2014 IEEE International Conference on Fuzzy Systems (FUZZ-IEEE)
July 6-11, 2014, Beijing, China

A Self-tuning Fuzzy PID Controller Design Using Gamma Aggregation Operator

Engin Yesil, Cagri Guzay

***Abstract*—In this paper, a novel tuning approach for aggregation operator of a fuzzy PID controller has been proposed. The gamma operator which has a free parameter (gamma) is used for the aggregation purpose. The change of the gamma parameter between 0 and 1 generates the aggregation operator hybrid output of the AND and OR operators. In this manner, firstly, the effect of the gamma parameter change on the control surface of the fuzzy PID controller and the closed loop system response are studied. Secondly, a gamma tuning mechanism is built by a fuzzy logic decision mechanism using the observations from the first various simulation studies. The aim of the gamma tuning mechanism is to change the gamma parameter in an online manner to obtain a fast response with no or less overshoot. The benefit of the proposed approach over the conventional aggregation operator is shown on a non-linear system via simulations. Simulations are performed in Matlab, and the performance of the proposed approach is studied for a sequence of different set-points in order to observe the set-point following performances. Moreover, the disturbance rejection performance is studied. The results of the simulations show the advantage of the proposed new self-tuning structure over the conventional structures.**

I. INTRODUCTION

Fuzzy Logic Controllers (FLCs) have being widely and successfully applied to different processes which may have both different complexity levels and varied non-linearity. Besides several types of FLCs, with the advantages offered by the PID (Proportional-Integral-Derivative) controllers, Fuzzy PID (FPID) type is used very common [1]–[4]. Although both conventional PID controllers and fuzzy PID type controllers are based on the same philosophy, since FPID controllers mimic the conventional PID, those diverge from each other in structural view [5]–[7]. In addition, there are three different structures of Fuzzy PID controllers; and there are several researches based on this variation [8]–[11].

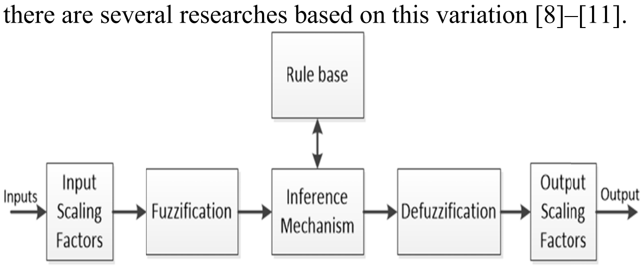

Fig. 1. The general interior design of a fuzzy controller

E. Yesil and C. Guzay are with the Control and Automation Engineering Department, Istanbul Technical University, Istanbul, Turkey (e-mail: {yesileng, guzay}@itu.edu.tr)

This research is supported by the Scientific and Technological Research Council of Turkey (TUBITAK) under the project (113E206). All of these supports are appreciated.

In design aspect, Fuzzy PID controllers have high degree of freedom. For more systematic architecture, the design parameters can be separated into two groups as structural and tuning parameters [12]. Structural parameters consist of input/output (I/O) arguments, membership functions with linguistic variables, rules, fuzzy inference and defuzzification mechanisms. Tuning parameters include I/O scaling factors and membership functions parameters. The general architecture of a fuzzy controller can be seen in Fig. 1.

In recent years, trend of the studies about tuning parameters have been rising. Researches can be categorized under a few titles. Firstly, the parameters of the conventional PID controllers are tuned by an Fuzzy Logic (FL) block that accepts error as input [13], secondly, a FL block that have different rule bases to tune the PID parameters [14], lastly, the use of the fuzzy rules and the genetic algorithm [15]. Similarly, the FL mechanism having inputs as the error and the derivative of error generates a coefficient which are used with ultimate gain and ultimate period values in order to calculate the PID parameters (K_p, T_i, T_d) [16]. In addition, auto tuning of the scaling factors constitutes another title. Only the output gains are adjusted online in analytical way [17], by neural networks [18], and online by the FL block [19]. In [20] and [21], inputs/output scaling factors are tuned online using analytical solution and FL mechanism for better performance. Moreover, the literature has significant studies for tuning the membership functions and fuzzy rule weights of the fuzzy logic controller [22]. To increase the effectiveness, the membership functions and the fuzzy rules are optimally adjusted via genetic algorithm [23]. In [24] and [25], the parameters of the membership functions are tuned by means of evolutionary algorithm and particle swarm optimization. In [22] an online tuning of rule weights by normalized acceleration is suggested.

In this study, a new on-line tuning method using the aggregation operator is proposed for fuzzy PID controllers. As mentioned above, up till now, the tuning of membership functions, the rule weights and the parameters of the conventional PID controllers have been mentioned. Indeed, beside these parameters, the aggregation operator also can be tuned; thus, aggregation operator becomes a tuning parameter. There is numerous aggregation operators studied in literature. In [26] and [27], the cases of t-norms, t-conorms and averaging operators; compensatory and self-dual operators in FL are presented. Min – Max, Min – Avg operators and a form of Gamma operator are utilized as aggregation operator in [28]. Moreover, in [29], the comparison of three parameter-free (logical product, Hamacher product, algebraic product) and parameterized (Dubois) operators is presented. In [30], an evaluation with a soft t-norm including a free parameter (α) that is optimally set by the evolution algorithm is presented. The mathematical expression for a typical gamma operator can be defined by a t-norm (T) and a t-conorm (S) as follows:

$$\Gamma_\gamma(x_1,\dots,x_n) = (T(x_1,\dots,x_n))^{1-\gamma}(S(x_1,\dots,x_n))^{\gamma} \qquad (1)$$

