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Performance Evaluation of Interval Type-2 and Online Rule weighing based Type-1 Fuzzy PID Controllers on a pH Process

Tufan Kumbasar, Cihan Ozturk, Engin Yesil, and Hani Hagras

***Abstract*—In this paper, we will explore whether the efficiency of the Interval Type-2 Fuzzy PID (IT2-FPID) lies in its ability to handle the high level of uncertainties rather than only having an extra degree of freedom provided by the Footprint of Uncertainty (FOU) on a highly nonlinear pH neutralization process. In order to illustrate the effect of the FOU on the control performance, the control performance of an IT2-FPID controller composed of 3x3 rules will be compared with a Type-1 Fuzzy PID (T1-FPID) controller of 5x5 rules. Moreover, in order to provide more extra degree of freedom to the T1-FPID structure, we will employ two self-tuning mechanisms where the weights of the fuzzy rules are adjusted in an online manner. Thus, we will present detailed comparative studies on how the extra degrees of freedom provided by the FOU or the employed tuning mechanisms affect the control and robustness performance. The presented analysis confirm that by tuning the FOU the performance of the IT2-FPID is better in wide range of operating points in comparison with its type-1 and self-tuning type-1 fuzzy counterparts which is not merely for the IT2-FPID use of extra parameters, but rather its different way of dealing with the disturbance, nonlinearities uncertainties and noise.**

Keywords—Interval type-2 fuzzy PID controllers; extra degress of freedom; pH neutralization model.

I. Introduction

Type-1 Fuzzy PID controllers (T1-FPID) are often considered as an alternative to conventional PID controllers [1-3]. Thus, the researchers proposed various T1-FPID control techniques including different analysis and designing methodology [3-6]. The design parameters of the T1-FPID controllers can be categorized within two groups which include the structural parameters and the tuning parameters [7]. Input/output variables to fuzzy inference, fuzzy sets, Membership Functions (MFs), rules and inference mechanism are included in structural parameters. On the other hand, tuning parameters include input/output Scaling Factors (SFs) and the parameters of the MFs. After the study of Qiao and Mizumoto [3] on self-tuning T1-FPID controllers, various self-tuning structures have been proposed to increase the performance of the control system in the presence of parameter variations and nonlinearities, such as online tuning of SFs [8-10] and antecedent MFs [11]. Moreover, online tuning methods for the fuzzy rule weights have been also proposed to provide extra degrees of freedom to the fuzzy control structure [12], [13].

Within the last decade, Interval Type-2 Fuzzy Logic Controllers (IT2-FLCs) attracted much attention since it has demonstrated significant control performance improvements when they are compared to their type-1 counterparts [14-17]. It has been presented in various studies that the T1-FPID controllers might not be able to deal with the high levels of uncertainties associated within control applications. On the other hand, Interval Type-2 Fuzzy PID (IT2-FPID) controllers using Interval Type-2 Fuzzy Sets (IT2-FSs) might be able to handle such high uncertainties with their additional degree of freedom provided by the Footprint of Uncertainty (FOU) in their antecedent MFs [17-20]. The design procedure of the IT2-FPID controllers is usually solved by extending the MFs of a baseline T1-FPID controller or by employing optimization algorithms [18-22].

In this paper, we will evaluate the control performance of an IT2-FPID controller composed of 3x3 rules on a pH neutralization process. We will try to explore whether the efficiency of the IT2-FPID lies in its ability to handle the high level of uncertainties rather than only having an extra degree of freedom provided by the FOU. Thus, the control performance of the IT2-FPID controller will be compared with a T1-FPID controller which has a bigger rule base, i.e. 5x5 rules. Moreover, we will present and compare the results of the IT2-FPID control system with two Fuzzy Rule Weighting adjustment based T1-FPID (FRWT1-FPID) controllers which provide extra degrees of freedom to the T1-FPID structure by tuning the rule weights in an online manner. In this context, we will present brief information about the internal structures of the employed controllers and then the employed design strategy. We will then present detailed comparative studies which have been conducted on the pH neutralization process to show that the control performance of the IT2-FPID is better in different operating points even at those at which the controller parameters are not designed. We will show that IT2-FPID control system is potentially more robust against noise, uncertainties and unknown system dynamics when compared to its T1-FPID, FRWT1-FPID counterparts.

Section II will first present the handled pH neutralization process. Section III will briefly present the internal structures and design strategies of the T1-FPID, FRWT1-FPID and IT2-FPID controllers. Section IV will present the simulation results and Section IV will present the conclusions and future work.

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II. pH NEUTRALIZATION PROCESS

In this section, we will present the employed pH neutralization process which is illustrated given in Fig.1. The control of the pH processes is a challenging control problem since it is highly nonlinear and sensitive to disturbances around neutralization point [20], [23].

