

DESIGNING OF A MRAC-FUZZY WITH PD FEEDBACK FOR marginally STABLE SECOND-ORDER SYSTEM WITH DEAD TIME

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DESIGNING OF A MRAC-FUZZY WITH PD FEEDBACK FOR marginally STABLE SECOND-ORDER SYSTEM WITH DEAD TIME

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Abstract

The performance of a traditional controller with fixed tuning is unsatisfactory for time-varying systems. This drawback can be resolved by using adaptive controllers, as their control policies can be changed in accordance with change in process dynamics. This research presents a model reference adaptive controller (MRAC) for controlling a nonlinear system through a network, subject to a time delay caused by a variable network. In MRAC, the controller outcome relies on the difference between actual process and reference model outcome with fixed adaptation gain. The desired requirements of the process outcome are given as a reference model. The main aim is to find further improvement of the traditional MRAC method and provide more accurate control to the marginally stable second-order process with dead time (MS-SOPDT) and minimize drawbacks of the traditional MRAC method. Here, a novel MRAC-Fuzzy based PD feedback (MRAC-FPD) control technique is proposed for MS-SOPDT. This paper also provides a comparative analysis of different MRAC strategies like MRAC-MIT, MRAC-PD, MRAC-Lyapunov, MRAC-Lyapunov-PD, MRAC-Fuzzy. Compare to other techniques, the proposed MRAC-Fuzzy-PD gives better response. This controller offers improved set point tracking with fewer oscillations and fast response. This fact is also verified by the use of different performance indices such as integral time absolute error (ITAE), integral square error (ISE), and integral absolute error (IAE) under closed-loop conditions. These methods are demonstrated with the help of MATLAB/Simulink.

Keywords: Lyapunov, Marginally stable, MRAC, MRAC-Fuzzy, MRAC-Fuzzy-PD, Second Order Process

Introduction

The aerospace engineers searched for a solution in the 1950s for the design of autopilots. The key goal was to identify a controller that could operate best in-flight conditions. An intensive study in the adaptive area had then begun, to lead to the development of such a controller. An innovative controller was developed to deliver high performances, like an adaptive controller

(Manna & Akella, 2020). On this basis, multiple adaptive flight control techniques have been proposed, and the one proposed by Whitaker et al., which is known most commonly in various publications (Astrom & Wittenmark, 2008; Astrom & Kumar, 2014; Ioannou & Fidan, 2006; Landau *et al.*, 2011). The Whitaker method that is still used in recent days is referred to as the

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MRAC and the approach that can fix the autopilot problem (Astrom & Wittenmark, 2008; Ioannou & Fidan, 2006; Landau *et al.*, 2011). The outcomes are outlined very well in (Astrom & Wittenmark, 2008; Astrom & Kumar, 2014; Levine, 2011). This technique was initially based only on the gradient method, and was named 'MIT rule'. This rule called for the automated parameter modification of the controller to be similar to that of the reference model (Astrom & Kumar, 2014; Ioannou & Fidan, 2006). In addition, by using Lyapunov stability (Astrom & Wittenmark, 2008; Astrom & Kumar, 2014; Ioannou & Fidan, 2006; Black *et al.*, 2014), Park improved the MRAC method in the 1960s.

MRAC, a significant branch of adaptive control, was closely investigated and its design technology and theories were systematically and effectively evolved to achieve maturity. A core advantage of MRAC is that the closed-loop control mechanism complies with the reference model, ensuring accurate matching of the plant model with nominal parameters determined from plant parameters, and achieving asymptotic performance monitoring using adaptive parameters modified by adaption laws to approximate nominal parameters. A broad range of MRAC literature is presented (i.e., basic adaptive control theory (Morse, 1980; Goodwin & Mayne, 1987; Narendra & Annaswamy, 1989; Sastry & Bodson, 1989; Ioannou & Sun, 1996; Tao, 2003), providing the complete proof of MRAC characteristics such as stability, tracking, and matching; see (Tao, 2014) which involves an analysis of some representative MRAC references). Tremendous efforts, improvement, and outcomes on tracking and stability of the various adaptive control system (i.e., few advanced adaptive control book (Tsakalis & Ioannou, 1993; Astolfi *et al.* 2008; Hovakimyan & Cao, 2010; Landau *et al.*, 2011; Stefanovic & Safonov, 2011; Lavretsky & Wise, 2013), and few extended adaptive control paper (Ortega *et al.*, 2003; Wang & Lin, 2012; Hoagg & Bernstein, 2012; Yucelen & Haddad, 2013; Serrani, 2013; Flores-Perez *et al.*, 2014; Chem *et al.*, 2016) have also been developed, for the study of MRAC's basic properties, its robustness in system modelling errors such as parameter variation and unmodeled dynamics, external disturbances, and effect of design parameters. A MRAC based speed controller (MRAC-SC) is designed for a surface-mounted permanent magnet synchronous motor drive. The proposed controller gives better performance compared to the non-adaptive model reference speed controller and traditional proportional-integral

SC in terms of good tracking, fast transient response, and robustness against parameter uncertainties (Nguyen *et al.*, 2018). A new control strategy is presented, which is the combination of MRAC and iterative learning control. This control strategy is used to speed control of ultrasonic motor (Jingzhuo & Huang, 2020). A MRAC is presented for aortic pressure regulation and maintaining the heart's physiological aerobic metabolism in ex vivo heart perfusion (Xin *et al.*, 2021). A MRAC-PD controller is designed for second-order integrating processes (Sengupta and Dey, 2017). This controller ensures improved response compare to traditional MRAC.

This article proposed a novel MRAC-Fuzzy based PD feedback control technique for MS-SOPDT and provides a comparative analysis of different MRAC strategies like MRAC-MIT, MRAC-PD, MRAC-Lyapunov, MRAC-Lyapunov-PD, MRAC-Fuzzy. The proposed control scheme provides better results compared to other techniques. Following is the outline of this article. The system description is explained in Section II. Section III describes the MRAC scheme with MIT rule and Lyapunov theory. Section III presents the other control scheme. Section IV displays the proposed control scheme. Section V presents the simulation results and discussions. Section VI introduces the conclusion of the paper.

System Description

This research is focused on a MS-SOPDT. Marginally stable systems, which have poles on the imaginary axis. In this case, system have sinusoidal oscillations, with a constant amplitude. The mentioned control scheme is validated by means of a simulation for a MS-SOPDT given below (Manna & Akella, 2020).

$$G(s) = \frac{4}{s(s+4)} e^{-0.1s} \quad (1)$$

The following reference model provides desired process performance specification.

$$G_m(s) = \frac{4}{s+4} \quad (2)$$

MRAC

The MRAC is a control system that provides desired parameters as a reference model. The basic MRAC diagram is displayed in Figure 1. It generally comprises of two loops; the inner loop is used to control normal feedback and the outer loop is used for adjusting the controller parameter. The outcome is compared between

process and reference model and the error between models are provided as feedback through the parameter adjustment loop. The controller parameters are modified to minimize the error until it becomes zero. To implement the MRAC, there are primarily two methods, namely, the Lyapunov theory and the MIT rule.