Minimum and product; maximum and probabilistic sum operations are commonly used t-norms and t-conorms, respectively. For a typical gamma operator, terms are consisted of minimum t-norm, probabilistic sum t-conorm and a free parameter, symbolized as γ. When the gamma operator is used in the inference mechanism seen in Fig. 1, and γ is changed numerically, the inference mechanism transforms to a dynamic structure. In other words, γ variable becomes the tuning parameter. In literature, effects of the change in gamma are analyzed and discussed in many researches. These include both application and theoretical based studies. In [31], γ operator is used for aggregation in a neuro-fuzzy structure to make integration advanced traveler information systems and advanced traffic management system. Also, γ operator as well as mere version can be formed as combined version that is utilized in the applications of geospatial information systems (GIS) as land assessment for flood spreading site selection [32] and enhancing cell-based information [33]. In [34], an application of fuzzy classification to a data warehouse in e-health is studied. Furthermore, the γ operator in fuzzy systems is examined on theoretical studies. In [35] the latent connectives in human decision making including effects of γ variable is discussed, and in [36] the applications of fuzzy rule based systems including the different t-norms and t-conorms are studied. As γ operator in a control strategy, controlling of a model car under challenging situations by FL using fuzzyTECH toolbox is presented in [37]. In none of the previous studies, the gamma operator is seen as an on-line tuning parameter, which can be changed for improving the performance of the FL system.

The outline of the paper is organized as follows: Section 2 includes detailed information about fuzzy PID controllers and design steps; Section 3 consists of the effect of the change in gamma value on the FL decision surface and system response, Section 4 explains the proposed gamma tuning method and the design of fuzzy tuning mechanism. Section 5 represents the simulation studies including the selection of the scaling factors, and moreover, Section 6 provides the conclusion, respectively.

II. Fuzzy PID Controllers

As stated in [10] and [38], that fuzzy PID controllers can be categorized into three main types: direct action, fuzzy gain scheduling and hybrid. Moreover, the direct action type fuzzy PID controllers can be divided into three classes according to the number of inputs: single, double, triple. In this study, the double input direct action type fuzzy PID (FPID) controller will be utilized. This FPID has the error and the derivative of error signals as inputs, and generates an output. In this respect, this configuration resembles a PD controller rather than PID one. As illustrated in Fig. 2, when fuzzy controller is formed with an integrator and a summation unit at the output, it becomes a fuzzy PID controller [8]. The equation for the output control signal is written as follows:

$$u = \alpha U + \beta \int U\, dt \qquad (2)$$

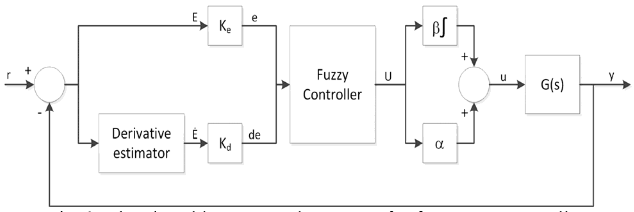

Fig. 2. The closed loop control structure for fuzzy PID controller

By the variables seen on Fig. 2, the error (E) and its derivative (Ė) are scaled down and become the normalized inputs (e, de respectively) for the FLC. Scaling factors for the inputs are K_e and K_d. Similarly but inverse, the output of the FLC (U) is scaled up (α) and summed with its scaled up (β) integral. Hence, generated signal from fuzzy PID controller turns out to be at meaningful level to be used in plant or process.

For both of error (e) and derivative of error (de), seven linguistic variables are determined. The membership functions are formed as triangular shape and intersecting with each other by 50% as given in Fig. 3a. The universes of discourse for all variables are selected as interval of [-1, 1]. The Takagi-Sugeno (T-S) fuzzy rules have singleton type membership functions for the consequent parts as illustrated in Fig. 3b. The rule base has 49 fuzzy rules presented on Table I. Also, membership functions for inputs and output, and control surface for γ = 0 are shown on Fig. 3c.

TABLE I. Rule Base For The Fuzzy Logic Controller

e/de	NB	NM	NS	Z	PS	PM	PB
NB	*NB*	*NB*	*NB*	*NB*	*NM*	*NS*	*Z*
NM	*NB*	*NB*	*NB*	*NM*	*NS*	*Z*	*PS*
NS	*NB*	*NB*	*NM*	*NS*	*Z*	*PS*	*PM*
Z	*NB*	*NM*	*NS*	*Z*	*PS*	*PM*	*PB*
PS	*NM*	*NS*	*Z*	*PS*	*PM*	*PB*	*PB*
PM	*NS*	*Z*	*PS*	*PM*	*PB*	*PB*	*PB*
PB	*Z*	*PS*	*PM*	*PB*	*PB*	*PB*	*PB*

In addition to configuration of the fuzzy PID controller defined above, algebraic product is generally used as the AND operator in T-S type fuzzy structures [39]. For the γ operator and its components, detailed statements will be done in next chapter.