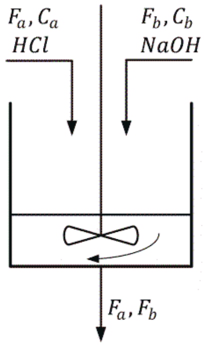


Fig. 1. Illustration of pH neutralization process

The process dynamics of the pH process are [23]:

$$V\frac{dw_a}{dt} = F_aC_a - (F_a + F_b)w_a \tag{1}$$

$$V\frac{dw_b}{dt} = F_bC_b - (F_a + F_b)w_b \tag{2}$$

while the process chemistry is:

$$pH = -\log([H^+]) \tag{3}$$

where

$$[H^+] = \frac{(w_a - w_b) + \sqrt{(w_a - w_b)^2 + 4K_w}}{2} \tag{4}$$

The parameter descriptions and the corresponding values are presented in Table I [17]. In order to obtain a single input-single output system, the acetic acid stream, F_a, is considered to be constant at its nominal value while the base flow rate is considered as the manipulated variable (F_b). Therefore, the process can be described as the sodium hydroxide stream as input (F_b) and the pH as the output [17].

TABLE I. THE PARAMETERS OF pH NEUTRALIZATION PROCESS

Symbol	Description	Value
V	Volume of the tank reactor	2 l
F_a	Flow rate of acidic stream	0.111 l/min
F_b	Flow rate of basic stream	0.001-0.211 l/min
C_a	Acidic concentration of acidic stream	0.001 M
C_b	Basic concentration of basic stream	0.001 M
w_a	Acidic concentration of tank reactor	-
w_b	Basic concentration of tank reactor	-
K_w	Water equilibrium constant	10^{-14}

III. TYPE-1 AND INTERVAL TYPE-2 FUZZY PID CONTROLLERS DESIGN METHODS

In this section, we will present the structures and design strategies of the employed T1-FPID, FRWT1-FPID and IT2-FPID controllers. The employed fuzzy PID controllers have two inputs, namely the error (e) defined as the difference between the set-point (r) and the process output(y) and the derivative of error $(\dot{e})$ as illustrated in Fig.2 [3]. The input SFs K_e and K_d normalize the inputs$(e, \dot{e})$ to the universe of discourse where the MFs of the inputs $(E, \dot{E})$ are defined. The output SFs that are K_a (proportional SF) and K_b (integral SF) convert the output (U) to the control signal (u) [9].

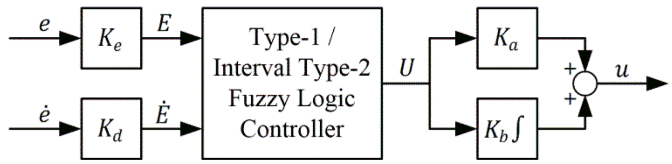


Fig. 2. Illustration of the T1-FPID / IT2-FPID controller structure

A. Type-1 Fuzzy PID Controllers Design Methodologies

In this subsection, we will present the structure of the employed T1-FPID controllers and then the design methodology. In T1-FPID structure, a symmetrical 5x5 rule base is used as shown in Fig.3a. The rule structure of the T1-FLC is as follows:

$$R_q:\ \text{If } E \text{ is } A_{1i} \text{ and } \dot{E} \text{ is } A_{2j} \text{ Then } U \text{ is } C_q \quad \text{with } w_q$$
$$i,j = 1,2,3,4,5; \quad q = 1, \dots, Q = 25 \tag{5}$$

where A_{1i} and A_{2j} are the antecedent MFs for the inputs E and $\dot{E}$, respectively where C_q is the consequent crisp set, w_q is the rule weight and Q is the number of rules.

In this study, we will define each input domain (E and $\dot{E}$) with five 50% overlapping MFs and denote them as *NB* (Negative Big), *N* (Negative), *Z* (Zero), *P* (Positive) and *PB* (Positive Big) as shown in Fig.3b. The outputs of the T1-FLC are defined with seven crisp singleton consequents (Negative Big (C_{NB}^{T1}) Negative Medium (C_{NM}^{T1}), Negative Small (C_{NS}^{T1}), Zero (Z), Positive Small (C_{PS}^{T1}), Positive Medium (C_{PM}^{T1}), Positive Big (C_{PB}^{T1})) as illustrated in Fig.3c. The implemented T1-FLCs use the product implication and the weighted average defuzzification method. We will employ $C_Z^{T1} = 0, C_{NB}^{T1} = -C_{PB}^{T1}$, $C_{NM}^{T1} = -C_{PM}^{T1}$ and $C_{NS}^{T1} = -C_{PS}^{T1}$ to have symmetrical rulebase.

1) Optimized Type-1 Fuzzy PID Controller

In design strategy of the Optimized T1-FPID (OT1-FPID) controller, we will only optimize the controller to minimize the Integral Absolute Error (IAE) measure via the Big Bang-Big Crunch (BB-BC) evolutionary algorithm [20]. The IAE measure is defined as:

$$IAE = \int_{t=0}^{\infty} |e|\, dt \tag{6}$$

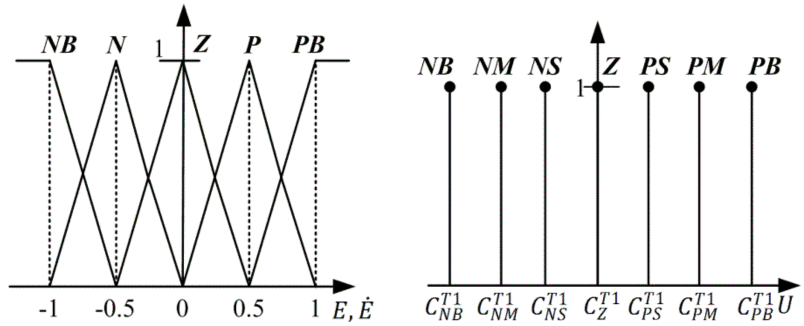
In the optimization procedure, we will optimize the crisp consequents parameters C_{PB}^{T1}, C_{PM}^{T1} and C_{PS}^{T1} and the SFs K_d, K_a, K_b while the SF K_e is calculated as follows:

$$K_e = \frac{1}{r(t_f) - y(t_f)} \tag{7}$$

where $r(t_f)$ and $y(t_f)$ are the values of the reference and system output at the time of the reference variation (t=t_f) [20]. Thus, the parameters to be determined are $K_d, K_a, K_b, C_{PB}^{T1}, C_{PM}^{T1}$ and C_{PS}^{T1}. Note that, the rule weights (w_q) of the T1-FPID controller structure are not optimized and set to the value "1".

E \ $\dot{E}$	NB	N	Z	P	PB
NB	$NB(w_1)$	$NB(w_2)$	$N(w_3)$	$NS(w_4)$	$Z(w_5)$
N	$NB(w_6)$	$N(w_7)$	$NS(w_8)$	$Z(w_9)$	$PS(w_{10})$
Z	$N(w_{11})$	$NS(w_{12})$	$Z(w_{13})$	$PS(w_{14})$	$P(w_{15})$
P	$NS(w_{16})$	$Z(w_{17})$	$PS(w_{18})$	$P(w_{19})$	$PB(w_{20})$
PB	$Z(w_{21})$	$PS(w_{22})$	$P(w_{23})$	$PB(w_{24})$	$PB(w_{25})$

(a)



(b) (c)

Fig. 3. Illustration of the (a) Rule base of T1-FLC, (b) Antecedent MFs of T1-FLC, (c) Consequent MFs of T1-FLC

2) Type-1 Fuzzy PID Controller with Online Error-Based Weight Adjustment

The first employed FRWT1-FPID structure is the Error-Based Weight Adjustment based T1-FPID (EBWAT1-FPID) controller [12]. In this structure, the fuzzy rule weights are adjusted in an online manner with respect to error (e) as shown in Fig.4. Thus, an additional degree of freedom is obtained by defining the weights of the rules (w_q) as tuning parameter. In this adjustment method, the step response of a closed loop system is divided into four main regions as illustrated in Fig. 4. The meta-rules derived to achieve the satisfactory control system performance are discussed in [12]. Here, the value of the system error(e) is used for tuning the fuzzy rule weights. Since the interval for rule weight values(w_q) should lie within the range [0, 1], the interval of the normalized error [-1, 1] is mapped to the interval [0, 1] using the absolute value function. Then, the tuning function is expressed as follows:

$$f_1^{EB}(e) = aAbs(e) \quad (10)$$

$$f_2^{EB}(e) = 1 - Abs(e) \quad (11)$$

where a is taken to be 1 for all the regions except the first region. In the first region, a is set to 0.5 as suggested in [12]. The values of the functions f_1^{EB}, f_2^{EB} are directly assigned to the rule weight values (w_q) as presented in [12].

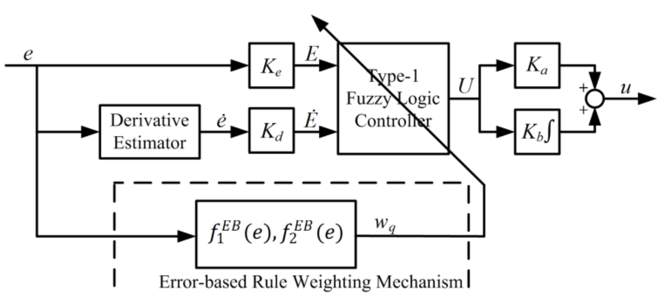


Fig. 4. Illustration of the EBWAT1-FPID controller structure

In design strategy of EBWAT1-FPID controller, the same antecedent and consequent MFs and SFs of the OT1-FPID are employed. Here, the EBWAT1-FPID controller structure provides extra degrees of freedom to T1-FPID controller structure via the fuzzy rule weight adjustment (i.e. 25 more parameters). It should be noted that the EBWAT1-FPID structure will have a smoother control surface in comparison to the baseline OT1-FPID counterpart which may reduce the overshoots and oscillations of the system response but with a compromise of settling time [12].

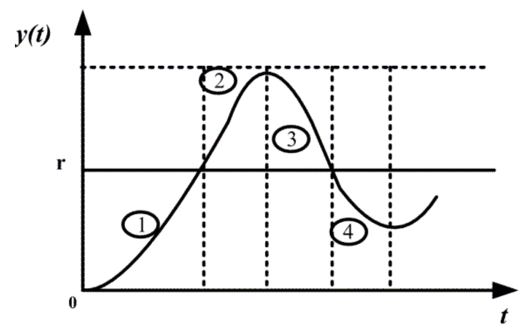


Fig. 5. Illustration of the partitioning of the step response

3) Type-1 Fuzzy PID Controller with Online Relative Rate Based Weight Adjustment

The second employed FRWT1-FPID structure is the Relative Rate Based Weight Adjustment based T1-FPID (RVBWAT1-FPID) controller which is shown in Fig.6 [13]. Similar to the EBWAT1-FPID design strategy, the step response of the closed loop system is divided into four main regions as illustrated in Fig.5. The importance of the corresponding fuzzy rule is determined and tuned respectively [13]. Here, the fuzzy rule weights (w_q) are adjusted in an online manner based on relative rate of the system (r_v) and the error signal (e). The r_v value gives information about the fastness or slowness of the system response and is defined as [13]:

$$r_v = \frac{de(k) - de(k-1)}{de(.)} = \frac{dde(k)}{de(.)} \quad (12)$$

where *de(k)* is the incremental change in error at a discrete instant, *dde(k)* is the incremental change in *de(k)* and *de(.)* defined as:

$$de(.) = \begin{Bmatrix} de(k) & if\ |de(k)| \geq |de(k-1)| \\ de(k-1) & if\ |de(k)| < |de(k-1)| \end{Bmatrix} \quad (13)$$

The online rule weight strategy is accomplished via a Mamdani fuzzy inference mechanism with two inputs (r_v and e), one output (γ); and has a 3x4 rule base where triangular type T1-FSs are used to define antecedent and consequent

MFs [13]. The meta-rules of the inference mechanism to achieve a satisfactory control performance are given in [13]. Here, γ is the update coefficient and is generated from the fuzzy inference system. The update functions of the rule weights are defined as:

$$f_1^{RV}(\gamma) = b\gamma \quad (14)$$

$$f_2^{RV}(\gamma) = 1 - \gamma \quad (15)$$

where b is taken to be 1 for all regions. The values of these functions are then directly assigned to the corresponding rule weight values (w_q) as proposed in [13].

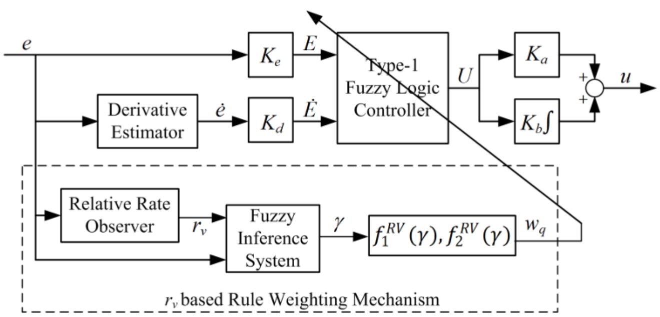


Fig. 6. Illustration of the RVBWAT1-FPID controller structure

In design strategy of RVBWAT1-FPID controller, the input and output MFs and SFs are set to the same values of the OT1-FPID ones and internal parameters of r_v based rule weighting fuzzy mechanism are set as given in [13]. Note that, the RVBWAT1-FPID structure provides extra degree of freedom to T1-FPID controller structure by the fuzzy rule weight update mechanism (i.e. 25 more parameters). This fuzzy rule weighting approach again provides a smooth system response which may result with less overshoot but longer settling time [13].

B. Interval Type-2 Fuzzy PID Controller Design Methodology

In this subsection, we will first present the general structure of the employed IT2-FPID controller and its design approach. In order to show the effect of the FOU on the system response clearly, we will employ a symmetrical 3x3 rule base for the IT2-FPID structure shown in Fig.7a (The T1-FPID controllers are composed of 5x5 rules). Thus, the rule structure is as follows:

$$R_q: \text{ IF } E \text{ is } \tilde{A}_{1i} \text{ and } \dot{E} \text{ is } \tilde{A}_{2j} \text{ THEN } U \text{ is } C_q \text{ with } w_q \quad (16)$$
$$i,j = 1,2,3; \quad q = 1,\dots,Q = 9$$

where C_q is the consequent crisp set, w_q is the rule weight, Q is the number of rules and $\tilde{A}_{1i}$ and $\tilde{A}_{2j}$ are the antecedent IT2-FSs. The antecedent IT2-FSs can be described in terms of upper MFs ($\overline{\mu}_{\tilde{A}_{1i}}$ and $\overline{\mu}_{\tilde{A}_{2i}}$) and lower MFs ($\underline{\mu}_{\tilde{A}_{1i}}$ and $\underline{\mu}_{\tilde{A}_{2i}}$) which creates the FOU (which provides extra degree of freedom) in IT2-FSs. The antecedent IT2-FSs are defined as shown in Fig.7b with parameter m_{ij}. Thus, the FOU will be created by the heights of the lower MFs (m_{ij}; $i=1,2$, $j=1,2,3$) of the IT2-FLC. We will denote the IT2-FSs as N (Negative), Z (Zero) and P (Positive). The outputs of the IT2-FLC are defined with five crisp singleton consequents which are Negative Big (C_{NB}^{IT2}), Negative (C_N^{IT2}), Zero (C_Z^{IT2}), Positive (C_P^{IT2}), Positive Big (C_{PB}^{IT2}) as illustrated in Fig.7c. The implemented IT2-FLC uses the center of sets type reduction/ defuzzification method [24].