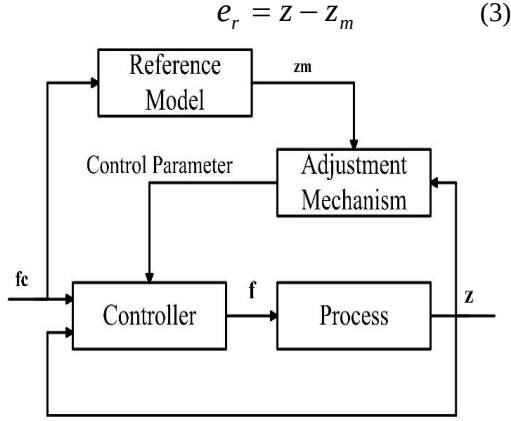


Figure1. MRAC block diagram [1]

MIT rule

The underlying principle behind this rule is to identify a minimization criterion to update controller parameters such that the error is minimized to zero. If the parameter vector is μ and e_r is the error, the selected cost function is

$$J(\mu) = \frac{e_r^2}{2} \quad (4)$$

It is important to change parameters in the form of a negative gradient. In those circumstances, Criterion J becomes small:

$$\frac{d\mu}{dt} = -\tau \frac{\partial J}{\partial \mu} = -\tau e_r \frac{\partial e_r}{\partial \mu}$$

Where τ and $\frac{\partial e_r}{\partial \mu}$ are adaptation gain and sensitivity respectively.

The process and reference model are considered as:

$$\frac{d^2 y(t)}{dt^2} = -a_1 \frac{dy(t)}{dt} - a_2 y(t) + b f(t) \quad (5)$$

$$\frac{d^2 y_m(t)}{dt^2} = -a_{m1} \frac{dy(t)}{dt} - a_{m2} y(t) + b_m f_c(t) \quad (6)$$

Where a , b , a_m , b_m are the system parameters, the control signal is f , and the command signal is f_c . The output of the MRAC controller is presented as:

$$f(t) = \mu_1 f_c(t) - \mu_2 z(t) - \mu_3 \dot{z}(t)$$

Where $\mu = [\mu_1 \quad \mu_2 \quad \mu_3]$.

The following relationships updated the controller parameters μ_1 , μ_2 , and μ_3 , on the basis of the MIT rules (Manna & Akella, 2020).

$$\begin{aligned} \frac{d\mu_1(t)}{dt} &= -\tau \left(\frac{1}{p^2 + a_{m1}p + a_{m2}} f_c(t) \right) e_r(t) \\ \frac{d\mu_2(t)}{dt} &= \tau \left(\frac{1}{p^2 + a_{m1}p + a_{m2}} z(t) \right) e_r(t) \end{aligned} \quad (7)$$

$$\frac{d\mu_3(t)}{dt} = -\tau \left(\frac{1}{p^2 + a_{m1}p + a_{m2}} \dot{z}(t) \right) \dot{e}_r(t)$$

Where $p = \frac{d}{dt}$

Lyapunov stability

Lyapunov stability, with an adaptation mechanism just like the one used for the MIT rule (Fig. 1 may be used), may be used as well for adaptive control.

The closed-loop system is expected to be defined by a differential equation:

$$\frac{dq(t)}{dt} = f(q(t)), f(0) = 0$$

Where q is the state vector. If the above equation is used for the system's dynamic, then Lyapunov-function (W), which depends on the parameters of the system, should be identified in order to satisfy the following conditions:

1. $W(q) > 0, q \neq 0$
2. $W(0) = 0$
3. W is differentiable
4. $\dot{W}(t) = \frac{\partial W}{\partial q} \dot{q}(t) \leq 0$

If W is positive definite (first and second conditions) and $\dot{W}$ is negative semi-definite (third and fourth conditions), then closed loop system becomes stable. However, the big question remains open as to how to define a function that satisfies the needs of (8).

The function W for the Lyapunov rule is [1]:

$$\begin{aligned} W(e_r, \dot{e}_r, \mu_1, \mu_2, \mu_3) &= \frac{1}{2} (\dot{e}_r)^2 + a_{m2} e_r^2 + \\ &+ \frac{1}{b\tau} (a_{m1} - a_1 - b\mu_3)^2 + \frac{1}{b\mu} (a_{m2} - a_2 - b\mu_2)^2 + \\ &+ \frac{1}{b\tau} (b\mu_1 - b_m)^2 \end{aligned}$$

With parameter adaptation:

$$\frac{d\mu_1}{dt} = -\tau \dot{f}(t) \dot{e}_r(t)$$

$$\frac{d\mu_2}{dt} = \tau z(t) \dot{e}_r(t)$$

$$\frac{d\theta_3}{dt} = \tau \dot{z}(t) \dot{e}_r(t)$$

Other Control Schemes

MRAC-MIT-PD

The PD feedback is connected to the conventional model and entire system is known as MRAC-PD. The basic block diagram of this scheme is shown below [1]. Here, it is to be noted that MRAC-PD output does not only depend on a fixed τ but also on the k_p and k_d .

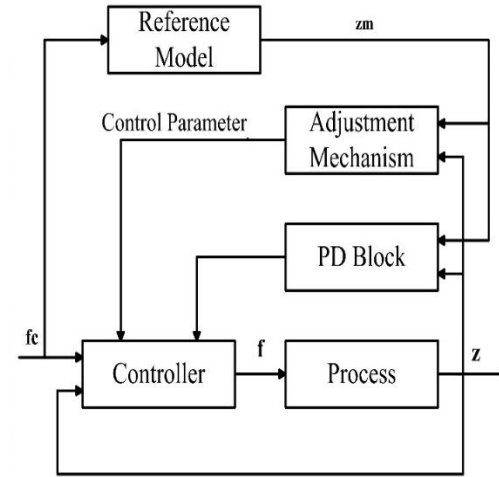


Figure 2. MRAC-PD block diagram

The Control law for this scheme is represented by,

$$f(t) = \mu_1 f_c(t) - \mu_2 z(t) - \mu_3 \dot{z}(t) - \left(k_p e_r + k_d \frac{de_r}{dt} \right)$$

Where k_p and k_d is proportional and derivative gain.

The following relationships updated the controller parameters μ_1 , μ_2 , and μ_3 , based on the MIT rules

$$\frac{d\mu_1(t)}{dt} = -\tau \left(\frac{4}{s^2 + 4s} f_c(t) \right) \dot{e}_r(t)$$

$$\frac{d\mu_2(t)}{dt} = \tau \left(\frac{4}{s^2 + 4s} z(t) \right) \dot{e}_r(t)$$

$$\frac{d\mu_3(t)}{dt} = -\tau \left(\frac{4}{s^2 + 4s} \dot{z}(t) \right) \dot{e}_r(t)$$

MRAC-Lyapunov-PD

It is the combination of PD controller and MRAC-Lyapunov approach. The Control law for this scheme is represented by,

$$f(t) = \mu_1 f_c(t) - \mu_2 z(t) - \mu_3 \dot{z}(t) - \left(k_p e_r + k_d \frac{de_r}{dt} \right)$$

The following relationships updated the controller parameters μ_1 , μ_2 , and μ_3 , based on the Lyapunov rules

$$\frac{d\mu_1}{dt} = -\tau \dot{f}(t) \dot{e}_r(t)$$

$$\frac{d\mu_2}{dt} = \tau z(t) \dot{e}_r(t)$$

$$\frac{d\theta_3}{dt} = \tau \dot{z}(t) \dot{e}_r(t)$$

MRAC-Fuzzy

A Direct fuzzy logic control (DFLC) is presented in this section in order to design the FMRAC. The basic diagram of this controller is displayed in Figure 3. The error and change in error are the DFLC input.