III. The Effect of Gamma Operator for Design

In literature, γ operator is defined as two different forms: exponential [32], [33], [35], [40] and linear [35]. The typical exponential form can be given as follows:

$$f_e(\mu_1,\mu_2) = (\mu_1.\mu_2)^{1-\gamma}(\mu_1+\mu_2-\mu_1.\mu_2)^{\gamma} \qquad (3)$$

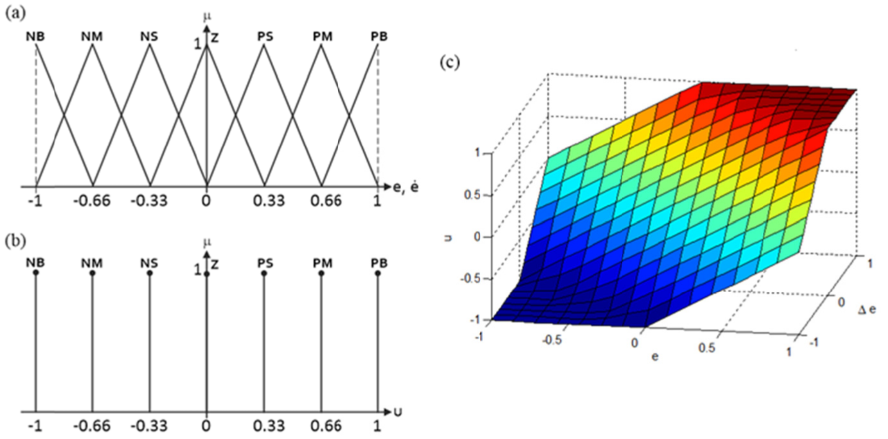

Fig. 3. (a) The input membership functions, (b) The output membership functions, (c) the control surface with γ = 0

where μ_n (n=1, 2) shows the membership grade of related inputs. The first term of (2) is named as fuzzy algebraic product (AND) and the second one is fuzzy algebraic sum (OR). In a similar way, the other form (linear) of the γ operator can be given as follows:

$$f_l(\mu_1, \mu_2) = (1-\gamma)(\mu_1 . \mu_2) + \gamma(\mu_1 + \mu_2 - \mu_1 . \mu_2) \qquad (4)$$

The γ weight can take a value in the closed interval of [0, 1]. Even though (3) and (4) seem to be very similar to each other, the outputs are completely different. Considering the requirement of the variation of control signal for any control system, γ tuning has no effect for exponential form. After various simulations, it is seen that the effect of the γ for the FLC output is nearly same all values of interval [0, 0.99] in exponential form. On the other hand, linear form results in linear effect on the output of the FLC. Thus, for a control application, it is observed that the linear gamma operator is suitable for control applications.

Due to changing of aggregation weight (γ), the control signal that is produced by fuzzy PID controller will be changed. In other words, tuning of γ, aggregation operator may be "AND", "OR", between "AND" with "OR". In Takagi-Sugeno type FLCs, control signal is generated via the firing strength (β). When the gamma operator is used the firing strengths (β) and control signal (u) can be expresses as follows:

$$\beta_i = \Gamma(\mu_e, \mu_{\dot{e}}, \gamma) \qquad (5)$$

$$u = \frac{\sum_{i=1}^{N} \beta_i y_i}{\sum_{i=1}^{N} \beta_i}, i = 1, 2, \ldots, N \qquad (6)$$

where N is the number of fuzzy rules and y_i is the consequent part of each fuzzy rule. As seen in (5), the modification of γ will change the firing strengths. Fig. 4 shows the surfaces which are consisted of all possible membership grades of error and derivative of error and calculated firing strengths by different γ values. As seen from Fig. 4, the linear form γ operator has a significant effect on firing strength, so the change of firing strengths leads to variations of control signal.

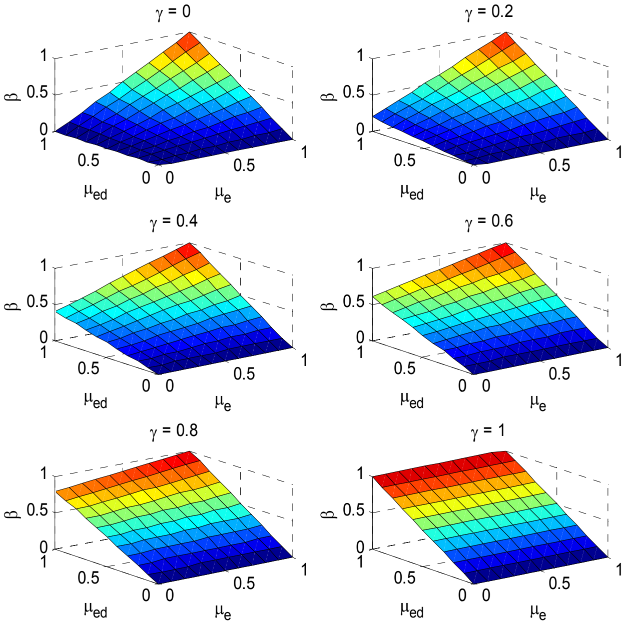

Fig. 4. Linear γ operator response with all possible membership grades of inputs under different γ values

