An International Journal of Optimization and Control: Theories & Applications
ISSN:2146-0957 eISSN:2146-5703
Vol.13, No.2, pp.139-150 (2023)
http://doi.org/10.11121/ijocta.2023.1247

RESEARCH ARTICLE

Adaptive MIMO fuzzy PID controller based on peak observer

Kemal Uçak,* Beyza Nur Arslantürk

Department of Electrical and Electronics Engineering, Muğla Sıtkı Koçman University, Turkey
ucak@mu.edu.tr, beyzanurarslanturk@posta.mu.edu.tr

ARTICLE INFO

Article History:
Received 27 March 2022
Accepted 8 February 2023
Available 9 July 2023

Keywords:
Adaptive control
Fuzzy PID controller
MIMO fuzzy PID controller
Peak observer
Peak observer based optimization

AMS Classification 2010:
93B52; 93C35; 93C40; 93C42

ABSTRACT

In this paper, a novel peak observer based adaptive multi-input multi-output (MIMO) fuzzy proportional-integral-derivative (PID) controller has been introduced for MIMO time delay systems. The adaptation mechanism proposed by Qiao and Mizumoto [1] for single-input single-output (SISO) systems has been enhanced for MIMO system adaptive control. The tracking, stabilization and disturbance rejection performances of the proposed adaptation mechanism have been evaluated for MIMO systems by comparing with non-adaptive fuzzy PID and classical PID controllers. The obtained results indicate that the introduced adjustment mechanism for MIMO fuzzy PID controller can be successfully deployed for MIMO time delay systems.

1. Introduction

Fuzzy controller (FC) has a more effective control performance compared to standard controller structures with fixed parameters since FC inherently has naturally changing dynamics due to its structure. The FC exhibits a time-varying PD controller behavior when examined under certain conditions as given in [1]. Considering that the system dynamics are uncertain and may change over time in controller structures, controller performances can be improved by integrating adaptive structures into classical control structures. For this reason, fuzzy PID structures that combine the nonlinear inference competence of fuzzy mechanisms(FM) with the robustness of classical PID structures are very often opted. By combining FM with adaptive control structures, the control performance of fuzzy PID architectures can be enhanced and empowered against uncertainty in control systems.

In technical literature, there are various parameter adjustment mechanisms for fuzzy controllers. Peak observer based adaptation method introduced in [1] can be considered as the simplest of these adaptation structures. Qiao and Mizumoto have proposed to tune the controller parameters by taking into account the overshoot value of the controlled systems. In [1], one of the scaling coefficients for controller input and output has been considered to enhance the closed-loop system performance. Chou and Lu introduced a real time implantable self-tuning fuzzy controller based on adjustment of scaling factors [2]. The update values of the controller parameters (ΔK) are calculated over the look-up tables created depending on the tracking error and the derivative of the error [2]. Adaptation schemes are to adjust the scaling factors according to individual adjustment rules and look-up tables [2]. Adjustments of scaling factors are converted into numerical adjustment tables by applying appropriate membership functions, with only matrix maps [2]. Jung et al. [3] deployed a real-time self-tuning mechanism based on variable reference tuning index to control the steam generator of a nuclear power plant for overshoot and non-overshoot cases. Maeda

*Corresponding Author

and Murakami [4] proposed to tune scaling coefficients and rule base to improve fuzzy controller performance by considering the reaching time of the system output, overshoot and amplitude of oscillations in system response. Mudi and Pal [5] introduced a robust gain tuning mechanism based on an additional fuzzy architecture to adjust output scaling coefficients of Fuzzy PI and PD controllers. The rule base required for the output scaling coefficients is defined depending on the derivative of the tracking error and the tracking error [5]. Zheng [6] proposed to update cores, supports, boundaries and the universe of discourse of the fuzzy variables to enhance controller performance. Chung et al. [7] utilized a fuzzy tuner to adapt the input-output scaling coefficients of a fuzzy PI controller to improve rise time, overshoot and steady state error of the controlled system. Chao and Teng [8] introduced two stage mechanism which is composed of a direct adaptation and a gradient descent based indirect adaptation mechanism to tune scaling coefficients of a PD type fuzzy controller for linear and nonlinear dynamical systems. Woo et al proposed an adaptation mechanism in which the controller parameters are adapted throughout the entire transient state [9]. Hu et al. obtained a PID mechanism with non-linear behavior by introducing a nonlinearity to the tracking error signal through a fuzzy mechanism [10]. The parameters of the fuzzy mechanism are seeked via genetic algorithms (GA) [10]. Ketata et al. have presented various look-up table-based fuzzy controller architectures constituted over tracking error and derivative of tracking error [11]. Kim and Chung introduced a fuzzy PID controller which is composed of fuzzy "PD" and linear "I" parts [12]. Kien et al. proposed a fuzzy inverse controller structure that tries to perform the inverse of the dynamics of the system [13]. Jaya algorithm is deployed for parameter adaptation [13]. In order to ensure stability, a sliding mode control surface is utilized [13]. Cherrat et al. proposed a fuzzy-based self-tuning mechanism to estimate the PID controller [14]. Gil et al. introduced a fuzzy adaptation mechanism in which the fuzzy PID controller parameters are adapted offline via the non-linear model and online via the local linear model [15]. Yordanova et al. [16] introduced a novel model free supervisor based adaptive fuzzy controller for nonlinear dynamical systems. Pinto et al. developed a fuzzy adaptation mechanism for SISO and MIMO systems, which estimates the gains of the PID controller [17]. Yeşil et al. presented a review paper that aims to examine various studies on fuzzy PID controllers in the literature and to classify these fuzzy controllers into categories [18]. In the related review paper, fuzzy controller architectures were categorized under three main headings: Direct action (DA) type fuzzy PID controllers, fuzzy gain scheduling (FGS) type fuzzy PID controllers and mixed type fuzzy PID controllers [18]. Kumaar et al unveiled a deep survey of classical and fuzzy PID controllers [19]. The paper [19] presents the historical development of fuzzy logic-based structures. Guzelkaya et al. [20] utilized a relative rate observer to tune the input scaling factor corresponding to the derivative coefficient and the output scaling factor corresponding to the integral coefficient of the PID type FLC. Peak observer based adaptation mechanisms have been utilized in various studies [21, 22], but only two scaling coefficients have been adapted in all these structures, as proposed in [1].

In this paper, the adjustment mechanism proposed by Qiao and Mizumoto [1] has been enhanced for all scaling coefficients of the fuzzy PID controller. Thus, all scaling coefficients of the controller can be tuned by considering the overshoot value observed via peak observer. In addition to this, the adaptation mechanism proposed for SISO systems has been improved for MIMO systems. Therefore, the introduced MIMO fuzzy PID has 16 parameters to be optimized. The introduced adaptation mechanism has been examined on a MIMO time-delay system. The tracking and stabilization performance of the introduced controller has been evaluated.

This paper is organized as follows: The basics of the adaptive fuzzy PID based on peak observer [1] has been overviewed in Section 2. In section 3, the introduced adjustment mechanism for MIMO systems has been presented. The performance evaluation of the introduced method has been examined on a MIMO time delay system in Section 4. The paper ends with a brief conclusion part in Section 5.