In design strategy of the IT2-FPID, we will set the rule base differently from T1-FPID ones but the SFs are set the same as T1-FPID ones. Thus, there are 6 parameters (m_{ij}; i=1,2, j=1,2,3) related with the antecedent MFs and 4 parameters (C_{NB}^{IT2}, C_N^{IT2}, C_Z^{IT2}, C_P^{IT2}, C_{PB}^{IT2}) related with the output MFs to be designed. However, we employ m_{11}=m_{13} and m_{21}=m_{23} to have symmetrical antecedent MFs and $C_{NB}^{IT2} = -C_{PB}^{IT2}, C_N^{IT2} = -C_P^{IT2}$ and $C_Z^{IT2} = 0$ to have symmetrical rules. Consequently, the design parameters of the IT2-FPID are m_{11}=m_{13}, m_{12}, m_{21}=m_{23}, m_{22}, $C_{NB}^{IT2} = -C_{PB}^{IT2}, C_N^{IT2} = -C_P^{IT2}$, in total 6 parameters. These parameters will be optimized via the BB-BC optimization to minimize the IAE measure. Note that, we will not optimize the rule weights (w_q) of the Optimized IT2-FPID (OIT2-FPID) controller and set them to the value "1" to show the effect the FOU on the system response clearly.

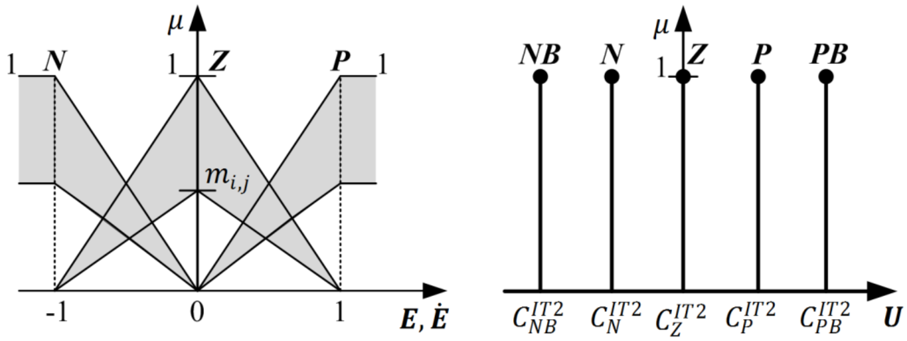
IV. Simulation Results

In this section, we will present different analyses in order to investigate the transient state and disturbance rejection performances of OT1-FPID, EBWAT1-FPID, RVBWAT1-FPID and OIT2-FPID controllers in presence of nonlinear dynamics, noise, and uncertainties. We will especially compare the control performances of the structures around the pH value of 7 since the major difficulty of controlling pH neutralization processes is the nonlinear S-shaped pH titration curve [17]. In order to make a fair comparison, three performance measures are considered which are Settling Time (T_s), Overshoot (OS%) and the IAE value. We will optimize the presented control structures for a varying reference trajectory with the values of 8, 7 and 5.5 pH. It will be assumed that the pH process is at steady state point at $pH^0 = 6pH$ and $F_b^0 = 0.122\ l/min$. For the training reference trajectory, the parameters of the OT1-FPID are obtained as $K_d = 0.001, K_a = 0.81, K_b = 0.63, C_{PB}^{T1} = 1, C_{PM}^{T1} = 0.6$ and $C_{PS}^{T1} = 0.4$.. Note that the SF K_e will be calculated via Equation (7) with respect to the reference signal. The design parameters of OIT2-FPID controller structure are found as $m_{11} = m_{13}$ =0.91, m_{12} =0.42, m_{21}=m_{23}=0.40, m_{22}=0.95, $C_{PB}^{IT2} = 1, C_P^{IT2} = 0.6$.

We will first analyze the control performances for the training reference trajectory at which the controllers are optimized. We will then investigate the robustness of the controllers against unknown system dynamics, uncertainties and noise. Finally, the robustness of the fuzzy PID controllers against input and output disturbances is examined in presence of noise.

E \ Ė	N	Z	P
N	$NB(w_1)$	$N(w_2)$	$Z(w_3)$
Z	$N(w_4)$	$Z(w_5)$	$P(w_6)$
P	$Z(w_7)$	$P(w_8)$	$PB(w_9)$

(a)



(b) (c)

Fig. 7. Illustration of the (a) Rule base of IT2-FLC (b) Antecedent MFs of IT2-FLC, (c) Consequent MFs of IT2-FLC

A. Control Performances Comparison

We will first examine the control performances of the employed controllers for the training reference trajectory. The system response of the OIT2-FPID and the other compared controller structures is shown in Fig.8a. As it can be clearly seen in Table II, the OIT2-FPID structure has better overall control performance in comparison to the other controller structures. For instance, for the reference value variation from pH 6 to pH 8, although all of the control systems have a zero overshoot value, the OIT2-FPID structure has reduced the T_s value by about 37.5% in comparison to the OT1-FPID with. Moreover, for the reference value variation from pH 8 to pH 7, although the RVBWAT1-FPID and OIT2-FPID have about the same performance measure OS=11.3% and OS=14.4% respectively, the OIT2-FPID has almost three times less settling time when compared to RVBWAT1-FPID counterpart. Another comment that can be underlined is that, the OIT2-FPID structure reduced the total IAE value more than two times when compared to the EBWAT1-FPID.