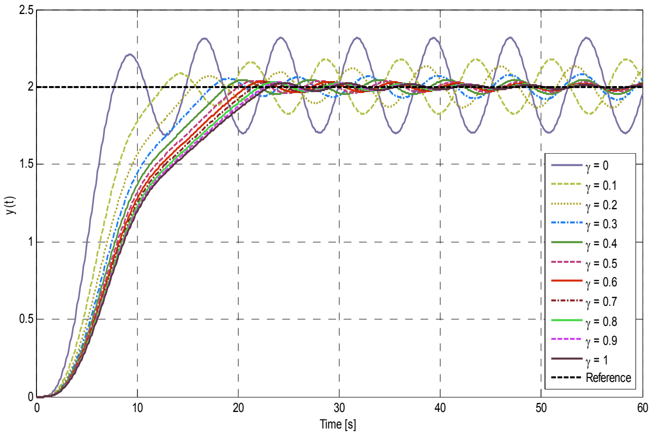

Fig. 5. System responses with different γ values

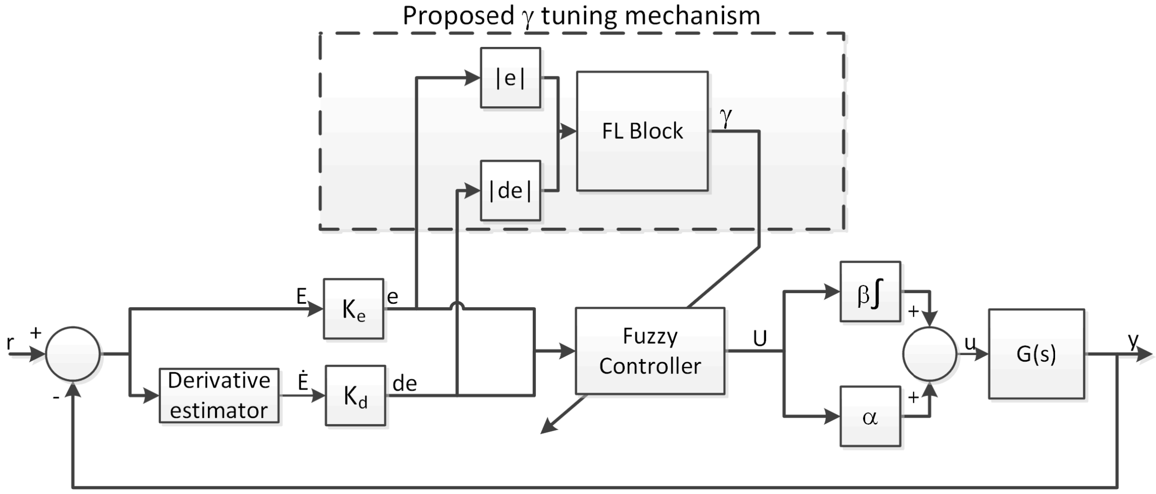

Fig. 6. The closed loop control system with on-line γ tuning mechanism

As mentioned above, the weight γ has a value between 0 and 1, and according to (4), this aggregation operator acts as AND (product) operator when γ is equal to 0 and OR (probabilistic sum) operator when γ is equal to 1. With this awareness, a simulation is performed in Matlab-Simulink using of predefined scaling factors with given non-linear system to understand the impact of the γ values over closed-loop system response. The nonlinear system is defined as follows [19]:

$$\frac{d^2y}{dt^2}+\frac{dy}{dt}+0.25y^2=u(t-L) \tag{7}$$

where L is 0.5. Since the objective of this simulation is only to visualize the effect of γ on the system response, the scaling factors proposed by [19] are used.

$$K_e=0.9,\quad K_d=11,\quad \beta=0.018,\quad \alpha=0 \tag{8}$$

For the simulations, γ is changed from 0 to 1 by 0.1 step, and the closed loop system responses are shown on Figure 5.

As seen from Fig. 6, the value of γ operation has a very serious effect on the over system response in transient and steady state. Firstly, the higher γ values cause a slow response when there is a change in the reference value. The smaller γ values, on the other hand, causes faster response. Secondly, even though the higher γ values have more sluggish response in transient, those can be used to be smoothened of the steady state behavior.

IV. THE DESIGN OF PROPOSED GAMMA TUNING MECHANISM

With the aid of the above analysis, it can be concluded that the higher γ values sluggish the transient state, and smoothen the steady state, and vice versa. Aside using of γ value as a static constant, compromising a little bit from faster transient response, and obtaining the response that have small rise time and no overshoot is possible by changing γ by time. To carry out this idea, an on-line γ tuning mechanism given in Fig. 6 is proposed.

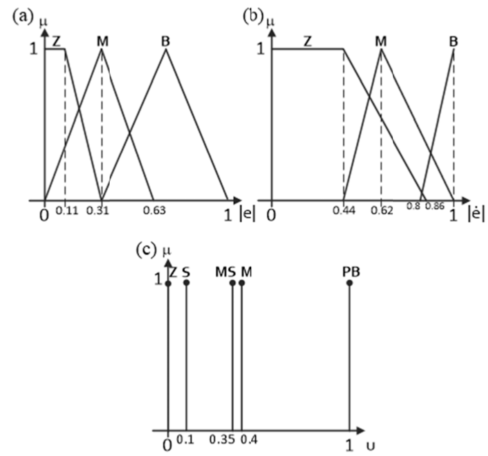

Fig. 7. The membership functions for the input of absolute error (a), input of absolute derivative of error (b) and output (c)

As a γ tuning mechanism, it is intended to use a fuzzy logic mechanism. In the proposed design strategy, the absolute value of the scaled error and the scaled absolute value of the derivative of the error as chosen as the inputs. The output is the generated γ value, which should have a value in the interval of [0, 1]. Therefore, the universe of discourse for both inputs is [0, 1]. Three linguistic variables (Z: Zero, M: Medium, B: Big) are defined for per input; thus rule base with 9 rules is designed. As illustrated in Fig. 7, the membership functions of the inputs are triangular and singleton for the output. In addition, the fuzzy rule base and the decision surface are shown on Table II and Figure 8, respectively.