2. Adaptive fuzzy PID controller

2.1. An overview of fuzzy PID controller

The structure of the incremental PID Type Fuzzy controller is illustrated in Figure 1 where K and K_d are input scaling coefficients, and α and β are output scaling coefficients of PD and PI part of the PID controller, respectively. The mathematical expression of the produced control law is derived as follows [1, 23–25]:

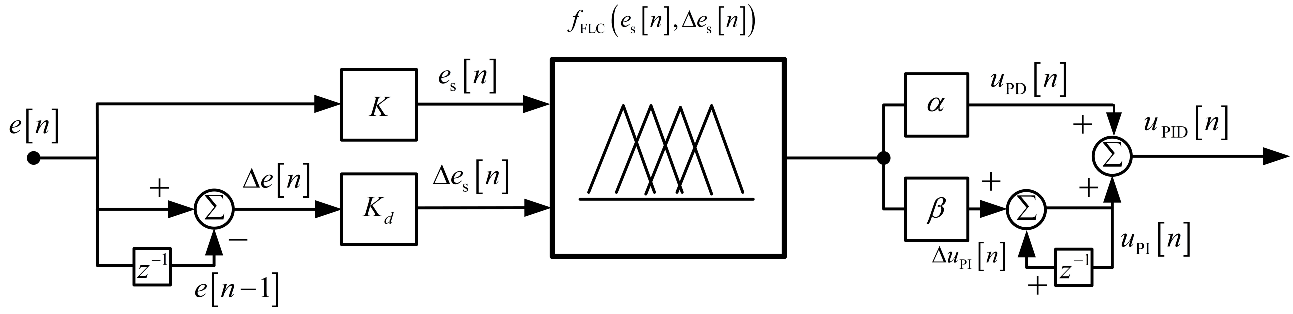

Figure 1. Fuzzy PID controller [1,23–26].

$$u_{PID}[n] = \overbrace{\alpha f_{FLC}(e_s[n], \Delta e_s[n])}^{u_{PD}[n]} + \underbrace{\beta f_{FLC}(e_s[n], \Delta e_s[n]) + u_{PI}[n-1]}_{u_{PI[n]}} \tag{1}$$

where $e_s[n]$ and $\Delta e_s[n]$ are scaled error and derivative of error. Triangular type input membership functions with cores $\{-1, -0.4, 0, 0.4, 1\}$ [1] depicted in Figure 2 are deployed. For given inputs of $e_s[n]$ and $\Delta e_s[n]$, four(4) rules illustrated in Figure 2 are fired at each sampling time. Thus, the output of the FLC can be obtained as follows using product-sum inference method and center of gravity method for defuzzification [1,23–25]:

$$\begin{aligned} f_{\mathrm{FLC}}(e_s[n], \Delta e_s[n]) &= \overbrace{A_i(e_s[n]) B_j(\Delta e_s[n])}^{w_{i\ j}} u_{i\ j} \\ &+ \overbrace{A_{i+1}(e_s[n]) B_j(\Delta e_s[n])}^{w_{i+1\ j}} u_{i+1\ j} \\ &+ \underbrace{A_i(e_s[n]) B_{j+1}(\Delta e_s[n])}_{w_{i\ j+1}} u_{i\ j+1} \\ &+ \underbrace{A_{i+1}(e_s[n]) B_{j+1}(\Delta e_s[n])}_{w_{i+1\ j+1}} u_{i+1\ j+1} \end{aligned} \tag{2}$$

where w_{ij}'s stand for the firing strength of fired rule, and membership values are given as follows [1,23–25]:

$$\begin{aligned} A_i(e_s[n]) &= \frac{e_{i+1} - e_s[n]}{e_{i+1} - e_i} \\ A_{i+1}(e_s[n]) &= \frac{e_s[n] - e_i}{e_{i+1} - e_i} \\ B_j(\Delta e_s[n]) &= \frac{\dot{e}_{j+1} - \Delta e_s[n]}{\dot{e}_{j+1} - \dot{e}_j} \\ B_{j+1}(\Delta e_s[n]) &= \frac{\Delta e_s[n] - \dot{e}_j}{\dot{e}_{j+1} - \dot{e}_j} \end{aligned} \tag{3}$$

The fuzzy control rule base utilized to constitute the FLC controller introduced in [1] is given in Table 1 for corresponding membership functions.

Table 1. Fuzzy control rule base [1,25,27].

MFs	$\dot{e}_{-2}$	$\dot{e}_{-1}$	$\dot{e}_0$	$\dot{e}_1$	$\dot{e}_2$
e_{-2}	-1.0	-0.7	-0.5	-0.3	0.0
e_{-1}	-0.7	-0.4	-0.2	0	0.3
e_0	-0.5	-0.2	0.0	0.2	0.5
e_1	-0.3	0.0	0.2	0.4	0.7
e_2	0.0	0.3	0.5	0.7	1.0

Linearization can be conducted in the neighborhood of the fired rules as detailed in [1] in order to analyze the dynamic behavior of the fuzzy PID controller by comparing with standard PID. Thus, the produced fuzzy control law can be rewritten as [1,25]:

$$\begin{aligned} u &= A + Pe_s[n] + D\Delta e_s[n] \\ A &= u_{ij} - Pe_i - D\dot{e}_j \\ P &= \frac{u_{i+1\ j} - u_{ij}}{e_{i+1} - e_i} \\ D &= \frac{u_{i\ j+1} - u_{ij}}{\dot{e}_{j+1} - \dot{e}_j} \end{aligned} \tag{4}$$

Using α and β parameters, the equivalent standard PID components can be derived as follows: "$\alpha KP + \beta K_d D$" represents the proportional term, "βKP" stands for the integral term and "$\alpha K_d D$" can be interpreted as the derivative term [1,25].

2.2. Peak observer based adaptation mechanism

The adjustment mechanism based on peak observer [1,18,20,21] is shown in Figure 3. Qiao and Mizumoto [1] aimed to decrease the integral coefficient while increasing the derivative parameter to increase the resistance against the overshoot and oscillation of the system by keeping the proportional term constant.

Therefore, Qiao and Mizumoto [1] proposed to update K_d and β parameters by observing the

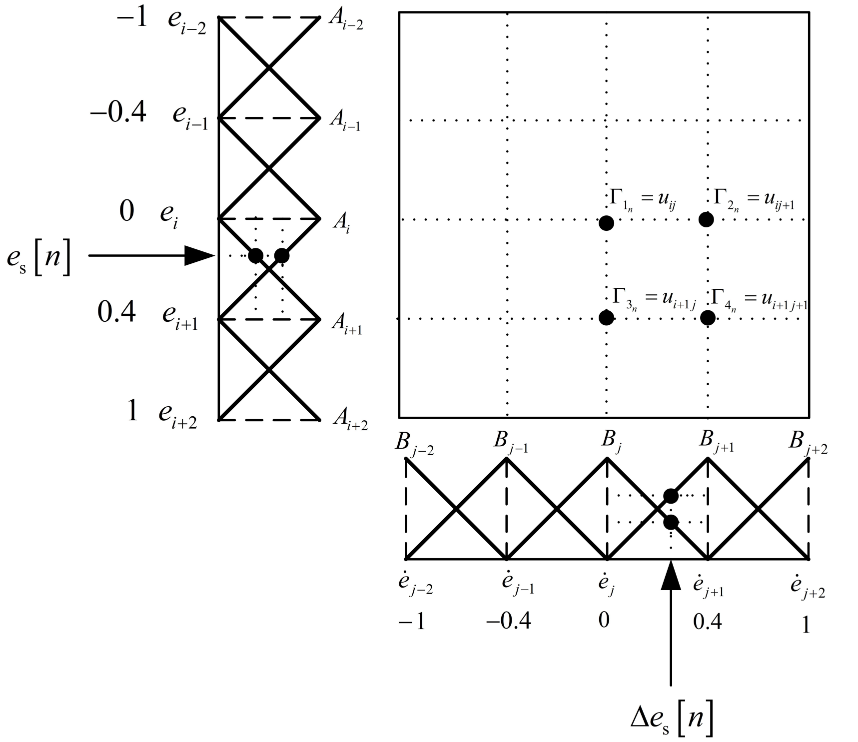

Figure 2. Input membership functions and fuzzy rule base [1, 23–25].