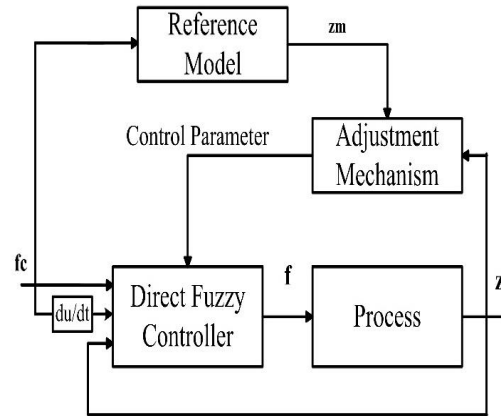


Figure 3. MRAC-Fuzzy block diagram

The variables include a limit of $[-2, 2]$ for e_r ,

$\dot{e}_r$, and $[-10, 10]$ for output are considered. For input error and change in error, three triangular membership functions are used and for output five membership functions are considered. Table 1 illustrate the rule base for DFLC (Saxena et al., 2016).

Table 1. Rule Base for DFCLC

$\begin{matrix} \bullet \\ e_r \end{matrix}$	P	Z	N
e_r			
P	PB	P	Z
Z	P	Z	N
N	Z	N	NB

The linguistic variables for FMRAC are as follows: Negative (N), Positive (P), Zero (Z), Positive Big (PB), Negative Big (NB). The adaptation law is the same as the MIT rule.

Proposed Controller

It is the combination of PD controller and Fuzzy MRAC (FMRAC) approach. A Direct fuzzy logic control (DFLC) is presented in this section in order to design the FMRAC. A proportional-derivative feedback is connected with FMRAC structure and the modified controller is known as MRAC-Fuzzy-PD. The basic diagram of the proposed controller is displayed in Figure 4. The rules that are used in MRAC-Fuzzy are used in this control scheme.

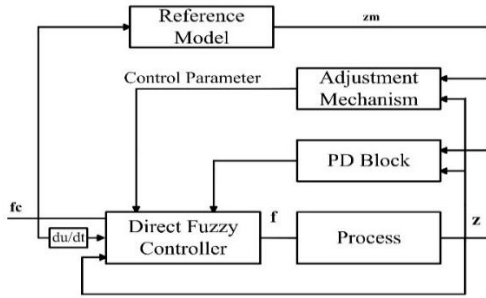


Figure 4. MRAC-FPD block diagram

The adaptation parameters are obtained from MIT rules as given in (7). Our proposed controller is able to provide an overall improvement in process response compared to other controllers.

Result and Discussion

The proposed work is validated by simulation experiments for a marginally stable SOPDT. During simulation analysis, a step input with amplitude 5 is used as a command signal. Considering the adaptation gain is fixed for all cases i.e. $\tau = 0.05$. The parameter of PD is considered as 5.2 and 1.2.

During the simulation analysis, it is observed that oscillations are detected in set-point tracking in the case of traditional MRAC based on the MIT rule. Figure 5. Shows the set point tracking of the conventional controller. The response of MRAC-Lyapunov and MRAC-Lyapunov-PD is illustrated in Figure 6 and Figure 7. The steady-state and transient response of MRAC-Fuzzy are displayed in Figure 8.

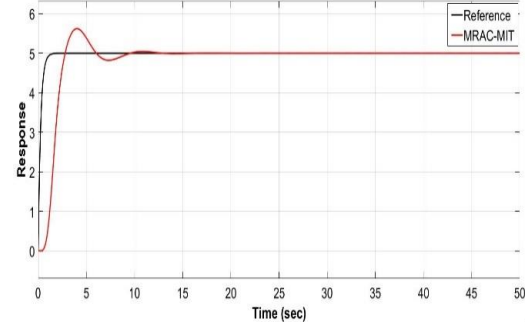


Figure 5. Steady-state and transient response for MRAC-MIT

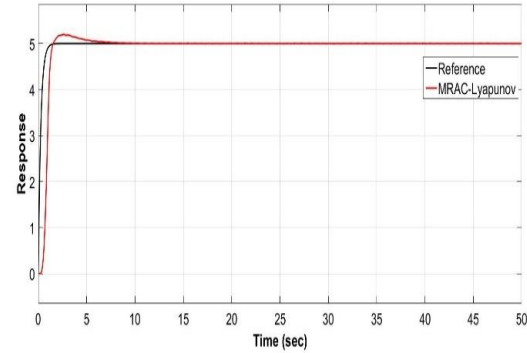


Figure 6. Steady-state and transient response for MRAC-Lyapunov

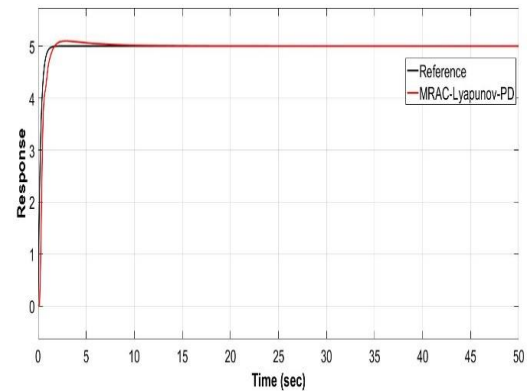


Figure 7. Steady-state and transient response for MRAC-Lyapunov-PD

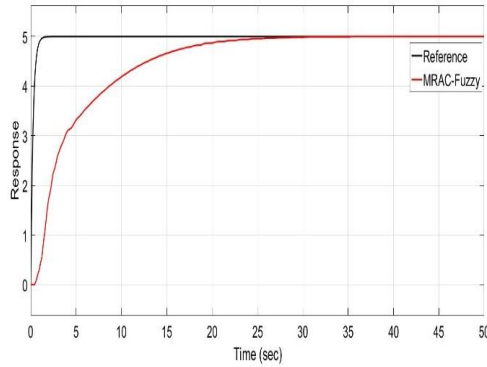


Figure 8. Steady-state and transient response for Fuzzy-MRAC

The proposed MRAC-Fuzzy-PD controller is tracking the setpoint perfectly. The outcome of the process reaches the set point smoothly. It gives a smooth response compare to other controllers. The transient and steady-state response is given in Figure 9.

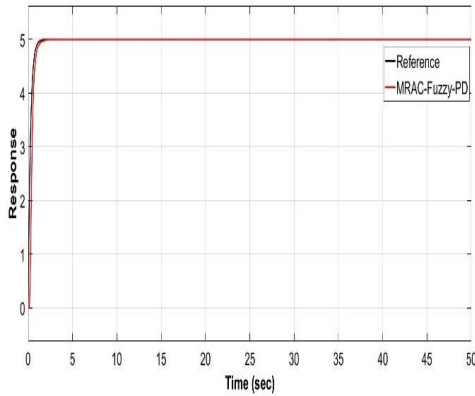


Figure 9. Transient and steady-state response for Fuzzy-MRAC-PD

Table 2 shows the set point tracking of all controllers. From this table, it is found that the proposed controller has less settling time and less rise time compare to other techniques. The MRAC-Fuzzy controller has no overshoot but it has a larger rise time. A larger rise time indicated that the process is slow.

Table 2. Set point Tracking

Controller	Settling time (sec)	Overshoot (%)	Rise Time
MRAC-MIT	15	13.068	1.424 sec
MRAC-PD	2	1.531	677.685 ms
MRAC-Lyapunov	13	3.464	644.042 ms
MRAC-Lyapunov-PD	10	1.531	762.073 ms
MRAC-Fuzzy	30	-	11.727 sec
MRAC-Fuzzy-PD	1.6	0.484	530.163 ms

Compare to other controllers, the proposed Controller has ensured the improvement in process output for second-order marginally stable second-order system through quantitative estimation of performances indices – ITAE, IAE, and ISE as displayed in Table 3.