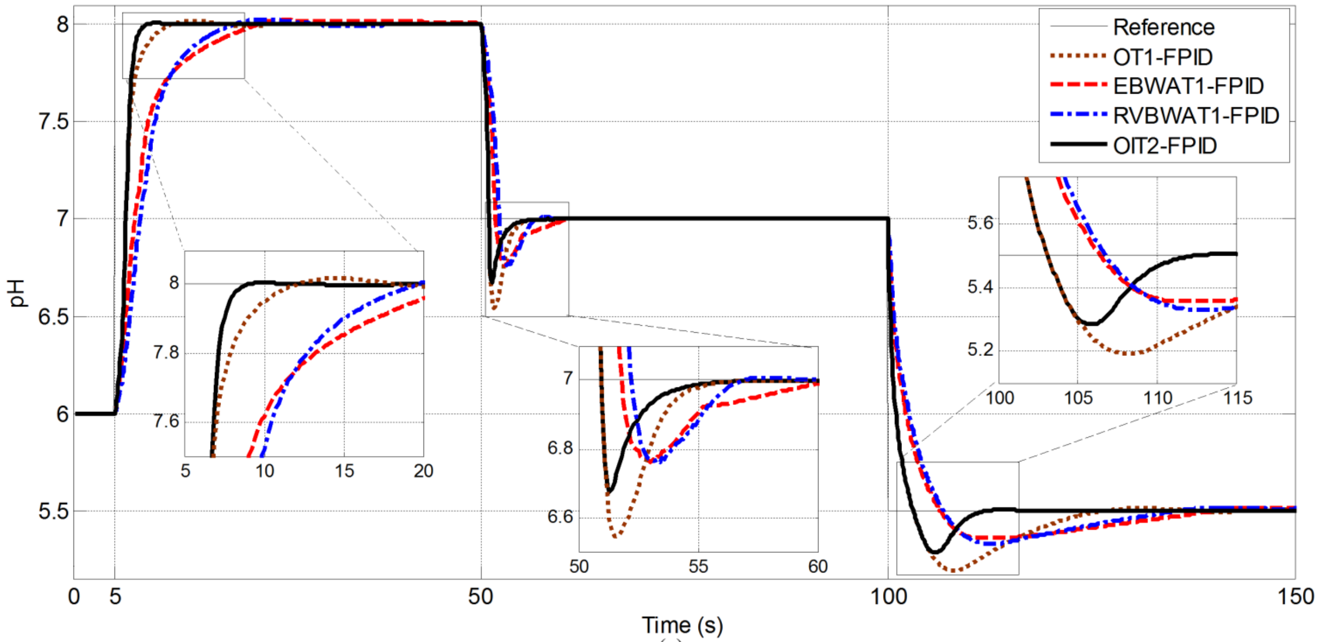
Consequently, OIT2-FPID control structure has better transient response in comparison to both OT1-FPID and FRWT1-FPID (EBWAT1-FPID and RVBWAT1-FPID) structures. It can be concluded that the extra degrees of freedom of IT2-FPID provided by the FOU leads to OIT2-FPID structure to have better control performances when compared to OT1-FPID and FRWT1-FPID structures which are composed of 5x5 rules (which have more rules than its type-2 counterpart). Moreover, although the online rule adjustment mechanism provide more extra degrees of freedom to the fuzzy controllers, their corresponding system response is not good as the OIT2-FPID and OT1-FPID (for certain operating points) structures. It can be said that the FRWT1-FPID controller structures have extra degrees of freedom, but they cannot improve OT1-FPID since their main aim is to smoothen the system response that leads to less overshoot with relatively more settling time values.

B. Robustness Performance Comparison

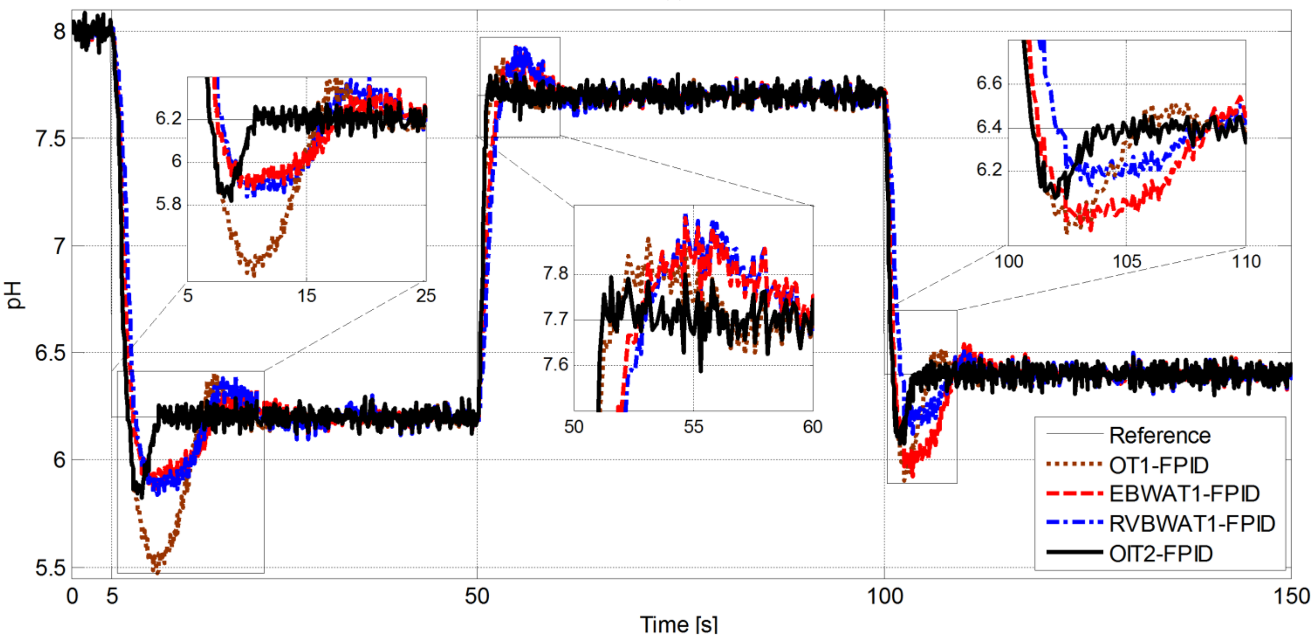
We will examine the control and robustness performances of the employed controllers for a varying reference trajectory with the values of 6.2, 7.7 and 6.4 pH (at which they are not optimized). Moreover, in order to investigate the robustness of the controllers against uncertainty and noise, we will present 20% uncertainty in the flow rate of acidic stream (F_a) and the noise in the system output. It will be assumed that the pH process is at steady state point at $pH^0 = 8pH$ and $F_b^0 = 0.1\ l/min$.