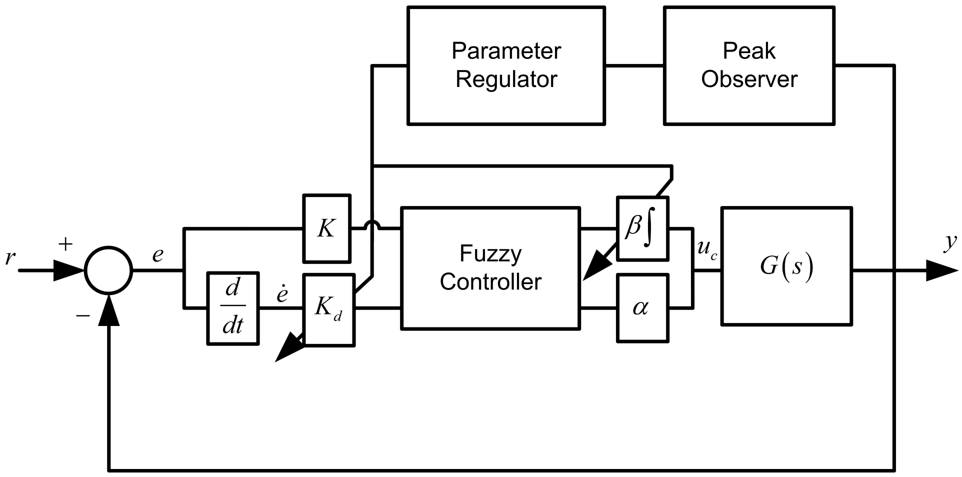

Figure 3. Peak observer based adaptation mechanism [1, 18, 20, 21].

absolute error value ($\delta_k = |e_k|$) at peak times as follows:

$$K_d = \frac{K_{d0}}{\delta_k},\ \beta = \beta_0 \delta_k \tag{5}$$

where $t_k,\ k \in \{1, 2, 3, \cdots\}$ are the peak times.

3. Adaptive MIMO fuzzy PID controller

In this study, firstly, it is aimed to adapt all parameters of a fuzzy PID controller, inspired by the peak observer approach of Qiao and Mizumoto in [1]. In addition, it is intended to extend the enhanced mechanism to MIMO fuzzy PID controllers. The proposed adaptation mechanism for a MIMO system is shown in Figure 4 where m stands for the mth system input and k denotes the kth controlled output of the MIMO system. The input-output scaling coefficients of the MIMO Fuzzy PID controller are adapted as follows:

$$\begin{bmatrix} K_{mk_{new}} \\ K_{d_{mk_{new}}} \\ \alpha_{mk_{new}} \\ \beta_{mk_{new}} \end{bmatrix} = \begin{bmatrix} K_{mk}\delta_m \\ \frac{K_{d_{mk}}}{\delta_m} \\ \frac{\alpha_{mk}}{\delta_m} \\ \beta_{mk}\delta_m \end{bmatrix} \tag{6}$$

where δ_m indicates the corresponding peak observer value [1, 25]. Thus, the derivative coefficient is increased while the integrator is decreased by keeping the proportional term fixed [25]. The internal structure of MIMO fuzzy PID controller

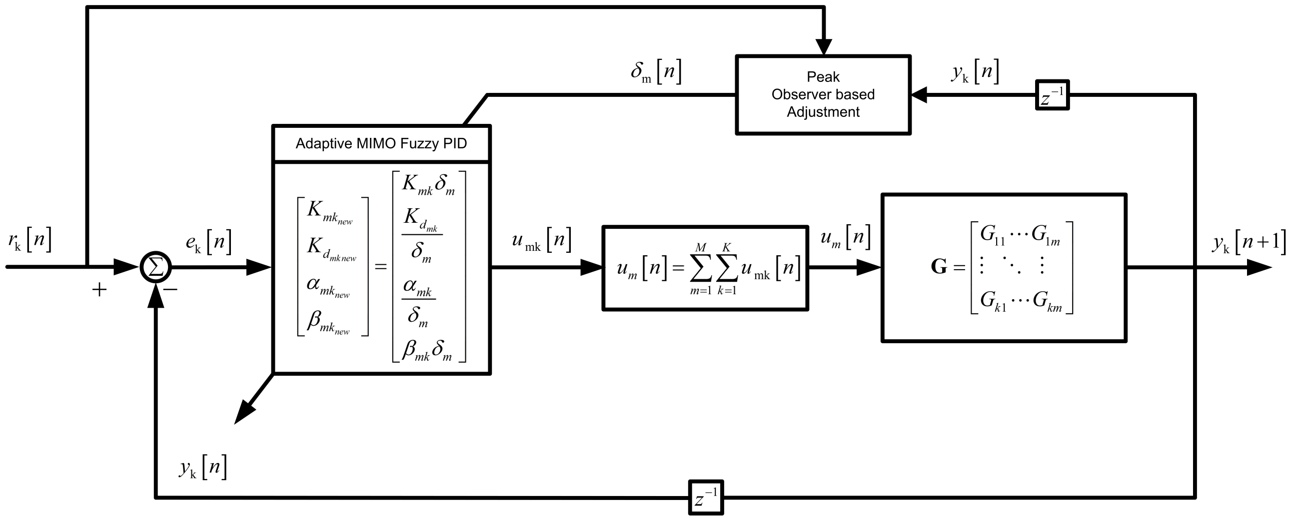

Figure 4. Adaptive MIMO fuzzy PID controller based on peak observer [1, 25].

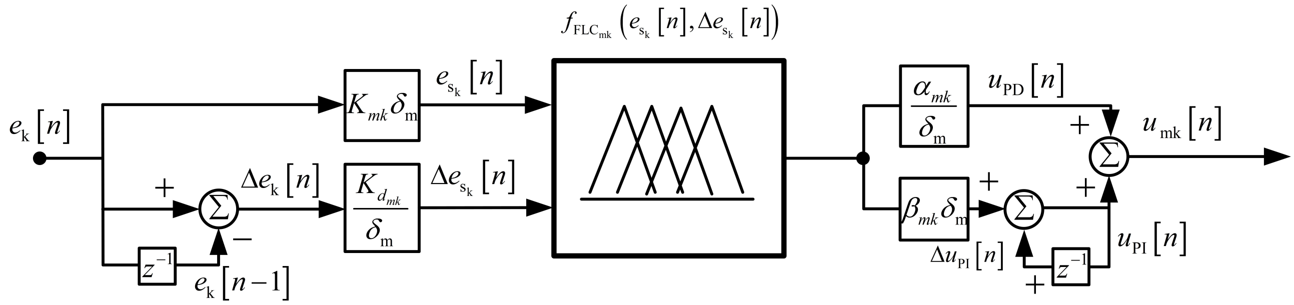

Figure 5. Inner structure of adaptive MIMO fuzzy PID controller [25].

representing the main and coupling controllers is given in Figure 5. Triangular type membership functions given in Figure 2 are used as input membership functions, and the fuzzy rule base in Table 1 is deployed to construct the fuzzy rules. As the inference mechanism and the defuzzification method, product operation and center of gravity method are used respectively.

In the case that δ term is interfused to the standard PID terms, the proportional term is fixed and acquired as $\alpha KP + \beta K_d D$, the integral term is derived as $\beta_0 K_0 \delta^2 P$, and the derivative term is given as $\frac{\alpha K_d D}{\delta^2}$ [25].

4. Simulation results

The tracking and stabilization performances of the introduced adaptation mechanism have been evaluated using the following two input two output(TITO) time delay system.

$$\begin{bmatrix} y_1(s) \\ y_2(s) \end{bmatrix} = \begin{bmatrix} \frac{6}{(s+1)(s+2)(s+3)} & \frac{1}{(s+15)}e^{-0.25\ s} \\ \frac{1}{(s+14)}e^{-0.275\ s} & \frac{6}{(s+1)(s+2)(s+3)} \end{bmatrix} \begin{bmatrix} u_1(s) \\ u_2(s) \end{bmatrix} \tag{7}$$

As given in (7), the coupling dynamics of the system have time delay dynamics. Considering the pade approximation, the time delay can be defined by an infinite number of zero-pole pairs. For this reason, there is a serious interaction between system dynamics. This interaction directly affects the controller performance.

4.1. Tracking performance

The tracking performance of the adaptation mechanism is examined for staircase input signals. The initial values of the fuzzy PIDs are given in Table 2. The performance of the non-adaptive and adaptive MIMO fuzzy PID controller and control signals are depictured in Figure 6 where black trajectory refers to non-adaptive mechanism and blue trajectory belongs to peak observed based adaptation mechanism.