TABLE II. DESIGNED RULE BASE FOR THE TUNING MECHANISM

|e|/|de|	Z	M	B
Z	*PB*	*S*	*S*
M	*S*	*MS*	*M*
B	*MS*	*M*	*PB*

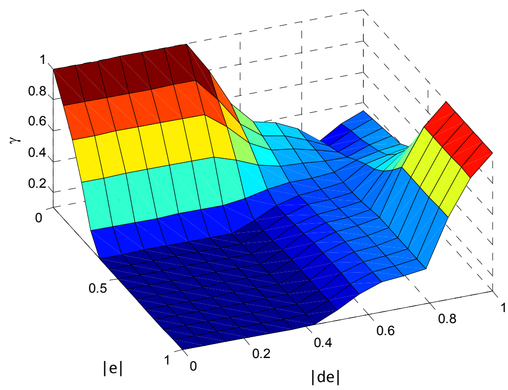

Fig. 8. The decision surface of the tuning mechanism

V. SIMULATION STUDIES

In order to show the benefit of the proposed self-tuning fuzzy PID controller the process given in (7) is used. In addition, fuzzy PID controller which has the scaling factor given in [19] is simulated first. Using these scaling factors leads the process to oscillatory system response with small rise time [22]. In consequence, these scaling factors are configured to obtain a fuzzy PI controller. Therefore, for this study, the scaling factors of the fuzzy PID controller are optimized for some objectives: Firstly, The disturbance rejection should be fast, secondly, the system response should have small rise time. It should be noted that, correspondingly, the faster response will lead a higher overshoot at transient state.

