.

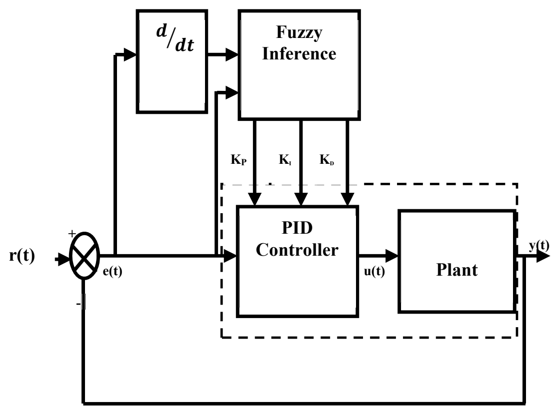

Fig. 2. Structure of a FPID controller

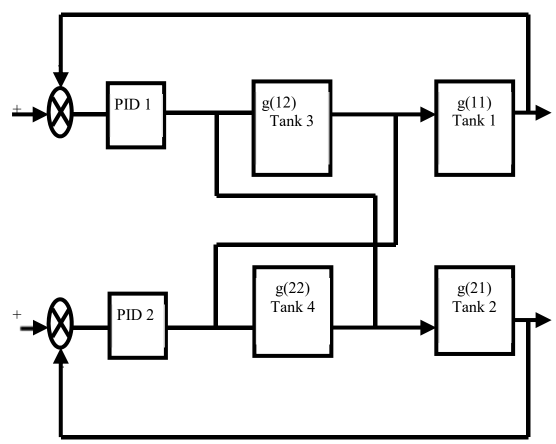

Fig. 3. Decentralized arrangement of FPID controller (Area enclosed in Fig. 2)

V. MODEL SIMULATION AND RESULTS

Simulation of the system model was performed for all the methods using the SIMULINK tool on Matlab R2009b. The arrangement of the system was in decentralized form for each of the methods used. Fig. 4 shows the SIMULINK model for the decentralized ZN, CHR and CC approaches, while Fig. 5 is for the DF-PID method. The set-points for liquid level in tank-1 and tank-2 are 15 cm and 10 cm respectively. However, these values are arbitrary and can be changed as desired. Rise time, settling time, peak value and percentage overshoot of the responses are used as performance metrics to evaluate the results. The responses for tank-1 and tank-2 are shown in Figs. 6 and 7 respectively.

Comparisons of responses from the various tuning methods are presented in Table VI; and as observed from the figures and table, DF-PID gave a better performance with smallest rise and settling times, desired peak value and zero overshoot, which are 1.48 s, 4.75 s, 15 cm and 0% respectively for tank-1; then 0.86 s, 2.62 s, 10 cm and 0% respectively for tank-2.

VI. CONCLUSION

In this paper, a four-coupled-tank laboratory apparatus was successfully modelled, which is a simpler form of the complex process control system. DF-PID controller was developed and applied to the developed model. This shows that fuzzy logic could appropriately be applied in auto-tuning industrial process control systems including paper-making, chemical, textile, soap-making and breweries equipments.

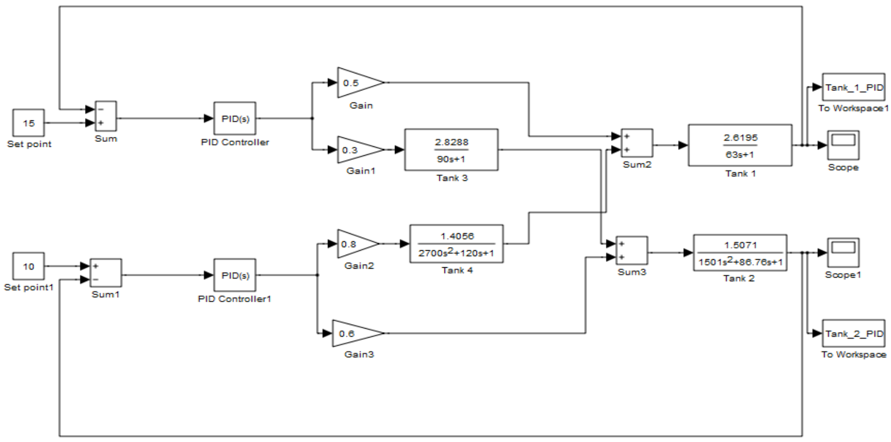

Fig. 4. SIMULINK model of PID controller for the four-coupled-tank system using ZN, CHR and CC PID tuning methods.