Table 2. Initial controller parameters for tracking case.

Parameters	FLC_{11}	FLC_{12}	FLC_{21}	FLC_{22}
K_{mk}	0.25	0.125	0.125	0.25
$K_{d_{mk}}$	0.25	0.125	0.125	0.25
α_{mk}	0.25	0.125	0.125	0.25
β_{mk}	0.75	0.125	0.125	0.75

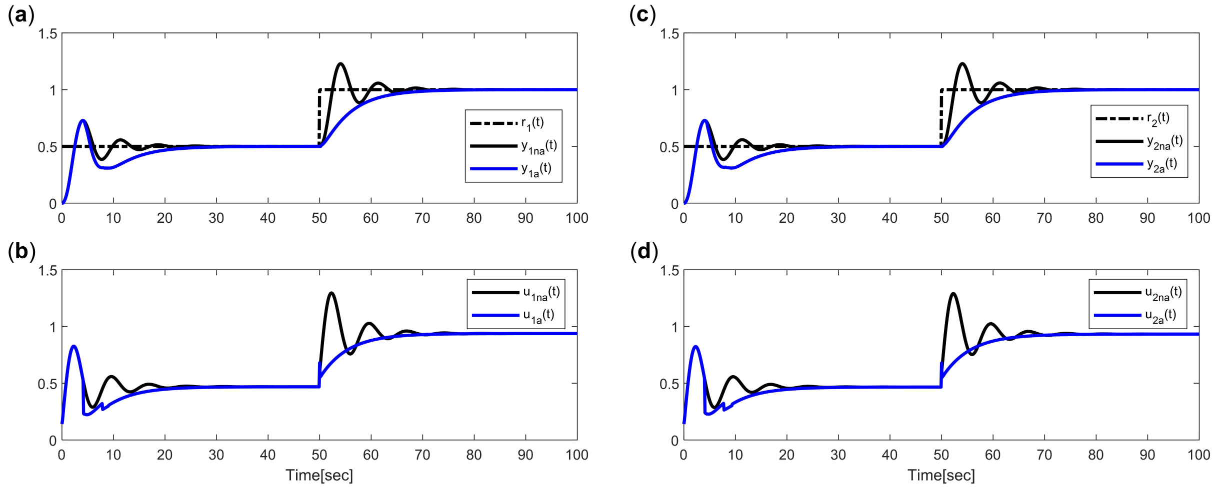

Figure 6. System outputs(**a**,**c**), control signals(**b**,**d**) for non-adaptive and adaptive MIMO fuzzy PID (Tracking Case).

As can be clearly seen from Figure 6(**a**,**c**), oscillations observed in non-adaptive fuzzy controller are suppressed successfully in case the peak observer-based adaptation mechanism is active. The adaptation mechanism is activated with the first peak and improves the control performance. In order to numerically evaluate the performances of the controllers, the behaviors between 50 and 100 sec are observed by taking into account the overshoots(OS %), settling times(t_s) and steady state errors(e_{ss}). While the non-adaptive system has 22.87 % overshoot(OS) and 18.5 sec settling time, peak observer based adaptive system has no overshoot and 15.5 sec settling time. Both controllers has no steady-state errors. These numerical values are tabulated in Table 3.

Table 3. Comparion of non-adaptive fuzzy PID and peak observer based fuzzy PID with respect to overshoot, settling time and steady state error.

Controller Type	OS %	t_s	e_{ss}
Non-adaptive FLC	22.87	18.5	0
Peak Observer FLC	0	15.5	0

The evaluations of the main fuzzy PID controller parameters are shown in Figure 7. The alternation of the coupling fuzzy PID controllers are depictured in Figure 8. By dynamically adapting the controller parameters, a closed-loop system response with less oscillations or even without overshoot can be achieved.

Table 4. Initial controller parameters for stabilization case.

Parameters	FLC_{11}	FLC_{12}	FLC_{21}	FLC_{22}
K_{mk}	0.485	0.2	0.1	0.5
$K_{d_{mk}}$	0.5	0.25	0.2	0.475
α_{mk}	7.5	0.25	0.5	7
β_{mk}	2	0.1	0.2	2

4.2. Stabilization performance

In order to examine the effectiveness of the proposed adjustment mechanism, the controller performance has been evaluated for the stabilization problem. For this purpose, the case that the non-adaptive MIMO fuzzy PID controller cannot control is considered. The initial values of the controller parameters are given in Table 4. As can be seen from Figure 9, non-adaptive MIMO fuzzy PID controller can not control the system dynamics. In case the peak observer based mechanism is activated, the system dynamics can be successfully forced to track the desired reference signals as illustrated in Figure 10. The evaluation of input-output scaling coefficients are given in Figures 11-12.

As given in Figures 11-12, since α and K_d parameter values increase, the derivative laws can increase the resistance against the overshoot and oscillation of the system [1]. Similarly, K and β parameter values decrease, thus decreasing the equivalent integral terms. The fact that the controller parameters are not updated until the next peak value can be considered as one of the most important disadvantages of this structure. However, this structure is open to development.

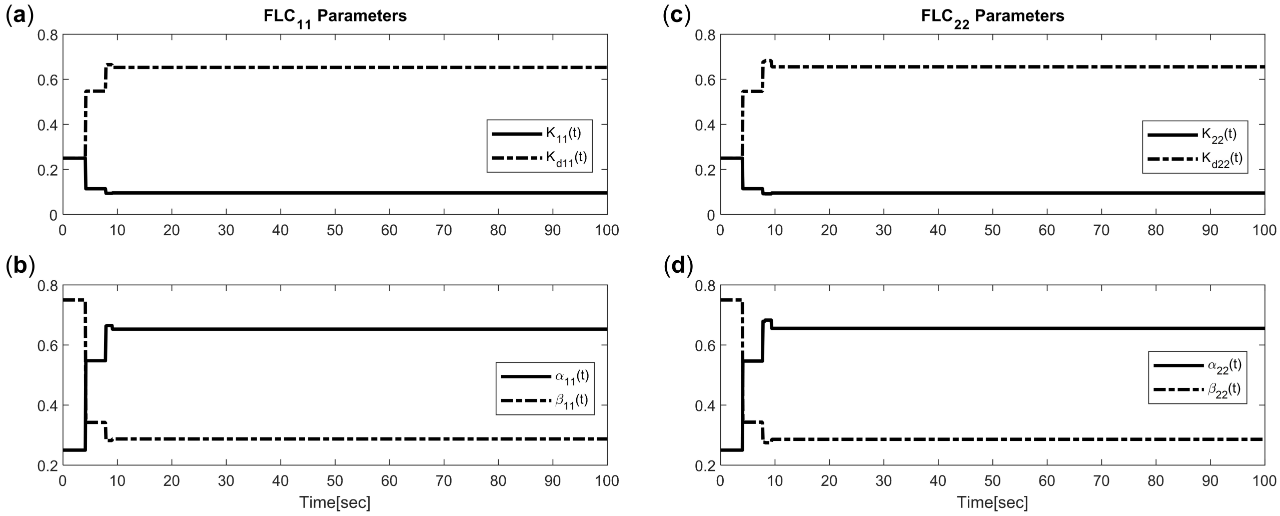

Figure 7. Input scaling coefficients (**a**,**c**), and output scaling coefficients (**b**,**d**) for FLC_{11} and FLC_{22} (Tracking Case) .