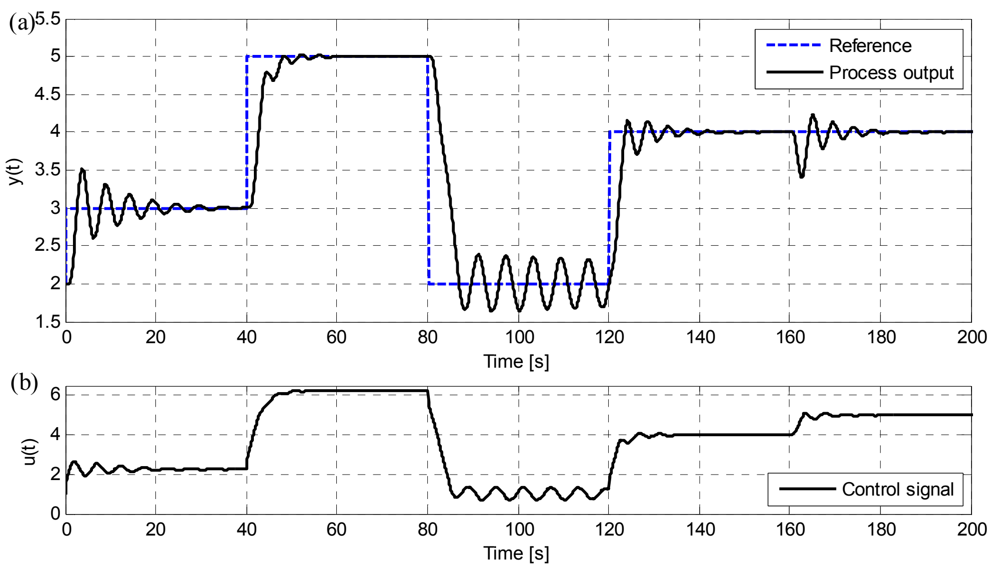

Fig. 9. Closed loop system response (a) and control signal (b) with $\gamma = 0$

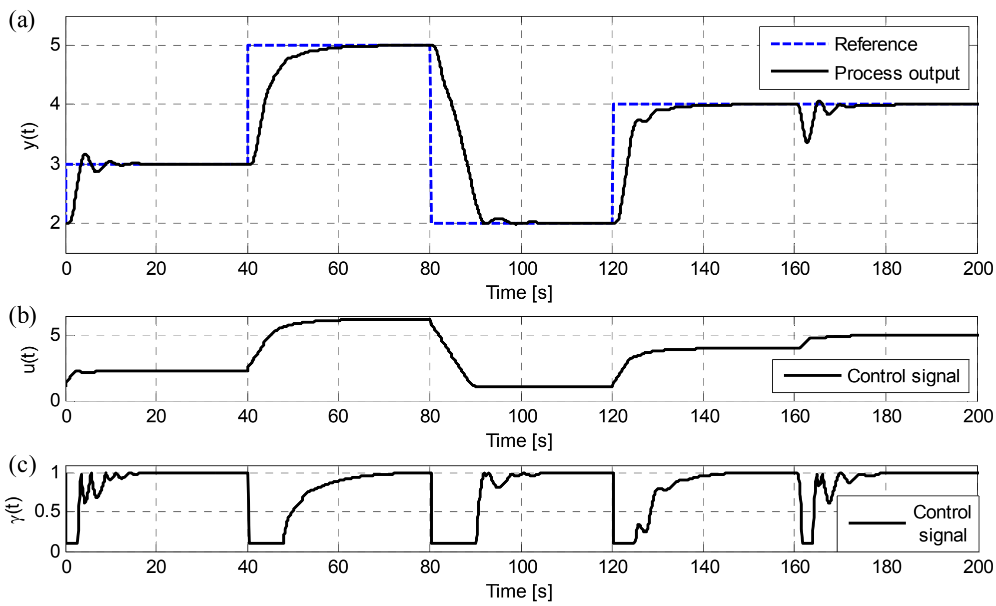

Fig. 10. Closed loop system response (a), control signal (b) and states of γ (c) with on-line γ-tuning

TABLE III. PERFORMANCE COMPARISON TABLE OF THE $\gamma = 0$ AND PROPOSED METHOD BY VARIOUS CRITERIA

	Ref: 2–3				Ref: 3–5				Ref: 5–2				Ref: 2–4			
	t_r [s]	OS %	t_s [s]	ITAE	t_r [s]	OS %	t_s [s]	ITAE	t_r [s]	OS %	t_s [s]	ITAE	t_r [s]	OS %	t_s [s]	ITAE
γ = 0	1.2	3.5	35.7	41.8	5.3	5.0	11.3	18.7	5.1	3.4	NS	187.2	2.8	4.1	16.0	20.1
Proposed	1.7	3.1	13.2	8.7	8.0	5.0	20.1	48.8	8.1	3.01	16.3	84.3	6.7	4.0	14.9	30.7

For the optimization of the scaling factors a very effective and simple method called Big Bang – Big Crunch (BB-BC) optimization is preferred [41]–[43]. The number of iterations and the population size are chosen as 100 and 20 for BB-BC algorithm. Since the fastest responses can be obtained at smaller γ values, during the optimization γ has been chosen as zero. The rise time optimal scaling factors are obtained as follows:

$$K_e = 1.0, \quad K_d = 0.3219, \quad \beta = 0.9357, \quad \alpha = 0.5431 \qquad (9)$$

For the control of the second order non-linear process with dead time given in (7), the settings for the fuzzy PID controller and tuning mechanism mentioned previously are used in all simulations. To clearly show the improvements by γ-tuning, the same simulations are performed first with constant $\gamma = 0$, namely AND (product) aggregation. In Fig.9, the closed loop responses of the controls system for different reference values are presented. The disturbance rejection performance, when a step disturbance is applied at 160th second, is also presented in Fig.9a. In Fig. 9b, the control signal is illustrated for different references and the step disturbance. The set point following and disturbance rejection performance of the proposed gamma-tuning method is presented in Fig. 10. Moreover, the output of the tuning mechanism which is the value of the gamma is illustrated in Fig. 10c. When Fig. 9 and Fig. 10 are compared, it can be concluded that the proposed method smoothens the control signal so that the oscillations and the overshoots decrease. In addition, the rise time decreases, but the process settles more quickly.

In order to make the comparisons between AND (γ=0) operation and γ-tuning in a fair way four different performance measures are considered. The three of these performance measures are selected from the classical transient system response criteria; namely, the rise time (t_r), the maximum overshoot (OS %), settling time (t_s). As the fourth measure ITAE values are calculated separately for each new reference. The performance comparison of the proposed structure with the standard FPID (γ=0) controller is given in Table III. Parallel to the observations from the proses responses, Table III shows that the rise time values are higher for γ -tuning rather than $\gamma = 0$. This issue has been already admitted due to trade-offs, consequently, less or no overshoot and much less settling time is observed.

TABLE IV. COMPARISON OF THE PERFORMANCE OF DISTURBANCE REJECTION BY VARIOUS CRITERIA

	Disturbance			
	IAE	ITAE	ISE	ITSE
γ = 0	2.4	16.1	0.69	2.71
Proposed	2.0	10.1	0.76	2.6

As mentioned before, the disturbance rejection performance is also examined via simulations. The disturbance rejection for a step input disturbance is applied at 160th second and the rejection performances of the AND (γ=0) and γ-tuning mechanism is compared via IAE, ITAE, ISE and ITSE criteria. The comparison is tabulated in Table IV. As it can be seen from Table IV, the proposed method has a much better disturbance rejection performance than the conventional one.

VI. CONCLUSIONS

In this study, a new fuzzy PID controller tuning mechanism based on the aggregation operator is presented. The gamma parameter which is the weight determining the strength of the t-norm and the t-conorm in the inference is used as an online tuning parameter. The proposed gamma-tuning mechanism is compared with the classical fuzzy PID controller that has gamma as zero.

Simulations are run on Matlab/Simulink environment and initially a number of meta-rules are derived from the various simulations. Later, the performance of the proposed method is obtained on a nonlinear system for different reference values. The simulations show that the proposed online tuning gamma tuning fuzzy PID controller has a better transient state response where the overshoot and the settling time are dramatically decreased. In addition, input disturbance rejection performance of the proposed method is tested via simulations. The simulation results are tabulated for different performance measurement. As it was expected the proposed online tuning method also improved the disturbance rejection performance.