The system responses of the employed fuzzy PID control systems are presented in Fig.8b while the performance measures are tabulated in Table II. It can be concluded that the OIT2-FPID structure has better overall control performance in comparison to the type-1 fuzzy structures. For instance, for the reference variation from pH 8 to pH 6.2, although the EBWAT1-FPID and OIT2-FPID have almost the same performance measure OS=18.6%, OS=20.8% respectively, however the OIT2-FPID has almost three times less settling time when compared to RVBWAT1-FPID. Moreover, for the reference value variation from pH 6.2 to pH 7.7, the OIT2-FPID control system has the performance measures T_s=1.1s and OS=0% while the type-1 fuzzy structures performed with higher T_s and OS values as given in Table III. Moreover, the IAE value of the OIT2-FPID control system response is the lowest one.

It can be concluded that OIT2-FPID controller has better control performance in comparison to type-1 fuzzy structures even though it has been composed of 3x3 rules while its type-1 counterparts are composed of 5x5 rules. Moreover, although the FRWT1-FPID controller structures have more extra degrees of freedom in comparison to the OT1-FPID, they could not improve the transient system response for all operating points since the main aim is to smooth the system response by online tuning rule weights. Moreover, since their tuning mechanism depends on the value of the error, the control performance of the FRWT1-FPID structures is affected in presence of noise. On the other hand, the extra degrees of freedom of IT2-FPID provided by the FOU leads to OIT2-FPID structure to have better control performances while providing more robustness against noise, uncertainties and unknown dynamics when compared to type-1 and self-tuning type-1 counterparts.



(a)



(b)

Fig. 8. Illustration of the responses of the fuzzy PID control systems for the (a) control performance studies, (b) the robustness performance studies

C. Disturbance Rejection Performances

We will examine the robustness of the controllers against input and output disturbances. We will present the disturbance rejection performances of the employed controllers in presence of noise and around the neutralization point (pH=7) where the pH process has a high sensitivity. Thus, an output disturbance with a magnitude of "1" has been applied in the 5^{th} second and an input disturbance with a magnitude of "0.05" has been applied in 40^{th} second. The disturbance rejection performances of the type-1 and interval type-2 fuzzy control systems are presented in Fig. 9. The corresponding IAE performance measures of the OT1-FPID EBWAT1-FPID, RVBWAT1-FPID, OIT2-FPID for the input disturbance are 2.26, 4.43,3.82 and 1.62 while for the output disturbance are 3.09,4.51,5.17 and 1.44, respectively. For both the input and output disturbance, the OIT2-FPID has outperformed the OT1-FPID, EBWAT1-FPID and RVBWAT1-FPID structures. In the disturbance rejection performance analysis, both EBWAT1-FPID and RVBWAT1-FPID structures presented the worst performance since they are highly effected by the high sensitivity of the neutralization point (pH=7) and the measurement noise. On the other hand, in comparison to the OT1-FPID structure (composed of 5x5 rules), the OIT2-FPID controller (composed of 3x3 rules) was able to improve the input disturbance performance by about 28% and the output disturbance performance by about 53%.