Table 3. Performance Evaluations

Controller	ISE	IAE	ITAE
MRAC-MIT	3.662×10^{-06}	0.001914	0.09569
MRAC-PD	2.035×10^{-10}	1.427×10^{-05}	0.0007133
MRAC-Lyapunov	1.110×10^{-05}	0.001042	0.0005241
MRAC-Lyapunov-PD	1.109×10^{-10}	1.053×10^{-05}	0.0005265
MRAC-Fuzzy	3.657×10^{-06}	0.001912	0.09562
MRAC-Fuzzy-PD	9.376×10^{-11}	9.683×10^{-06}	0.0004842

It is observed that MRAC-FPD controller suggests an overall enhancement in process response during transient and steady phase. Settling time, Peak Overshoot and Rise time is reduced during set point tracking in case of proposed controller. Moreover, the proposed controller produced small ISE, IAE, and ITAE errors compared to other controllers.

Conclusion

MRAC scheme is considered very efficient for the time-varying process. A fuzzy PD feedback scheme modifies the control technique of the traditional MRAC and is analyzed over marginally stable second-order processes. The results of the simulation show clearly that the control strategy of the proposed MRAC-FPD is considerably superior to the other MRAC controllers. The proposed method indicated better performance with lower settling time, rise time, and peak overshoot during set point tracking. The MRAC-FPD controller performance is also verified with model uncertainty in terms of process dead time. The second-order marginally stable process provides considerably better performance for the proposed MRAC-Fuzzy-PD than the other controllers for the same reference model as supported by various performance indices ITAE, ISE, and IAE.

REFERENCES

Flores-Pérez A., Grave I., and Tang Y., "Comparative analysis of passive algorithms in adaptive control,"

- Int. J. Adapt. Control Signal Process.*, vol. 28, no. 10, pp. 1043–1053, 2014.
- Morse A. S., “Global stability of parameter adaptive control systems,” *IEEE Trans. Automat. Control*, vol. AC-25, no. 3, pp. 433–439, Jun. 1980.
- Serrani A., “An output regulation perspective on the model reference adaptive control problem,” *Int. J. Adapt. Control Signal Process.*, vol. 27, no. 1–2, pp. 22–34, 2013.
- Nguyen A. T., Rafiq M. S., Choi H. H. and Jung J., “A Model Reference Adaptive Control Based Speed Controller for a Surface-Mounted Permanent Magnet Synchronous Motor Drive,” in *IEEE Transactions on Industrial Electronics*, vol. 65, no. 12, pp. 9399–9409, Dec. 2018, doi: 10.1109/TIE.2018.2826480.
- Astolfi A., Karagiannis D., and Ortega R., *Nonlinear and Adaptive Control With Applications*. New York, NY, USA: Springer-Verlag, 2008.
- Wang C. and Lin Y., “Multivariable adaptive backstepping control: A norm estimation approach,” *IEEE Trans. Automat. Control*, vol. 57, no. 4, pp. 989–995, Apr. 2012.
- Lavretsky E. and Wise K.A., *Robust and Adaptive Control With Aerospace Applications*. New York, NY, USA: Springer, 2013.
- Goodwin G. C. and Mayne D. Q., “A parameter estimation perspective of continuous time model reference adaptive control,” *Automatica*, vol. 23, no. 1, pp. 57–70, 1987.
- Tao G., “Multivariable adaptive control: A survey,” *Automatica*, vol. 50, no. 11, pp. 2737–2764, Nov. 2014.
- Tao G., *Adaptive Control Design and Analysis*. Hoboken, NJ, USA: Wiley, 2003.
- Landau I., Lozano R., M’Saad M., and Karimi A., “Adaptive Control: Algorithms, Analysis and Applications,” Second Edition, Springer-Verlag, London, 2011.
- Hoagg J. B. and Bernstein D. S., “Retrospective cost model reference adaptive control for nonminimum-phase systems,” *J. Guid., Control, Dyn.*, vol. 35, no. 6, pp. 1767–1786, 2012.
- Astrom K. and Wittenmark B., “Adaptive Control,” Courier-Dover, USA, 2008.
- Astrom K., Kumar P.-R., “Control: A Perspective,” *Journal of IFAC - The International Federation of Automatic Control*, Elsevier, vol. 50, no.1, pp.1-43, January 2014.
- Narendra K. S. and Annaswamy A. M., *Stable Adaptive Systems*. Englewood Cliffs, NJ, USA: Prentice-Hall, 1989.
- Tsakalis K. and Ioannou P. A., *Linear Time Varying Systems: Control and Application*. Englewood Cliffs, NJ, USA: Prentice-Hall, 1993.
- Xin L. et al., “Model Reference Adaptive Control for Aortic Pressure Regulation in Ex Vivo Heart Perfusion,” in *IEEE Transactions on Control Systems Technology*, vol. 29, no. 2, pp. 884–892, March 2021, doi: 10.1109/TCST.2020.2978448.
- Stefanovic M. and Safonov M. G., *Safe Adaptive Control: Data-Driven Stability Analysis and Robust Synthesis*. London, U.K.: Springer, 2011.
- Hovakimyan N. and Cao C., *L1 Adaptive Control Theory: Guaranteed Robustness With Fast Adaptation*. Philadelphia, PA, USA: Soc. Ind. Appl. Math., 2010.
- Ioannou P. A. and Sun J., *Robust Adaptive Control*. Englewood Cliffs, NJ, USA: Prentice-Hall, 1996.
- Ioannou P., and Fidan B., “Adaptive Control Tutorial,” Society for Industrial and Applied Mathematics, USA, 2006;
- Saxena P., Gaur P. and Yadav A. K., “A comparative analysis between MRAC and FMRAC for an unstable system,” 2016 3rd International Conference on Computing for Sustainable Global Development (INDIACom), New Delhi, 2016, pp. 2449–2455.
- Ortega R., Hsu L., and Astolfi A., “Immersion and invariance adaptive control of linear multivariable systems,” *Syst. Control Lett.*, vol. 49, no. 1, pp. 37–47, 2003.
- Sengupta R., Dey C. (2017) Design and Performance Analysis of a Modified MRAC for Second-Order Integrating Processes. In: Mandal J., Dutta P., Mukhopadhyay S. (eds) Computational Intelligence, Communications, and Business Analytics. CICBA 2017. Communications in Computer and Information Science, vol 775. Springer, Singapore. https://doi.org/10.1007/978-981-10-6427-2_37
- Jingzhuo S. and Huang W., “Model Reference Adaptive Iterative Learning Speed Control for Ultrasonic Motor,” in *IEEE Access*, vol. 8, pp. 181815–181824, 2020, doi: 10.1109/ACCESS.2020.3029106.
- Manna S. and Akella A. K., “Designing of an updated MRAC with PD Feedback for Marginally Stable Second-order process with Dead Time,” 2020 IEEE 5th International Conference on Computing Communication and Automation (ICCCA), Greater Noida, India, 2020, pp. 63–66, doi: 10.1109/ICCCA49541.2020.9250754.
- Sastry S. and Bodson M., *Adaptive Control: Stability, Convergence, and Robustness*. Englewood Cliffs, NJ, USA: Prentice-Hall, 1989.
- Yucelen T. and Haddad W. M., “Low-frequency learning and fast adaptation in model reference adaptive control,” *IEEE Trans. Automat. Control*, vol. 58, no. 4, pp. 1080–1085, Apr. 2013.
- Black W., Haghi P., and Ariyur K., “Adaptive Systems: History, Techniques, Problems and Perspectives,” *Systems*, pp. 606–660, November 2014.
- Levine W.-S., “Control System Advanced Methods,” CRC Press, USA 2011.
- Chen X., Feng Y., and Su C., “Adaptive control for continuous-time systems with actuator and sensor hysteresis,” *Automatica*, vol. 64, pp. 196–207, 2016.
- Landau Y. D., Lozano R., M’Saad M., and Karimi A., *Adaptive Control: Algorithms, Analysis and Applications*, 2nd ed. London, U.K.: Springer, 2011.