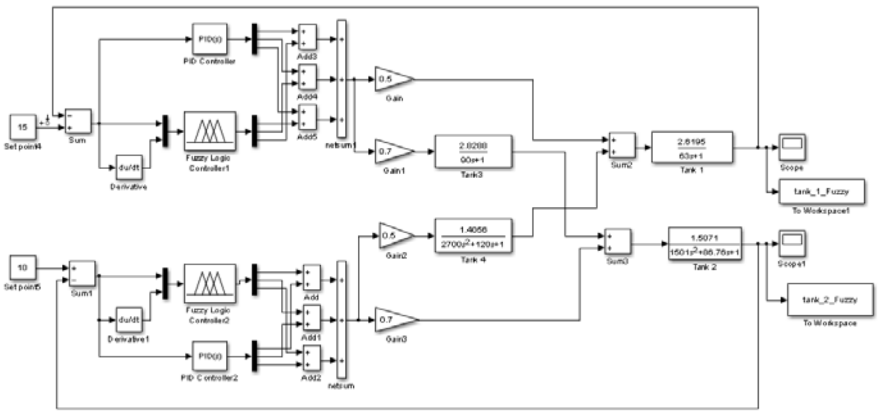

Fig. 5. SIMULINK model of DF-PID controller for the four-coupled-tank system

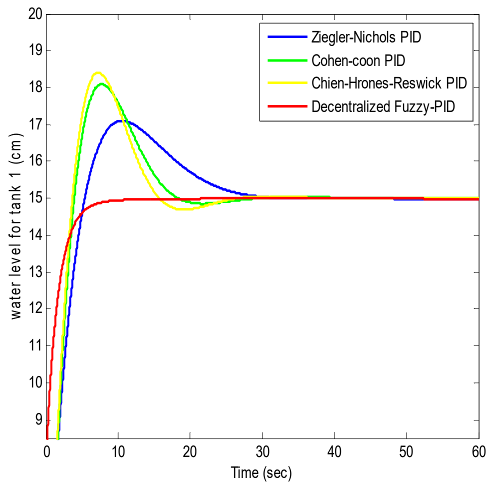

Fig. 6. Set-point responses for tank-1 using different PID tuning methods.

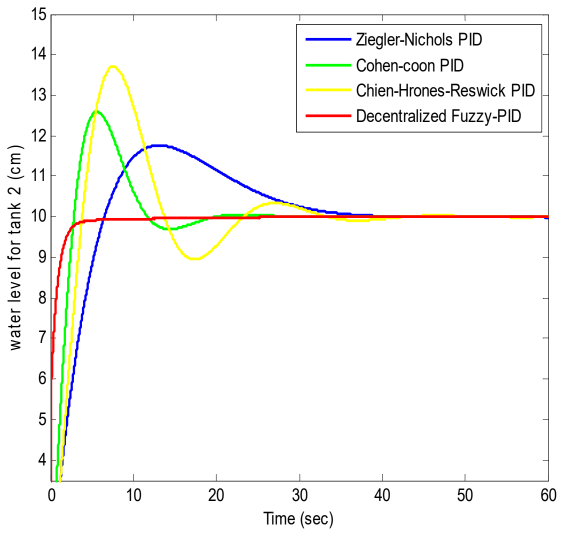

Fig. 7. Set-point responses for tank-2 using different PID tuning methods.

TABLE VI
COMPARISON OF RESPONSE CHARACTERISTICS WITH VARIOUS PID TUNING METHODS.

Method		RT (s)	ST (s)	PV (cm)	PO (%)
Tank 1	CHR	2.93	20.9	18.36	22.4
	CC	3.08	16.1	18.02	20.1
	ZN	4.19	22.6	17.01	13.4
	DF	1.48	4.75	15.00	0
Tank 2	CHR	3.11	30.0	13.60	36.0
	CC	2.23	17.0	12.58	25.8
	ZN	5.08	27.9	11.56	15.6
	DF	0.86	2.62	10.00	0

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