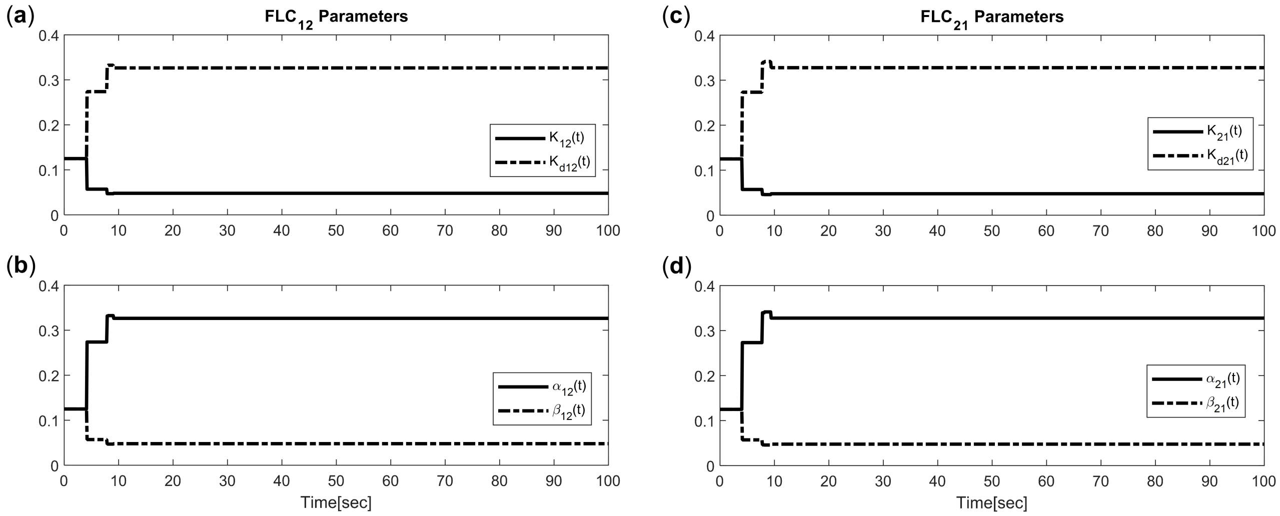

Figure 8. Input scaling coefficients (**a**,**c**), and output scaling coefficients (**b**,**d**) for FLC_{12} and FLC_{21} (Tracking Case) .

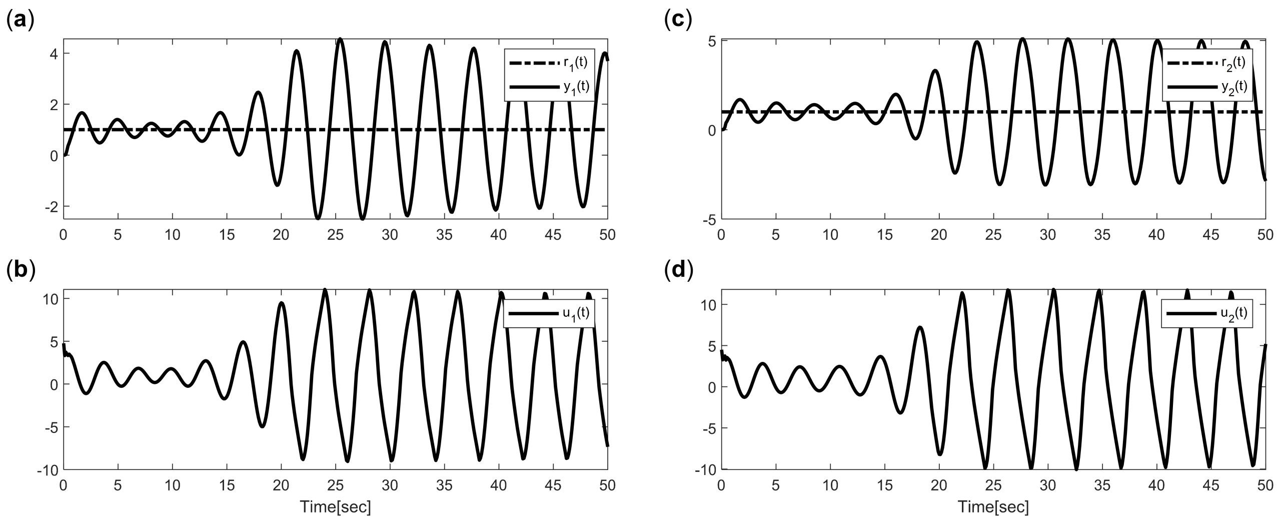

Figure 9. Syste outputs (**a**,**c**), control signals for non-adaptive MIMO fuzzy PID (Stabilization Case).

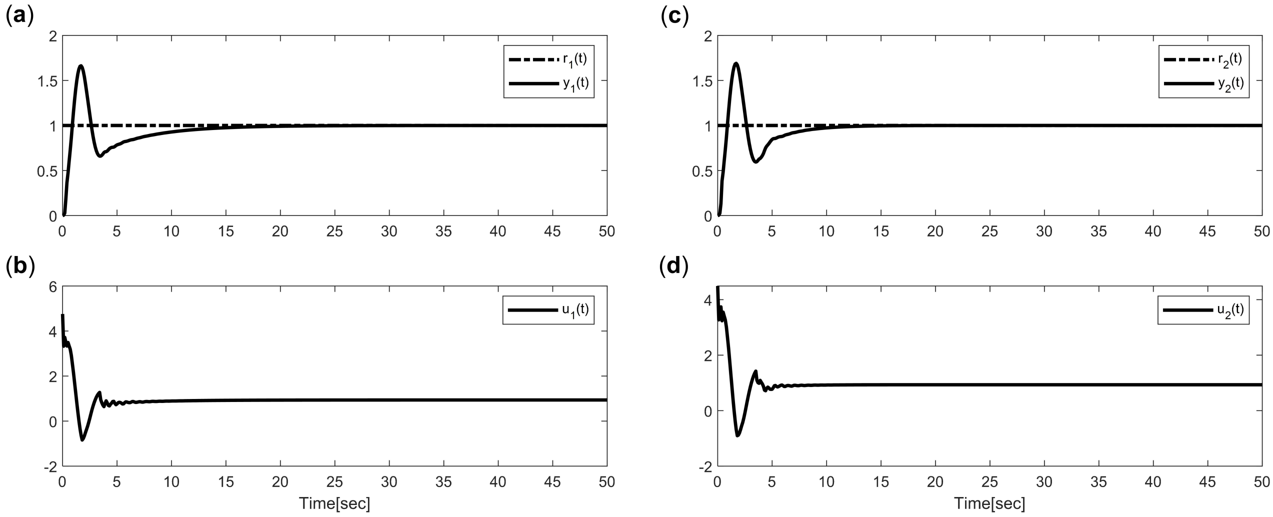

Figure 10. System outputs (**a**,**c**), control signals (**b**,**d**) for adaptive MIMO fuzzy PID (Stabilization Case).

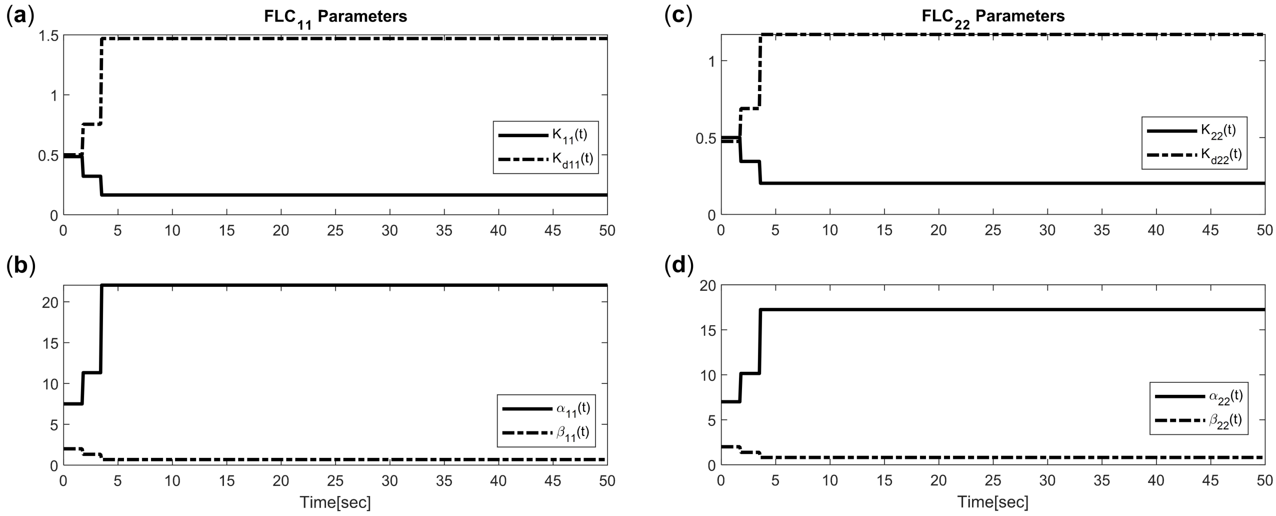

Figure 11. Input scaling coefficients (**a**,**c**), and output scaling coefficients (**b**,**d**) for FLC_{11} and FLC_{22} (Stabilization Case) .