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DESIGNING OF A MRAC-FUZZY WITH PD FEEDBACK FOR marginally STABLE SECOND-ORDER SYSTEM WITH DEAD TIME

Saibal Manna^{1,*}, Deepak Kumar Singh² and Ashok Kumar Akella³
Abstract

The performance of a traditional controller with fixed tuning is unsatisfactory for time-varying systems. This drawback can be resolved by using adaptive controllers, as their control parameters can be changed in accordance with change in process dynamics. This research presents a model reference adaptive controller (MRAC) for controlling a nonlinear system through a network, subject to a time delay caused by a variable network. In MRAC, the controller outcome relies on the difference between actual process and reference model outcome with fixed adaptation gain. The desired requirements of the process outcome are given as a reference model. The main aim is to find further improvement of the traditional MRAC method and provide more accurate control to the marginally stable second-order process with dead time (MS-SOPDT) and minimize drawbacks of the traditional MRAC method. Here, a novel MRAC-Fuzzy based PD feedback (MRAC-FPD) control technique is proposed for MS-SOPDT. This paper also provides a comparative analysis of different MRAC strategies like MRAC-MIT, MRAC-PD, MRAC-Lyapunov, MRAC-Lyapunov-PD, MRAC-Fuzzy. Compared to other techniques, the proposed MRAC-Fuzzy-PD gives better response. This controller offers improved set point tracking with fewer oscillations and fast response. This fact is also verified by the use of different performance indices such as integral time absolute error (ITAE), integral square error (ISE), and integral absolute error (IAE) under closed-loop conditions. These methods are demonstrated with the help of MATLAB/Simulink.

Keywords: Lyapunov, Marginally stable, MRAC, MRAC-Fuzzy, MRAC-Fuzzy-PD, Second Order Process

Introduction

The aerospace engineers searched for a solution in the 1950s for the design of autopilots. The key goal was to identify a controller that could operate best in-flight conditions. An intensive study in the adaptive area had then begun, to lead to the development of such a controller. An innovative controller was developed to deliver high performances, like an adaptive controller (Manna & Akella, 2020). On this basis, multiple adaptive flight control techniques have been proposed, and the one proposed by Whitaker et al., which is known most commonly in various publications (Astrom & Wittenmark, 2008; Astrom & Kumar, 2014; Ioannou & Fidan, 2006; Landau et al., 2011). The Whitaker method that is still used in recent days is referred to as the MRAC and the approach that can fix the autopilot problem (Astrom & Wittenmark, 2008; Ioannou & Fidan, 2006; Landau et al., 2011). The outcomes are outlined very well in (Astrom & Wittenmark, 2008; Astrom & Kumar, 2014; Levine, 2011). This technique was initially based only on the gradient method, and was named 'MIT rule'. This rule called for the automated parameter modification of the controller to be similar to that of the reference model (Astrom & Kumar, 2014; Ioannou & Fidan, 2006). In addition, by using Lyapunov stability (Astrom & Wittenmark, 2008; Astrom & Kumar, 2014; Ioannou & Fidan, 2006; Black et al., 2014), Park improved the MRAC method in the 1960s.

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MRAC, a significant branch of adaptive control, was closely investigated and its design technology and theories were systematically and effectively evolved to achieve maturity. A core advantage of MRAC is that the closed-loop control mechanism complies with the reference model, ensuring accurate matching of the plant model with nominal parameters determined from plant parameters, and achieving asymptotic performance monitoring using adaptive parameters modified by adaption laws to approximate nominal parameters. A broad range of MRAC literature presented (i.e., basic adaptive control theory (Morse, 1980; Goodwin & Mayne, 1987; Narendra & Annaswamy, 1989; Sastry & Bodson, 1989; Ioannou & Sun, 1996; Tao, 2003), providing the complete proof of MRAC characteristics such as stability, tracking, and matching; see (Tao, 2014) which involves an analysis of some representative MRAC references). Tremendous efforts, improvement, and outcomes on tracking and stability of the various adaptive control system (i.e., few advanced adaptive control book (Tsakalis & Ioannou, 1993; Astolfi et al. 2008; Hovakimyan & Cao, 2010; Landau et al., 2011; Stefanovic & Safonov, 2011; Lavretsky & Wise, 2013), and few extended adaptive control paper (Ortega et al., 2003; Wang & Lin, 2012; Hoagg & Bernstein, 2012; Yucelen & Haddad, 2013; Serrani, 2013; Flores-Perez et al., 2014; Chem et al., 2016) have also been developed, for the study of MRAC's basic properties, its robustness in system modelling errors such as parameter variation and unmodeled dynamics, external disturbances, and effect of design parameters. A MRAC based speed controller (MRAC-SC) is designed for a surface-mounted permanent magnet synchronous motor drive. The proposed controller gives better performance compared to the non-adaptive model reference speed controller and traditional proportional-integral SC in terms of good tracking, fast transient response, and robustness against parameter uncertainties (Nguyen et al., 2018). A new control strategy is presented which is the combination of MRAC and iterative learning control. This control strategy is used to speed control of ultrasonic motor (Jingzhuo & Huang, 2020). A MRAC is presented for aortic pressure regulation and maintaining the heart's physiological aerobic metabolism in ex vivo heart perfusion (Xin et al., 2021). A MRAC-PD controller is designed for second-order integrating processes (Sengupta and Dey, 2017). This controller ensures improved response compared to traditional MRAC.

This article proposed a novel MRAC-Fuzzy based PD feedback control technique for MS-SOPDT and provides a comparative analysis of different MRAC strategies like MRAC-MIT, MRAC-PD, MRAC-Lyapunov, MRAC-Lyapunov-PD, MRAC-Fuzzy. The proposed control scheme provides better results compared to other techniques. Following is the outline of this article. The system description is explained in Section II. Section III describes the MRAC scheme with MIT rule and Lyapunov theory. Section III presents the other control scheme. Section IV displays the proposed control scheme. Section V presents the simulation results and discussions. Section VI introduces the conclusion of the paper.