As future works, an experimental study in real world will be performed. Thus, the practical implementation of the proposed novel online tuning method for fuzzy PID controllers will be presented. Moreover, the rules and the membership functions of the gamma tuning mechanism may be modified for future practical studies.

REFERENCES

[1] O. Karasakal, E. Yesil, M. Guzelkaya, and I. Eksin, “Implementation of a new selftuning fuzzy PID controller on PLC,” *Turk. J. Electr. Eng. Comput. Sci.*, vol. 13, no. 2, pp. 277–286, 2005.

[2] M. J. Fuente, C. Robles, O. Casado, S. Syafiie, and F. Tadeo, “Fuzzy control of a neutralization process,” *Eng. Appl. Artif. Intell.*, vol. 19, pp. 905–914, 2006.

[3] K.-Y. Chen, P.-C. Tung, M.-T. Tsai, and Y.-H. Fan, “A self-tuning fuzzy PID-type controller design for unbalance compensation in an active magnetic bearing,” *Expert Syst. Appl.*, vol. 36, pp. 8560–8570, 2009.

[4] N. Saad and M. Arrofiq, “A PLC-based modified-fuzzy controller for PWM-driven induction motor drive with constant V/Hz ratio control,” Robot. Comput.-Integr. Manuf., vol. 28, no. 2, pp. 95–112, 2012.

[5] S. Galichet and L. Foulloy, “Fuzzy controllers: synthesis and equivalences,” *IEEE Trans. Fuzzy Syst.*, vol. 3, pp. 140–148, 1995.

[6] B. S. Moon, “Equivalence between fuzzy logic controllers and PI controllers for single input systems,” *Fuzzy Sets Syst.*, vol. 69, pp. 105–113, 1995.

[7] T.-T. Huang, H.-Y. Chung, and J.-J. Lin, "A fuzzy PID controller being like parameter varying PID," in *IEEE International Fuzzy Systems Conf. Proc.*, Seoul, Korea, vol. 1, 1999, pp. 269–275.

[8] W. Z. Qiao and M. Mizumoto, "PID type fuzzy controller and parameters adaptive method," *Fuzzy Sets Syst.*, vol. 78, pp. 23–35, 1996.

[9] H. X. Li and H. B. Gatland, "Conventional fuzzy control and its enhancement," *IEEE Trans. Syst. Man Cybern.*, part B, vol. 26, no. 5, pp. 791–797, 1996.

[10] E. Yesil, M. Guzelkaya, and I. Eksin, "Fuzzy PID controllers: An overview," in *The 3rd Triennial ETAI International Conference on Applied Automatic Systems*, Ohrid, Macedonia, 2003.

[11] X.-G. Duan, H.-X. Li, and H. Deng, "Effective tuning method for fuzzy PID with internal model control," *Ind. Eng. Chem. Res.*, vol. 47, pp. 8317–8323, 2008.

[12] B. Hu, G. K. I. Mann, and R. G. Gosine, "New methodology for analytical and optimal design of fuzzy PID controllers," *IEEE Trans. Fuzzy Syst.*, vol. 7, no. 5, pp. 521–539, 1999.

[13] A. Fadaei and K. Salahsoor, "A Novel Real-time Fuzzy Adaptive Auto-tuning Scheme for Cascade PID Controllers," *Int. J. of Control, Automation and Syst.*, vol. 9, no. 5, pp. 82–833, 2011.

[14] A. S. Potts, B. T. de Freitas, and J. C. Amaro, "Fuzzy auto-tuning for a PID controller," in *Industry Applications (INDUSCON), 2010 9th IEEE/IAS Int. Conf.*, 2010, pp. 1–5, Sao Paulo, Brasil.

[15] F. Jingzhou, M. Xiuzhen, and S. Yong, "The software of auto-tuning parameters of PID controller based on fuzzy genetic algorithm," in *Computational Intelligence and Software Engineering (CiSE), 2010 Int. Conf.*, 2010, pp. 1–4, Wuhan, China.

[16] S. J. Huang and Y. H. Lo, "Metal chamber temperature control by using fuzzy PID gain auto-tuning strategy," *WSEAS Trans. on Syst. and Control*, vol. 4, no. 1, pp. 1–10, 2009.

[17] R. R. De, R. Mudi, and A. K. Pal, "A PD-type self-tuning FLC for second-order systems with dead-time," in *Advanced Communication Control and Computing Technologies (ICACCCT), 2012 IEEE Int. Conf.*, 2012, pp. 409–413, Ramanathapuram, India.

[18] H. Deng and Y. Wang, "An adaptive fuzzy logic controller with self-tuning scaling factors based on neural networks," *Autonomous Decentralized Syst., 2005. ISADS 2005. Proceedings*, pp. 392–396, 2005.

[19] R. K. Mudi and N. R. Pal, "A robust self-tuning scheme for PI- and PD-type fuzzy controllers," *IEEE Trans. Fuzzy Syst.*, vol. 7, pp. 2–16, 1999.

[20] Z.-W. Woo, H.-Y. Chung, and J.-J. Lin, "A PID type fuzzy controller with self-tuning scaling factors," *Fuzzy Sets and Syst.*, vol. 115, no. 2, pp. 321–326, 1998.

[21] S. Chopra, R. Mitra, and V. Kumar, "Auto tuning of fuzzy PI type controller using fuzzy logic," *Int. J. of Computational Cognition*, vol. 6, no. 1, pp. 12–18, 2008.