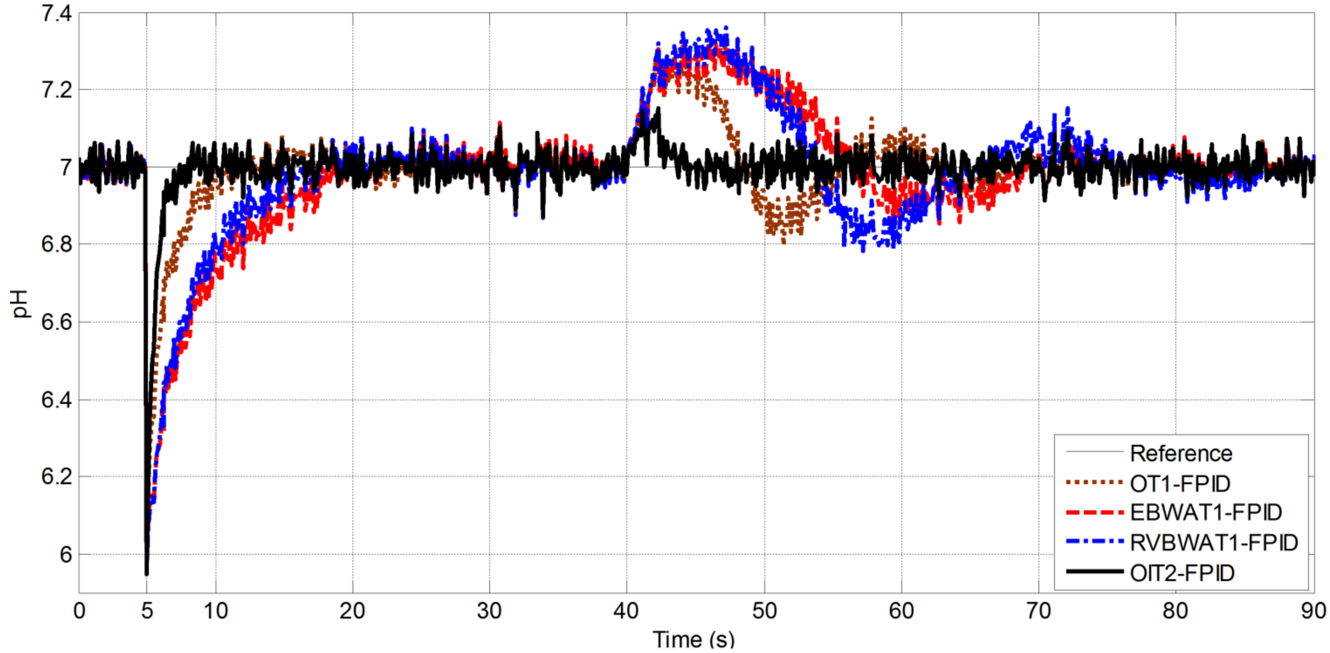


Fig. 9. Illustration of the input and output disturbances rejection performances of the fuzzy PID control systems

TABLE II. PERFORMANCES COMPARISON OF THE FUZZY PID CONTROL SYSTEMS

	The Control Performance Study							The Robustness Performance Study						
	pH 6-8		pH 8-7		pH 7-5.5		Total	pH 8-6.2		pH 6.2-7.7		pH 7.7-6.4		Total
	Ts	OS	Ts	OS	Ts	OS	IAE	Ts	OS	Ts	OS	Ts	OS	IAE
OT1-FPID	4.0s	0%	4.2s	45.7%	9.8s	20.6%	9.89	14.2s	40.2%	5.8s	11.8%	7.6s	38.1%	13.31
EBWAT1-FPID	11.9s	0%	7.4s	24.0%	27.5s	9.6%	15.33	17.8s	18.6%	9.3s	14.9%	12.8s	36.5%	13.58
RVBWAT1-FPID	10.0s	0%	5.8s	23.9%	25.2s	11.3%	16.05	17.8s	20.3%	8.5s	15.7%	11.8s	21.2%	14.24
OIT2-FPID	2.5s	0%	3.4s	32.6%	8.8s	14.4%	6.26	5.1s	20.8%	1.1s	0%	3.5s	25.0%	9.17

V. CONCLUSIONS AND FUTURE WORK

In this paper, we have explored whether the efficiency of the IT2-FPID lies in its ability to handle the high level of uncertainties rather than only having an extra degree of freedom provided by the FOU on a highly nonlinear pH neutralization process. In order to illustrate the effect of the FOU on the system performance clearly, we have constructed the IT2-FPID controller of 3x3 rules while the T1-FPID controllers used a rule base of 5x5 rules. Moreover, we presented two FRWT1-FPID controllers which provide extra degrees of freedom to the T1-FPID structure by tuning the rule weights in an online manner. We conducted detailed comparative studies on the pH process to show how the extra degrees of freedom provided by the FOU or the employed tuning mechanism affect the closed system response. The presented analysis confirm that by tuning the FOU the control performance of the IT2-FPID is better in different operating points (even at those at which the controller parameters are not optimized) which could not be accomplished with its type-1 and self-tuning counterparts which have a bigger rule base and/or extra online tuning mechanisms. Moreover, in the robustness analysis, we have illustrated that IT2-FPID control system is potentially more robust against noise, uncertainties and unknown system dynamics when compared to its T1-FPID, FRWT1-FPID counterparts.

The results of the comparative studies have showed that that the reason for the superior control performance of IT2-FPID (which is composed of 3x3 rules) in comparison to the T1-FPID (which is composed of 5x5 rules) FRWT1-FPID structures (which is composed of 5x5 rules and provide extra degrees of freedom related to the fuzzy rule weights) under high levels of uncertainty, noise and is not merely for its use of extra parameters, but rather its different way of dealing with the uncertainties and noise.

Future work will focus on extending and generalizing the type-1 fuzzy self-tuning mechanisms to type-2 fuzzy controllers while taking in consideration the effect of the FOU on the system response.

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