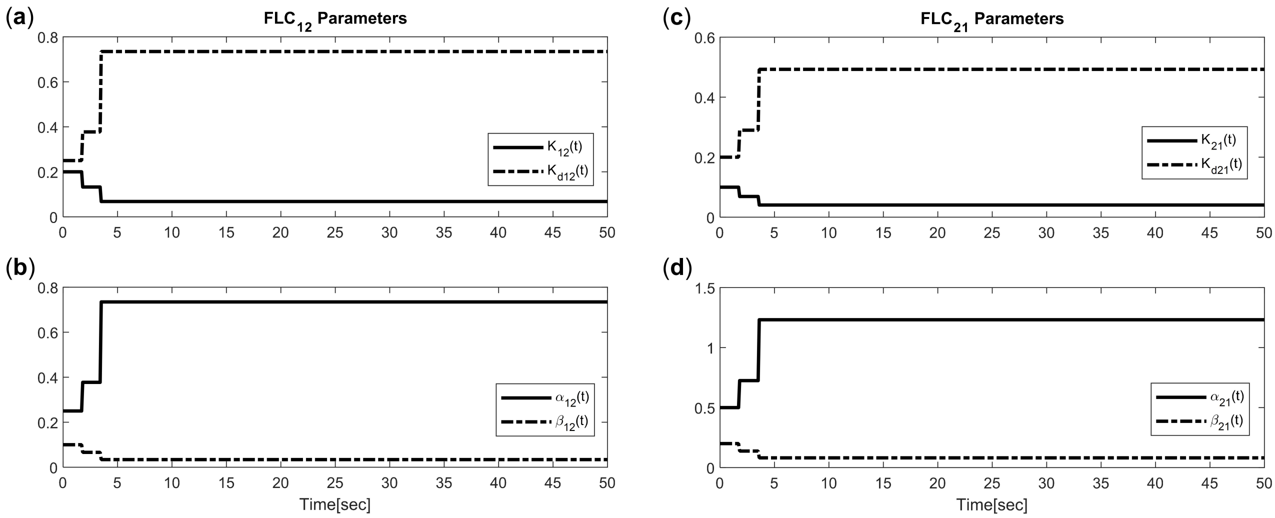

Figure 12. Input scaling coefficients (**a**,**c**), and output scaling coefficients (**b**,**d**) for FLC_{12} and FLC_{21} (Stabilization Case) .

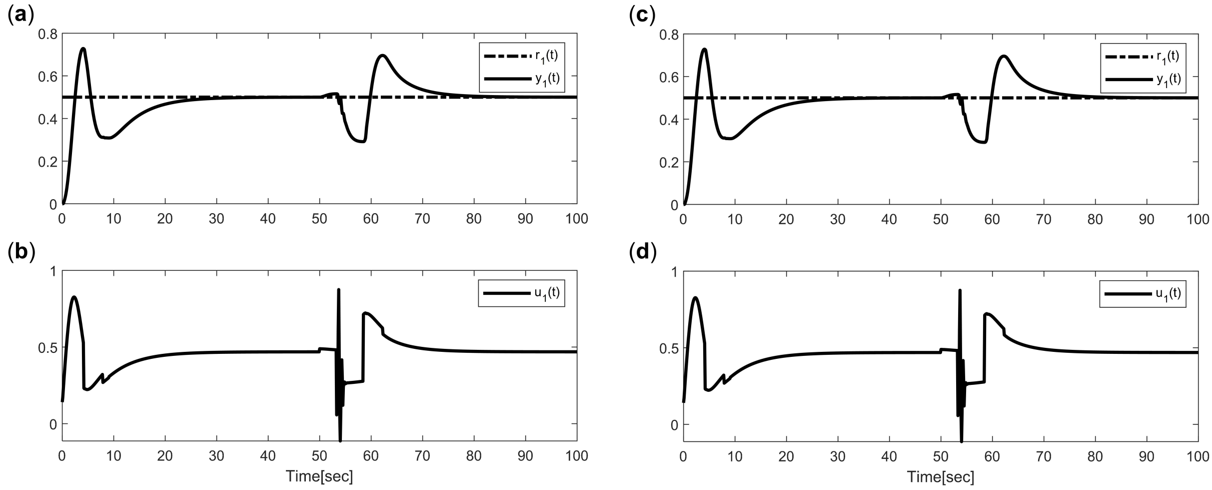

Figure 13. System outputs (**a**,**c**), control signals (**b**,**d**) for adaptive MIMO fuzzy PID (Disturbance Rejection Case)

.

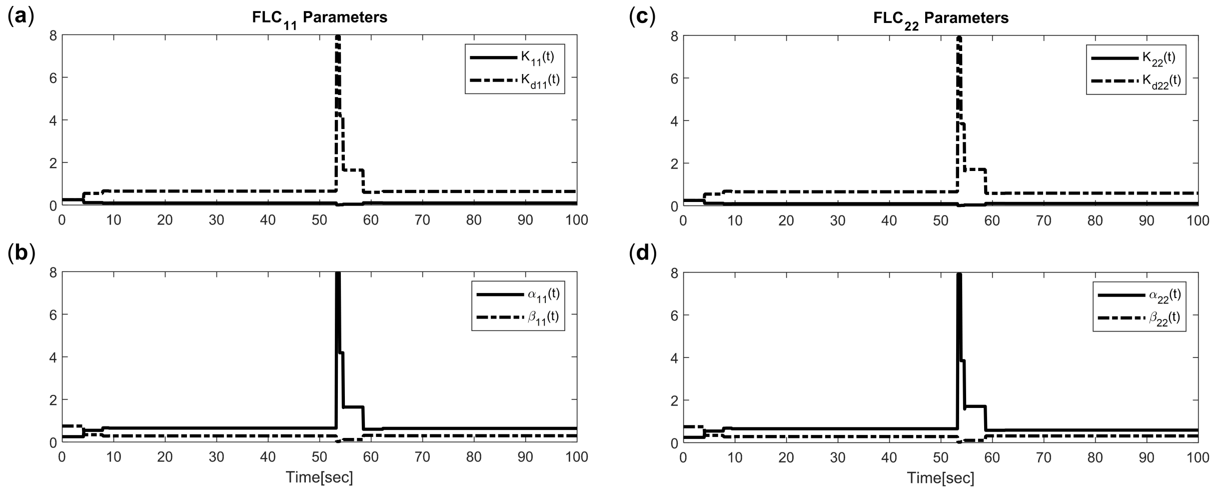

Figure 14. Input scaling coefficients (**a**,**c**), and output scaling coefficients (**b**,**d**) for FLC$_{11}$ and FLC$_{22}$ (Disturbance Rejection Case)

.