System Description

This research is focused on a MS-SOPDT. Marginally stable systems, which have poles on the imaginary axis. In this case, system have sinusoidal oscillations, with a constant amplitude. The mentioned control scheme is validated by means of a simulation for a MS-SOPDT given below (Manna & Akella, 2020).

$$G(s) = \frac{4}{s(s+4)} e^{-0.1s} \quad (1)$$

The following reference model provides desired process performance specification.

$$G_m(s) = \frac{4}{s+4} \quad (2)$$

MRAC

The MRAC is a control system that provides desired parameters as a reference model. The basic MRAC diagram is displayed in Figure 1. It generally comprises of two loops; the inner loop is used to control normal feedback and the outer loop is used for adjusting the controller parameter. The outcome is compared between process and reference model and the error between models are provided as feedback through the parameter adjustment loop. The controller parameters are modified

8

to minimize the error until it becomes zero. To implement the MRAC, there are primarily two methods, namely, the Lyapunov theory and the MIT rule.

$$e_r = z - z_m \quad (3)$$

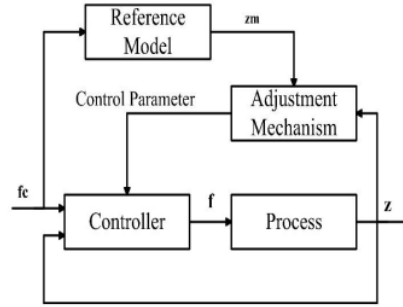


Figure1. MRAC block diagram [1]

MIT rule

2

The underlying principle behind this rule is to identify a minimization criterion to update controller parameters such that the error is minimized to zero. If the parameter vector is μ and e_r is the error, the selected cost function is

$$J(\mu) = \frac{e_r^2}{2} \quad (4)$$

2

It is important to change parameters in the form of a negative gradient. In those circumstances, Criterion J becomes small:

$$\frac{d\mu}{dt} = -\tau \frac{\partial J}{\partial \mu} = -\tau e_r \frac{\partial e_r}{\partial \mu}$$

Where τ and $\frac{\partial e_r}{\partial \mu}$ are adaptation gain and sensitivity respectively.

The process and reference model are considered as:

$$\frac{d^2 y(t)}{dt^2} = -a_1 \frac{dy(t)}{dt} - a_2 y(t) + b f(t) \quad (5)$$

$$\frac{d^2 y_m(t)}{dt^2} = -a_{m1} \frac{dy(t)}{dt} - a_{m2} y(t) + b_m f_c(t) \quad (6)$$

Where a , b , a_m , b_m are the system parameters, the control signal is f , and the command signal is f_c . The output of the MRAC controller is presented as:

$$f(t) = \mu_1 f_c(t) - \mu_2 z(t) - \mu_3 \dot{z}(t)$$

Where $\mu = [\mu_1 \quad \mu_2 \quad \mu_3]$.

The following relationships updated the controller parameters μ_1 , μ_2 , and μ_3 , on the basis of the MIT rules (Manna & Akella, 2020).

$$\begin{aligned} \frac{d\mu_1(t)}{dt} &= -\tau \left(\frac{1}{p^2 + a_{m1}p + a_{m2}} f_c(t) \right) e_r(t) \\ \frac{d\mu_2(t)}{dt} &= \tau \left(\frac{1}{p^2 + a_{m1}p + a_{m2}} z(t) \right) e_r(t) \end{aligned} \quad (7)$$

$$\frac{d\mu_3(t)}{dt} = -\tau \left(\frac{1}{p^2 + a_{m1}p + a_{m2}} \dot{z}(t) \right) \dot{e}_r(t)$$

Where $p = \frac{d}{dt}$

Lyapunov stability ²

Lyapunov stability, with an adaptation mechanism just like the one used for the MIT rule (Fig. 1 may be used), may be used as well for adaptive control.

The closed-loop system is expected to be defined ¹ a differential equation:

$$\frac{dq(t)}{dt} = f(q(t)), f(0) = 0$$

Where q is the state vector. If the above equation is used for the system's dynamic, then Lyapunov-function (W), which depends on the parameters of the system, should be identified in order to satisfy the following conditions:

1. $W(q) > 0, q \neq 0$
2. $W(0) = 0$
3. W is differentiable (8)
4. $\dot{W}(t) = \frac{\partial W}{\partial q} \dot{q}(t) \leq 0$

If W is positive definite (first and second conditions) and $\dot{W}$ is negative semi-definite (third and fourth conditions), then closed loop system becomes stable. However, the big question remains open as to how to define a function that satisfies the needs of (8).

The function W for the Lyapunov rule is [1]:

$$W(e_r, \dot{e}_r, \mu_1, \mu_2, \mu_3) = \frac{1}{2} (\dot{e}_r(t) + a_{m2} e_r^2(t) + \frac{1}{b\tau} (a_{m1} - a_1 - b\mu_3)^2 + \frac{1}{b\mu} (a_{m2} - a_2 - b\mu_2)^2 + \frac{1}{b\tau} (b\mu_1 - b_m)^2)$$

With parameter adaptation:

$$\begin{aligned} \frac{d\mu_1}{dt} &= -\tau \dot{e}_r(t) \dot{e}_r(t) \\ \frac{d\mu_2}{dt} &= \tau \dot{e}_r(t) \dot{e}_r(t) \\ \frac{d\theta_3}{dt} &= \tau \dot{z}(t) \dot{e}_r(t) \end{aligned} \quad (9)$$

Other Control Schemes

MRAC MIT-PD ¹

The PD feedback is connected to the conventional model and entire system is known as ⁴ RAC-PD. The basic block diagram of this scheme is shown below [1]. Here, it is to be noted that MRAC-PD output does not only depend on a fixed τ but also on the k_p and k_d .

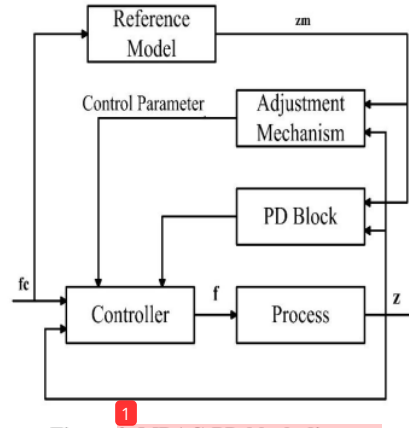


Figure 2. MRAC-PD block diagram

The Control law for this scheme is represented by,

$$f(t) = \mu_1 f_c(t) - \mu_2 z(t) - \mu_3 \dot{z}(t) - \left(k_p e_r + k_d \frac{de_r}{dt} \right)$$

Where k_p and k_d is proportional and derivative gain.

The following relationships updated the controller parameters μ_1 , μ_2 , and μ_3 , based on the MIT rules

$$\begin{aligned} \frac{d\mu_1(t)}{dt} &= -\tau \left(\frac{4}{s^2 + 4s} f_c(t) \right) e_r(t) \\ \frac{d\mu_2(t)}{dt} &= \tau \left(\frac{4}{s^2 + 4s} z(t) \right) e_r(t) \\ \frac{d\mu_3(t)}{dt} &= -\tau \left(\frac{4}{s^2 + 4s} \dot{z}(t) \right) e_r(t) \end{aligned}$$

MRAC-Lyapunov-PD

It is the combination of PD controller and MRAC-Lyapunov approach. The Control law for this scheme is represented by,

$$f(t) = \mu_1 f_c(t) - \mu_2 z(t) - \mu_3 \dot{z}(t) - \left(k_p e_r + k_d \frac{de_r}{dt} \right)$$

The following relationships updated the controller parameters μ_1 , μ_2 , and μ_3 , based on the Lyapunov rules

$$\begin{aligned} \frac{d\mu_1}{dt} &= -\tau f(t) e_r(t) \\ \frac{d\mu_2}{dt} &= \tau z(t) e_r(t) \end{aligned}$$

$$\frac{d\theta_3}{dt} = \tau \dot{z}(t) \dot{e}_r(t)$$

MRAC-Fuzzy

A Direct fuzzy logic control (DFLC) is presented in this section in order to design the FMRAC. The basic diagram of this controller is displayed in Figure 3. The error and change in error are the DFLC input.

