International Journal of Applied Engineering Research
ISSN 0973-4562 Volume 20, Number 3 (2025) pp. 581-592

http://www.ripublication.com

Performance Evaluation of Fuzzy Logic Controller in Tracking Control of a Single-Mass Rotary System

N. Hasim [1]*, M. A. S. M. Nizam [1], M. F. Basar [1], M. R. Ghazali [2] and M. M. Ghazaly [1]

[1] *Faculty of Electrical Technology and Engineering, Universiti Teknikal Malaysia Melaka (UTeM), Malaysia*

[2] *Faculty of Electrical and Electronics Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah (UMPSA), Malaysia*
**Correspondence: Correspondence author*

Abstract

Tracking control is a crucial procedure for machining equipment in the manufacturing sector, particularly in ensuring effective unmanned plant operations. The single-mass rotary system driven by a direct current (DC) motor is often employed as the fundamental apparatus in such applications. This study evaluates the tracking performance of a DC motor-based rotary system using a Fuzzy Logic Controller (FLC) and compares it with a conventional Proportional–Integral–Derivative (PID) controller, which is widely adopted in industry due to its high performance and simplicity. Both controllers were designed and developed using MATLAB Simulink R2015b. To assess tracking performance, sinusoidal reference inputs at three different frequencies (0.3 Hz, 0.5 Hz, and 0.7 Hz) were applied for angular positions of 45°. The findings demonstrated that the FLC achieves superior tracking performance compared to the PID controller, highlighting its potential as an effective intelligent control approach for rotary systems.

Keywords: Fuzzy Logic Controller (FLC); Single-Mass Rotary System; Tracking Control; Proportional–Integral–Derivative (PID) Controller; MATLAB/Simulink; Simulation Validation.

Introduction

In the automation sector, large and intricate machinery is employed in real-time applications to support and facilitate daily production. These systems often integrate hardware and software components to perform complex operations. However, the operation of such machinery can sometimes be challenging due to its complexity. To address this, researchers and engineers continuously innovate to simplify and improve tracking control methods for industrial equipment.

One of the key advantages of real-time tracking and monitoring is the ability to respond quickly in the event of production errors. Furthermore, by incorporating preventive measures and safety precautions during design and manufacturing, the overall reliability of machines can be enhanced [1]. This approach helps minimize production disruptions and significantly reduces the time and cost associated with equipment repair. Sensors and actuators play a critical role in tracking and monitoring these machines, as they continuously collect, process, and manage input data within the system. In this study, the DC servo motor—also referred to as a rotary actuator—serves as the primary actuator.

Over time, the performance of conventional controllers may deteriorate [1]. Controllers are generally categorized into conventional and intelligent types. Conventional controllers include proportional (P), integral (I), derivative (D), proportional–integral (PI), proportional–derivative (PD), and proportional–integral–derivative (PID) controllers [2]. An effective controller is typically characterized by fast response, minimal overshoot, and low steady-state error [2]. PID controllers are widely used in industrial applications due to their ability to respond quickly to changes in system dynamics. They achieve this by adjusting the control signal according to the error between the actual and desired positions, as well as the rate of change of error. Nevertheless, uncertainties and external disturbances affecting system dynamics can degrade PID controller performance. To overcome these challenges, optimization methods are often applied to tune the controller's parameters and improve performance [3].

In contrast, fuzzy logic controllers (FLCs) provide a flexible and intuitive framework for control system design. By incorporating linguistic variables and expert knowledge, FLCs can handle system uncertainties and imprecise information. Unlike classical logic, which relies on binary values of 0 or 1, fuzzy logic evaluates input variables using continuous values between 0 and 1. This mathematical framework forms the foundation of fuzzy control systems [4]. With its human-like reasoning and systematic rule-based structure, fuzzy logic is capable of translating expert knowledge into effective automatic control strategies. Due to these strengths, FLCs have been proven suitable for position control applications, offering a versatile and user-friendly solution for managing uncertainties and inaccuracies [5]. This study aims to investigate the tracking control performance of a single-mass rotary system through a simulation study, with a specific emphasis on comparing FLC and PID controllers.

Literature Review

Introduction

In control systems, the output of a closed-loop configuration is continuously measured and compared with the desired reference input to minimize error and maintain stability [6]. The feedback signal is generated by sensors, which act as measurement devices, and is compared with the reference input to produce an error signal. This error is then processed by the controller, whose role is to generate the appropriate control action to reduce the deviation from the desired output [6], [7]. The actuating signal generated by the controller is subsequently fed to the plant, thus closing the loop. A generic closed-loop block diagram is illustrated in Figure 1.