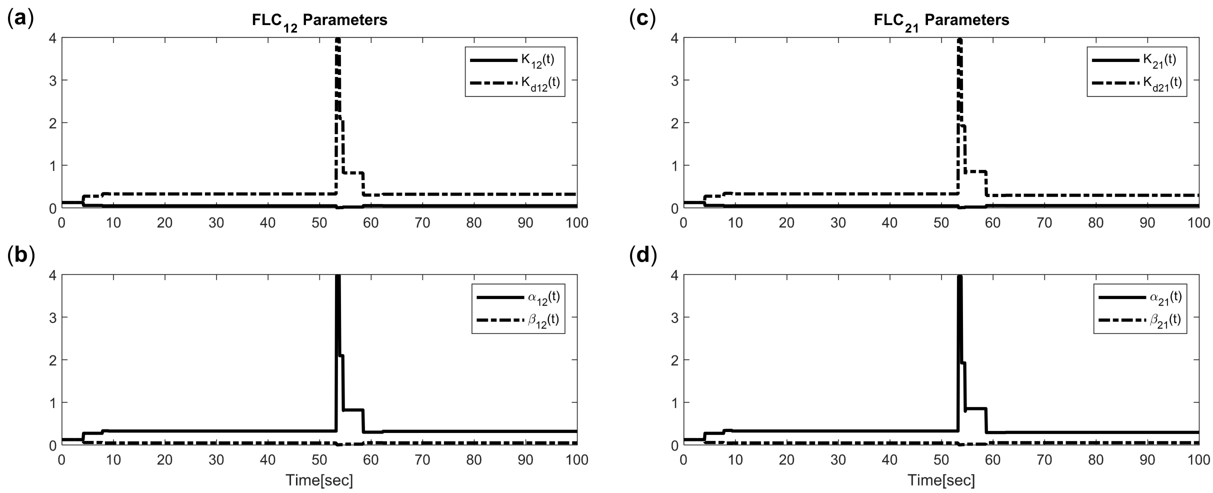

Figure 15. Input scaling coefficients (**a**,**c**), and output scaling coefficients (**b**,**d**) for FLC$_{12}$ and FLC$_{21}$ (Disturbance Rejection Case

.

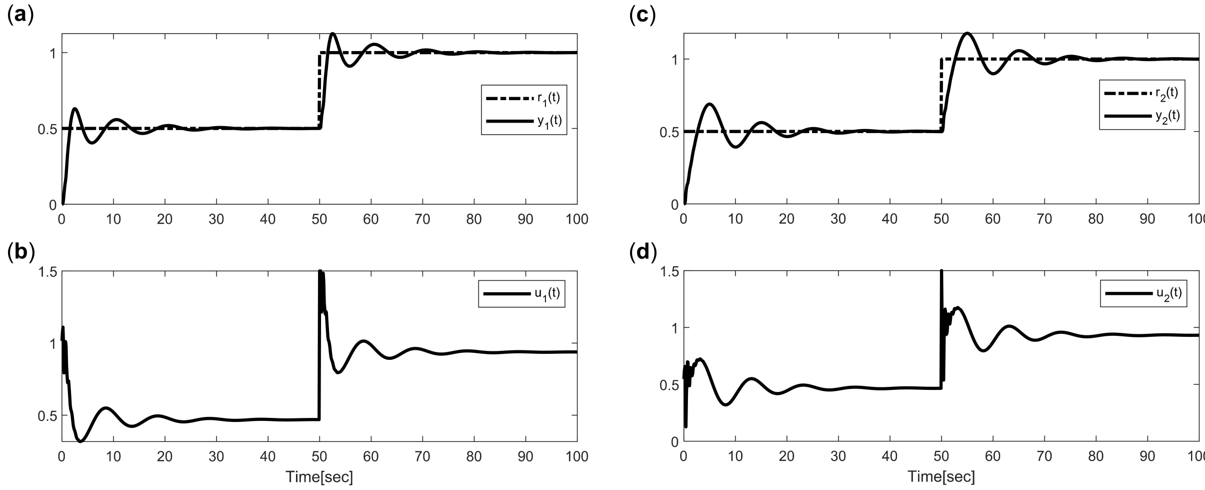

Figure 16. System outputs (**a**,**c**), control signals (**b**,**d**) for MIMO PID (Tracking Performance Case).

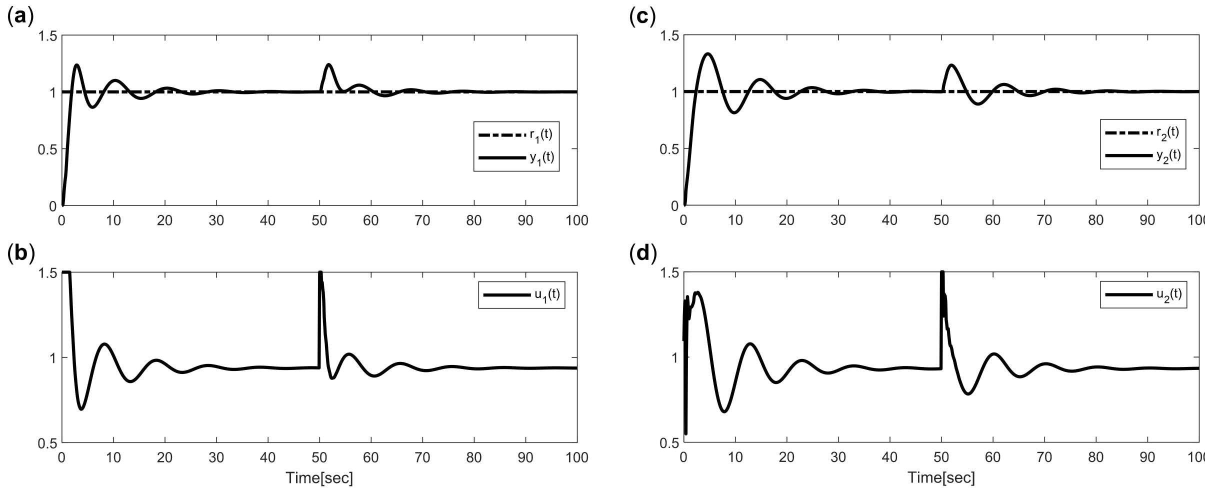

Figure 17. System outputs (**a**,**c**), control signals (**b**,**d**) for MIMO PID (Disturbance Rejection Case).

4.3. Disturbance rejection performance

In order to examine the robustness of the adaptation mechanism, a step type input disturbance is applied to the system at 50 seconds.

The disturbance rejection performance of the adaptation mechanism is illustrated in Figure 13. The adaptations of the controller parameters against the disturbance case are shown in Figures 14-15. The adaptation mechanism readjusts all controller parameters to suppress the disturbance.

As can be clearly seen from Figures 14-15, it can be observed that the coefficients of the derivative parts are very sensitive to disturbances. The introduced adaptation mechanism effectively rejects the step type input disturbances. The disturbance rejection performance of this structure is an open problem to be developed.

4.4. Comparison with conventional PID

The control performances of the non-adaptive fuzzy PID and peak observer based fuzzy PID are compared with the classical PID controller. Equivalent PID_{11} and PID_{22} values have been calculated with the help of the initial values of Fuzzy PID controllers in Table 4. The parameters of the coupling (PID_{12} and PID_{21}) controllers are chosen as 5 times the equivalent parameters obtained via Table 4. Thus, the parameters of MIMO PID are given in Table 5.

Table 5. MIMO PID controller parameters.

Parameters	PID_{11}	PID_{12}	PID_{21}	PID_{22}
K_p	1.25	0.78125	0.78125	1.25
K_i	0.9375	0.390625	0.390625	0.9375
K_d	0.3125	0.390625	0.390625	0.3125

In order to compare the controller performances, the following performance index function is utilized to constitute the comparison table in Table 6.

$$J_c = \int_{t=0}^{t_f} |e_1(t)| + \lambda_1 |\frac{du_1(t)}{dt}| + |e_2(t)| + \lambda_2 |\frac{du_2(t)}{dt}| \, dt \quad (8)$$

where $\lambda_1 = \lambda_2 = 20$ is chosen to minimize and limit the variation of the control signal.

Table 6. Performance comparisons(J_c).

Cases	FPID$_{po}$	FPID$_{n-po}$	MIMO PID
Nominal	28.033	31.832	180.422
Disturbance	48.393	48.393	201.04

The tracking and disturbance rejection performances of MIMO PID controller have been illustrated in Figure 16 and 17.

As can be seen from Figure 16, MIMO PID controller provokes too much oscillation and overshoot. As can be seen from Table 6, the performance of MIMO PID is the worst for both tracking and disturbance rejection performances. It is observed that the adaptation mechanism in FLC significantly improves the controller performance.