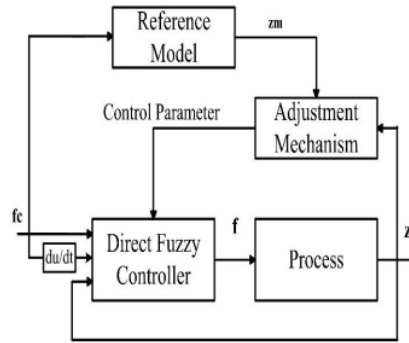


Figure 3. MRAC-Fuzzy block diagram

The variables include a limit of $[-2, 2]$ for e_r , $[-4, 4]$ for $\dot{e}_r$, and $[-10, 10]$ for output are considered. For input error and change in error, three triangular membership functions are used and for output five membership functions are considered. Table 1 illustrate the rule base for DFLC (Saxena et al., 2016).

Table 1. Rule Base for DFLC

$\begin{matrix} \dot{e}_r \\ e_r \end{matrix}$		13			
		P	Z	N	
P		PB	P	Z	
Z		P	Z	N	
N		Z	N	NB	

The linguistic variables for FMRAC are as follows: Negative (N), Positive (P), Zero (Z), Positive Big (PB), Negative Big (NB). The adaptation law is the same as the MIT rule.

Proposed Controller

It is the combination of PD controller and Fuzzy MRAC (FMRAC) approach. A Direct fuzzy logic control (DFLC) is presented in this section in order to design the FMRAC. A proportional-derivative feedback is connected with FMRAC structure and the modified controller is known as MRAC-Fuzzy-PD. The basic diagram of the proposed controller is displayed in Figure 4. The rules that are used in MRAC-Fuzzy are used in this control scheme.

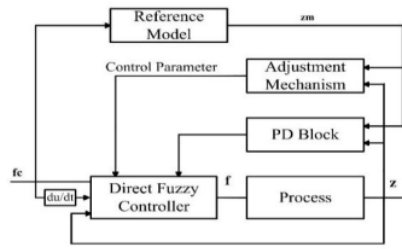


Figure 4. MRAC-FPD block diagram

The adaptation parameters are obtained from MIT rules as given in (7). Our proposed controller is able to provide an overall improvement in process response compared to other controllers.

Result and Discussion

The proposed work is validated by simulation experiments for a marginally stable SOPDT. During simulation analysis, a step input with amplitude 5 is used as a command signal. Considering the adaptation gain is fixed for all cases i.e. $\tau = 0.05$. The parameter of PD is considered as 5.2 and 1.2.

During the simulation analysis, it is observed that oscillations are detected in the case of traditional MRAC based on the MIT rule. Figure 5. Shows the set point tracking of the conventional controller. The response of MRAC-Lyapunov and MRAC-Lyapunov-PD is illustrated in Figure 6 and Figure 7. The steady-state and transient response of MRAC-Fuzzy are displayed in Figure 8.

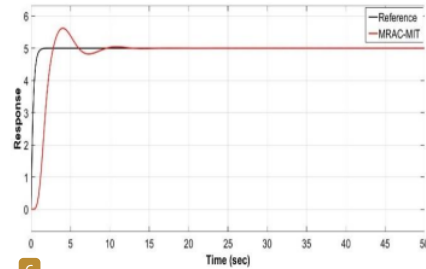


Figure 5. Steady-state and transient response for MRAC-MIT

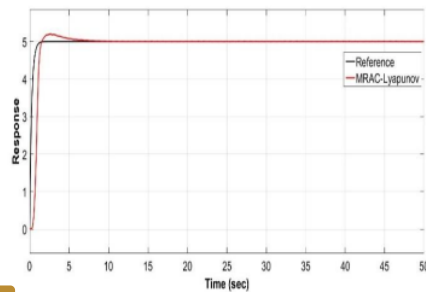
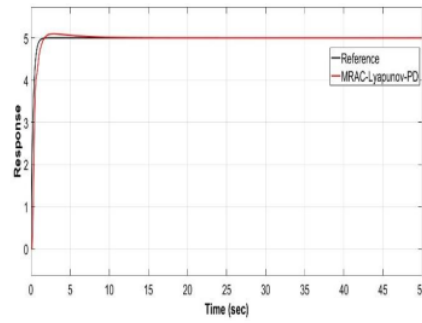
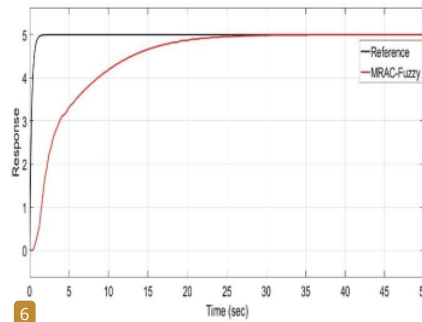


Figure 6. Steady-state and transient response for MRAC-Lyapunov

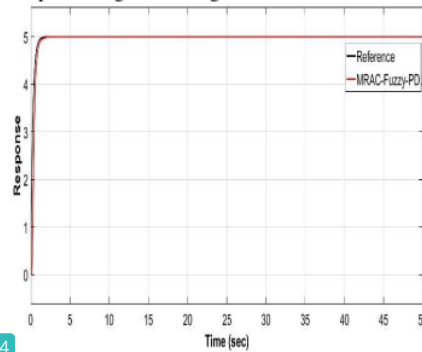


6
Figure 7. Steady-state and transient response for MRAC-Lyapunov-PD



6
Figure 8. Steady-state and transient response for Fuzzy-MRAC

The proposed MRAC-Fuzzy-PD controller is tracking the setpoint perfectly. The outcome of the process reaches the set point smoothly. It gives a smooth response compare to other controllers. The transient and steady-state response is given in Figure 9.



4
Figure 9. Transient and steady-state response for Fuzzy-MRAC-PD

Table 2 shows the set point tracking of all controllers. From this table, it is found that the proposed controller has less settling time and less rise time compare to other techniques. The MRAC-Fuzzy controller has no overshoot but it has a larger rise time. A larger rise time indicated that the process is slow.

Table 2. Set point Tracking

Controller	Settling time (sec)	Overshoot (%)	Rise Time
MRAC-MIT	15	13.068	1.424 sec
MRAC-PD	2	1.531	677.685 ms
MRAC-Lyapunov	13	3.464	644.042 ms
MRAC-Lyapunov-PD	10	1.531	762.073 ms
MRAC-Fuzzy	30	-	11.727 sec
MRAC-Fuzzy-PD	1.6	0.484	530.163 ms

Compare to other controllers, the proposed Controller has ensured the improvement in process output for second-order marginally stable second-order system through quantitative estimation of performances indices – ITAE, IAE, and ISE as displayed in Table 3.

Table 3. Performance Evaluations

Controller	ISE	IAE	ITAE
MRAC-MIT	3.662×10^{-06}	0.001914	0.09569
MRAC-PD	2.035×10^{-10}	1.427×10^{-05}	0.0007133
MRAC-Lyapunov	1.110×10^{-05}	0.001042	0.0005241
MRAC-Lyapunov-PD	1.109×10^{-10}	1.053×10^{-05}	0.0005265
MRAC-Fuzzy	3.657×10^{-06}	0.001912	0.09562
MRAC-Fuzzy-PD	9.376×10^{-11}	9.683×10^{-06}	0.0004842

It is observed that MRAC-FPD controller suggests an overall enhancement in process response during transient and steady phase. Settling time, Peak Overshoot and Rise time is reduced during set point tracking in case of proposed controller. Moreover, the proposed controller produced small ISE, IAE, and ITAE errors compared to other controllers.