[22] O. Karasakal, M. Guzelkaya, I. Eksin, E. Yesil, and T. Kumbasar, "Online tuning of fuzzy PID controllers via rule weighing based on normalized acceleration," *Eng. Applicat. of Artificial Intell.*, vol. 26, no. 1, pp. 184–197, 2013.

[23] K. Shimojima, T. Fukuda, and Y. Hasegawa, "Self-tuning fuzzy modeling with adaptive membership function, rules, and hierarchical structure based on genetic algorithm," *Fuzzy Sets and Syst.*, vol. 71, no. 3, pp. 295–309, 1995.

[24] P. D. Domanski, S. Plamowski, and J. S. Lesniewski, "An evolutionary algorithm for membership fuzzy function auto tuning," in *Intelligent Control. 2003 IEEE Int. Symp.*, 2003, pp. 985–989, Houston, TX, USA.

[25] G. Fang, N. M. Kwok, and Q. Ha, "Automatic fuzzy membership function tuning using the particle swarm optimisation," in *Computational Intelligence and Industrial Application, 2008. PACIIA '08. Pacific-Asia Workshop*, vol. 2, 2008, pp. 324–328, Wuhan, China.

[26] M. Mizumoto, "Pictorial representations of fuzzy connectives, part I: cases of t-norms, t-conorms and averaging operators," *Fuzzy Sets Syst.*, vol. 31, pp. 217–242, 1989.

[27] M. Mizumoto, "Pictorial representations of fuzzy connectives, part II: cases of compensatory operators and self-dual operators," *Fuzzy Sets Syst.*, vol. 32, pp. 45–79, 1989.

[28] J. Yang, D. J. Edwards, and P. E. D. Love, "A computational intelligent fuzzy model approach for excavator cycle time simulation", *Automation in Construction*, vol. 12, no. 6, pp. 725–735, 2003.

[29] F. Herrera, F. A. Marquez, and A. Peregrin, "Genetic adaption of rule connectives and conjunction operators in fuzzy rule based systems: an experimental comparative study," in *EUSFLAT Conf.*, 2003, pp. 100–104.

[30] Y. Jin and W. V. Seelen, "Evaluating flexible fuzzy controllers via evolution strategies," *Fuzzy Sets and Syst.*, vol. 108, no. 3, pp. 243–252, 1999.

[31] Y. E. Hawas, "A supervisory control system for ATIS/ATMS integration. Part 2: neuro-fuzzy calibration and analyses," *Proc. of the ICE-Transport*, vol. 153, no. 4, pp. 245–254, 2002.

[32] A. A. Alesheikh, M. J. Soltani, N. Nouri, and M. Khalilzadeh, "Land assessment for flood spreading site selection using geospatial information system," *Int. J. of Enviornmental Sci. and Technology*, vol. 5, no. 4, pp. 455–462, 2008.

[33] J. Benedikt, S. Reinberg, and L. Riedl, "A GIS application to enhance cell-based information modeling," *Inform. Sci.—Informatics and Comput. Sci.: An Int. J. - Special Issue: Intelligent Inform. Syst. and Applicat.*, vol. 142, no. 1, pp. 151–160, 2002.

[34] M. Kaufmann, "Application of fuzzy classification to a data warehouse in e-health," M.S. thesis, Dept. of Informatics, Univ. of Fribourg, Fribourg, Switzerland, 2006.

[35] H.-J Zimmerman and P. Zysno, "Latent connectives in human decision making," *Fuzzy Sets and Syst.*, vol. 4, no. 1, pp. 37–51, 1980.

[36] D. K. Chaturvedi, "Applications of fuzzy rule based system," in *Soft Computing Techniques and its Applications in Electrical Engineering, Studies in Computational Intelligence (SCI)*, vol. 103, Springer,2008, pp. 295–362,

[37] C.V. Altrock, B. Krause, and H.-J. Zimmerman, "Advanced fuzzy logic control of a model car in extreme situations," *Fuzzy Sets and Syst.*, vol. 48, no. 1, pp. 41–52, 1992.

[38] B. Akbiyik, I. Eksin, M. Guzelkaya, and E. Yesil, "Evaluation of the Performance of Various Fuzzy PID Controller Structures on Benchmark Systems," in *ELECO '2005, 4rd Int. Conf. on Elect. and Electron. Eng.*, 2005.

[39] G. Orban and P. Varlaki, "Fuzzy modeling for service strategy and operational control of loading systems," *Acta Technica Series Logistica*, vol. 2, no. 3, pp. 375–391, 2009.

[40] S. Lee, "Application and verification of fuzzy algebraic operators to landslide susceptibility mapping," *Environmental Geology*, vol. 52, no. 4, pp. 615–623, 2007.

[41] T. Kumbasar, E. Yesil, I. Eksin, and M. Guzelkaya, "Inverse Fuzzy Model Control With Online Adaptation via Big Bang-Big Crunch Optimization," in *The 3rd International Symposium on Communications, Control and Signal Processing, ISCCSP 2008*, Malta.

[42] T. Kumbasar, I. Eksin, M. Guzelkaya, and E. Yesil, "Adaptive fuzzy model based inverse controller design using BB-BC optimization algorithm," *Expert Syst. with Applicat.*, vol. 38, no. 10, pp. 12356–12364, 2011.