5. Conclusion

In this paper, an adaptation mechanism for MIMO fuzzy PID controller has been introduced for MIMO systems. The performance of the proposed mechanism is examined on tracking, stabilization and disturbance rejection problems. In order to examine the effect of the proposed adaptation structure in depth, it is compared with non-adaptive fuzzy PID and classical PID controller. The obtained results indicate that the introduced adjustment mechanism provides quite successful tracking, stabilization and disturbance rejection performances for the control of MIMO systems. As future works, the drawbacks of peak observer can be resolved by constantly observing the tracking error, not just at peak times. For this purpose, it is aimed to propose novel adaptive control architectures in which the tracking error is constantly deployed in the adaptation mechanism.

Acknowledgement

This work is supported by the Scientific and Technological Research Council of Turkey(TUBITAK)-BIDEB 2209/A University Students Research Projects Support Programme with the applied number 1919B012113187 (2021/2nd term).

References

[1] Qiao, W.Z. & Mizumoto, M. (1996). PID type fuzzy controller and parameters adaptive method. *Fuzzy Sets and Systems*, 78(1), 23–35.

[2] Chou, C.H. & Lu, H.C. (1994). A heuristic self-tuning fuzzy controller. *Fuzzy Sets and Systems*, 61(3), 249–264.

[3] Jung, C.H. Ham, C.S. & Lee, K.I. (1995). A real-time self-tuning fuzzy controller through scaling factor adjustment for the steam generator of NPP. *Fuzzy Sets and Systems*, 74(1), 53–60.

[4] Maeda, M. & Murakami, S. (1992). A Self-tuning fuzzy controller. *Fuzzy Sets and Systems*, 51(1), 29–40.

[5] Mudi, R.K. & Pal, N.R. (1999). A robust self-tuning scheme for PI- and PD-type fuzzy controllers. *IEEE Transactions on Fuzzy Systems*, 7(1), 2–16.

[6] Zheng, L. (1992). A practical guide to tune of proportional and integral (PI) like fuzzy controllers. *IEEE International Conference on Fuzzy Systems*, 633–640

[7] Chung, H.Y. Chen, B.C. & Lin, J.J. (1998). A PI-type fuzzy controller with self-tuning scaling factors. *Fuzzy Sets and Systems*, 93(1), 23–28.

[8] Chao, C.T. & Teng, C.C. (1997). A PD-like self-tuning fuzzy controller without steady-state error. *Fuzzy Sets and Systems*, 87(2), 141–154.

[9] Woo, Z.H., Chung, H.Y. & Lin, J.J. (2000). A PID type fuzzy controller with self-tuning scaling factors. *Fuzzy Sets and Systems*, 115(2), 321–326.

[10] Hu, B., Mann, G.K.I. & Gosine, R.G. (1999). New methodology for analytical and optimal design of fuzzy PID controllers. *IEEE Transactions on Fuzzy Systems*, 7(5), 521–539.

[11] Ketata, R., Geest, D.D. & Titli, A. (1995). Fuzzy controller: design, evaluation, parallel and hierarchical combination with a PID controller. *Fuzzy Sets and Systems*, 71(1), 113–129.

[12] Kim, B.J. & Chung, C.C. (2001). Design of fuzzy PID controller for tracking control. *Journal of Institute of Control*, 7(7), 1–7.

[13] Kien, C.V., Son, N.N. & Anh, H.P.H. (2020). Adaptive MIMO fuzzy controller for double coupled tank system optimizing by jaya algorithm. 5th International Conference on Green Technology and Sustainable Development (GTSD), Ho Chi Minh City, Vietnam, 495–499.

[14] Cherrat, N., Boubertakh, H. & Arioui, H. (2018). Adaptive fuzzy PID control for a class of uncertain MIMO nonlinear systems with dead-zone inputs' Nonlinearities. *Iranian Journal of Science and Technology, Transactions of Electrical Engineering*, 42, 21–39.

[15] Gil, P., Lucena, C., Cardoso, A. & Palma, L.B. (2015). Gain tuning of fuzzy PID controllers for MIMO systems: a performance-driven approach. *IEEE Transactions on Fuzzy Systems*, 23(4), 757–768.

[16] Yordanova, S., Yankov, V. & Jain, L. (2017). MIMO fuzzy logic supervisor-based adaptive control using the example of coupled-tanks levels control. International Journal of Innovative Computing, *Information and Control*, 13(2), 453–470.

[17] Pinto, M.B.B., Mota, J.G.R. & Almeida, O.M. (2010). PID self-adjustable fuzzy logic MIMO case: method and application. 9th IEEE/IAS International Conference on Industry Applications, Sao Paulo, Brazil, 1–6.

[18] Yeşil, E., Güzelkaya, M. & Eksin, I. (2003). Fuzzy PID controllers: an overview. 3rd Triennial ETAI International Conference on Applied Automatic Systems, Ohrid, Macedonia, 1–8.

[19] Kumar, V., Nakra, B.C. & Mittal, A. (2011). A review of classical and fuzzy PID controllers. *International Journal of Intelligent Control and Systems*, 16(3), 170–181.

[20] Güzelkaya, M., Eksin, I. & Yeşil, E. (2003). Self-tuning of PID-type fuzzy logic controller coefficients via relative rate observer. *Engineering Applications of Artificial Intelligence*, 16(3), 227–236.

[21] Karasakal, O., Yeşil, E., Güzelkaya, M. & Eksin, I. (2003). An implementation of peak observer based self-tuning fuzzy PID-type controller on PLC. 3rd International Conference on Electrical and Electronics Engineering, ELECO, Bursa, Turkey, 1–5.

[22] Yeşil, E., Kumbasar, T., Dodurka, M. & Sakallı, A. (2014). Peak observer based self-tuning of type-2 fuzzy PID controller. 10th IFIP International Conference on Artificial Intelligence Applications and Innovations (AIAI), Rhodes, Greece, 487–497.

[23] Uçak, K. & Günel, G.Ö. (2017). Generalized self-tuning regulator based on online support vector regression. *Neural Computing and Applications*, 28, S775–S801.

[24] Uçak, K. & Günel, G.Ö. (2017). Fuzzy PID type STR based on SVR for nonlinear systems. 10th International Conference on Electrical and Electronics Engineering (ELECO), Bursa, Turkey, 764–768.

[25] Arslanturk, B. & Uçak, K. (2022). An improved adaptive fuzzy PID controller based on peak observer for nonlinear dynamical systems. International ONLINE Conference on Mathematical Advances and Applications (ICOMAA-2022), Istanbul, Turkey, 85–91.

[26] Bouallegue, S., Haggege, J., Ayadi, M. & Benrejeb, M. (2012) PID-type fuzzy logic controller tuning based on particle swarm optimization. *Engineering Applications of Artificial Intelligence*, 25(3), 484–493.

[27] Karaman, K., Bekaroğlu, Y.T., Söylemez, M.T., Uçak, K. & Günel, G.Ö. (2015). Controlling 3-DOF helicopter via fuzzy PID controller. 9th International Conference on Electrical and Electronics Engineering (ELECO), Bursa, Turkey, 869–873.

Kemal Uçak *received his M.Sc. and Ph.D. degree in Control and Automation Engineering from Istanbul Technical University in 2012 and 2016 respectively. He has been a member of the faculty at Istanbul Technical University, and Muğla Sıtkı Koçman University where currently he is an Assistant Professor in the Department of Electrical and Electronics Engineering. He carried out his postdoctoral studies at Massachusetts Institute of Technology (MIT) in 2020. His research interests pertain to adaptive control, artificial intelligence, machine learning, and robust control. Dr. Uçak is a member of IEEE and IFAC.*

https://orcid.org/0000-0001-7005-7940

Beyza Nur Arslantürk *is a graduate student in Electrical and Electronics Engineering at Muğla Sıtkı Koçman University. Her research interests are adaptive control, adaptive fuzzy control architectures, and fuzzy system identification.*

https://orcid.org/0000-0001-5358-8811