Conclusion

MRAC scheme is considered very efficient for the time-varying process. A fuzzy PD feedback scheme modifies the control technique of the traditional MRAC and is analyzed over marginally stable second-order processes. The results of the simulation show clearly that the control strategy of the proposed MRAC-FPD is considerably superior to the other MRAC controllers. The proposed method indicated better performance with lower settling time, rise time, and peak overshoot during set point tracking. The MRAC-FPD controller performance is also verified with model uncertainty in term of process dead time. The second-order marginally stable process provides considerably better performance for the proposed MRAC-Fuzzy-PD than the other controllers for the same reference model as supported by various performance indices ITAE, ISE, and IAE.

REFERENCES

- Flores-Pérez A., Grave I., and Tang Y., "Comparative analysis of passive algorithms in adaptive control," *Int. J. Adapt. Control Signal Process.*, vol. 28, no. 10, pp. 1043–1053, 2014.
- Morse A. S., "Global stability of parameter adaptive control systems," *IEEE Trans. Automat. Control*, vol. AC-25, no. 3, pp. 433–439, Jun. 1980.
- Serani A., "An output regulation perspective on the model reference adaptive control problem," *Int. J. Adapt. Control Signal Process.*, vol. 27, no. 1–2, pp. 22–34, 2013.

- Nguyen A. T., Rafiq M. S., Choi H. H. and Jung J., "A Model Reference Adaptive Control Based Speed Controller for a Surface-Mounted Permanent Magnet Synchronous Motor Drive," in *IEEE Transactions on Industrial Electronics*, vol. 65, no. 12, pp. 9399-9409, Dec. 2018, doi: 10.1109/TIE.2018.2826480.
- Astolfi A., Karagiannis D., and Ortega R., *Nonlinear and Adaptive Control With Applications*. New York, NY, USA: Springer-Verlag, 2008.
- Wang C. and Lin Y., "Multivariable adaptive backstepping control: A norm estimation approach," *IEEE Trans. Automat. Control*, vol. 57, no. 4, pp. 989-995, Apr. 2012.
- Lavretsky E. and Wise K.A., *Robust and Adaptive Control With Aerospace Applications*. New York, NY, USA: Springer, 2013.
- Goodwin G. C. and Mayne D. Q., "A parameter estimation perspective of continuous time model reference adaptive control," *Automatica*, vol. 23, no. 1, pp. 57-70, 1987.
- Tao G., "Multivariable adaptive control: A survey," *Automatica*, vol. 50, no. 11, pp. 2737-2764, Nov. 2014.
- Tao G., *Adaptive Control Design and Analysis*. Hoboken NJ, USA: Wiley, 2003.
- Landau I., Lozano R., M'Saad M., and Karimi A., "Adaptive Control: Algorithms, Analysis and Applications," Second Edition, Springer-Verlag, London, 2011.
- Hoagg J. B. and Bernstein D. S., "Retrospective cost model reference adaptive control for nonminimum-phase systems," *J. Guid., Control, Dyn.*, vol. 35, no. 6, pp. 1767-1786, 2012.
- Astrom K. and Wittenmark B., "Adaptive Control," Courier-Dover, USA, 2008.
- Astrom K., Kumar P.-R., "Control: A Perspective," *Journal of IFAC - The International Federation of Automatic Control*, Elsevier, vol. 50, no. 1, pp. 1-43, January 2014.
- Narendra K. S. and Annaswamy A. M., *Stable Adaptive Systems*. Englewood Cliffs, NJ, USA: Prentice-Hall, 1989.
- Tsakalis K. and Ioannou P. A., *Linear Time Varying Systems: Control and Application*. Englewood Cliffs, NJ, USA: Prentice-Hall, 1993.
- Xin L., et al., "Model Reference Adaptive Control for Aortic Pressure Regulation in Ex Vivo Heart Perfusion," in *IEEE Transactions on Control Systems Technology*, vol. 29, no. 2, pp. 884-892, March 2021, doi: 10.1109/TCST.2020.2978448.
- Stefanovic M. and Safonov M. G., *Safe Adaptive Control: Data-Driven Stability Analysis and Robust Synthesis*. London, U.K.: Springer, 2011.
- Hovakimyan N. and Cao C., *L1 Adaptive Control Theory: Guaranteed Robustness With Fast Adaptation*. Philadelphia, PA, USA: Soc. Ind. Appl. Math., 2010.
- Ioannou P. A. and Sun J., *Robust Adaptive Control*. Englewood Cliffs, NJ, USA: Prentice-Hall, 1996.
- Ioannou P., and Fidan B., "Adaptive Control Tutorial," Society for Industrial and Applied Mathematics, USA, 2006;
- Saxena P., Gaur P. and Yadav A. K., "A comparative analysis between MRAC and FMRAC for an unstable system," 2016 3rd International Conference on Computing for Sustainable Global Development (INDIACom), New Delhi, 2016, pp. 2449-2455.
- Ortega R., Hsu L., and Astolfi A., "Immersion and invariance adaptive control of linear multivariable systems," *Syst. Control Lett.*, vol. 49, no. 1, pp. 37-47, 2003.
- Sengupta R., Dey C. (2017) Design and Performance Analysis of a Modified MRAC for Second-Order Integrating Processes. In: Mandal J., Dutta P., Mukhopadhyay S. (eds) *Computational Intelligence, Communications, and Business Analytics. CICBA 2017. Communications in Computer and Information Science*, vol 775. Springer, Singapore. https://doi.org/10.1007/978-981-10-6427-2_37
- Jingzhuo S. and Huang W., "Model Reference Adaptive Iterative Learning Speed Control for Ultrasonic Motor," in *IEEE Access*, vol. 8, pp. 181815-181824, 2020, doi: 10.1109/ACCESS.2020.3029106.
- Manna S. and Akella A. K., "Designing of an updated MRAC with PD Feedback for Marginally Stable Second-order process with Dead Time," 2020 IEEE 5th International Conference on Computing Communication and Automation (ICCCA), Greater Noida, India, 2020, pp. 63-66, doi: 10.1109/ICCCA49541.2020.9250754.
- Sastry S. and Bodson M., *Adaptive Control: Stability, Convergence, and Robustness*. Englewood Cliffs, NJ, USA: Prentice-Hall, 1989.
- Yucelen T. and Haddad W. M., "Low-frequency learning and fast adaptation in model reference adaptive control," *IEEE Trans. Automat. Control*, vol. 58, no. 4, pp. 1080-1085, Apr. 2013.
- Black W., Haghi P., and Ariyur K., "Adaptive Systems: History, Techniques, Problems and Perspectives," *Systems*, pp. 606-660, November 2014.
- Levine W.-S., "Control System Advanced Methods," CRC Press, USA 2011.
- Chen X., Feng Y., and Su C., "Adaptive control for continuous-time systems with actuator and sensor hysteresis," *Automatica*, vol. 64, pp. 196-207, 2016.
- Landau Y. D., Lozano R., M'Saad M., and Karimi A., *Adaptive Control: Algorithms, Analysis and Applications*, 2nd ed. London, U.K.: Springer, 2011.

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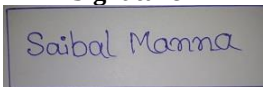
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