Closed-loop systems have significant advantages over open-loop systems, such as enhanced accuracy, improved stability, and reduced sensitivity to disturbances through continuous automatic correction [7]. By contrast, open-loop systems cannot automatically compensate for variations in the environment or load, which results in performance degradation when disturbances occur [8].

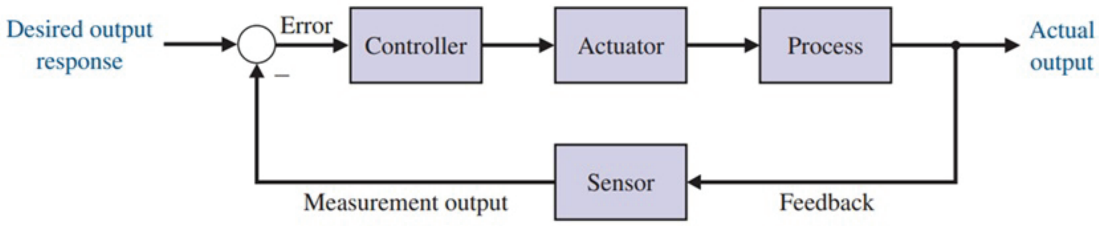


Figure 1. Closed loop block diagram [6]

Proportional (P), Proportional-Integral (PI), Proportional-Derivative (PD), and Proportional-Integral-Derivative (PID) controllers remain the most widely used control methods in industry [6], [9], [18]. Their popularity stems from simplicity, ease of implementation, and effectiveness in many linear, time-invariant systems [7], [14]. Although versatile, PID controllers face challenges in higher-order, nonlinear, or time-delay systems, where parameter tuning becomes difficult and performance may degrade under disturbances [3], [8], [15], [18]. To address these limitations, researchers have explored hybrid approaches, including fuzzy-PID [16], adaptive fuzzy sliding mode [21], and neural-fuzzy controllers [10], which offer improved robustness and adaptability.

Methodology

This paper focuses on tracking control of a single mass rotary device using fuzzy logic
and PID controllers. To find the plant transfer function, the DC motor is first simulated using the appropriate parameters. To obtain the run compensated feedback result, a DC motor open loop performance simulation is conducted. The tuning of the fuzzy logic controller and PID controller results in a percentage overshoot of less than 10%. After they have been adjusted, the controllers will be included in the closed loop system.

3.1 *Plant Model*

For the single mass rotary system, the DC motor was selected as the most straightforward and fundamental mechanism. DC motors are widely adopted in industrial applications due to their simple structure, ease of speed regulation, and cost-effectiveness [9], [11]. Because of its flexibility in controlling the motor's speed, the DC motor is also the actuator that is most frequently used in industrial applications [9,11]. Figure 2 shows the equivalent circuit of a DC motor [9].

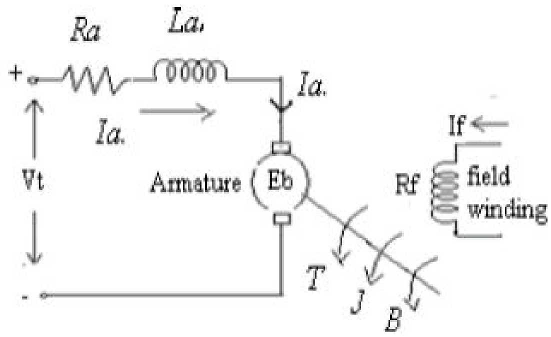


Figure 2. Equivalent circuit of a DC motor [9].

The transfer function for the model can be expressed as:

$$G(s) = \frac{\theta(s)}{E(s)} = \frac{K_t}{s[(L_a s + R_a)(J_s + B) + K_b K_t]}$$

The motor parameters and variables involved that represent the one mass rotary system are defined as the following:

Table 1. DC motor's parameters and values.

Parameter	Symbol	Value
Armature inductance	L_a	$4.6906 \ x \ 10^{-3} H$
Armature resistance	R_a	$2.5604 \ H$
Back-emf constant	K_b	$1.8259 \ x \ 10^{-2} V.s/rad$
Torque constant	K_t	$1.8259 \ x \ 10^{-2} N.m/A$
Viscous-friction coefficient	B	$9.1358 \ x \ 10^{-5} N.m.s/rad$
Total load inertia	J	$7.2019 \ x \ 10^{-6} kg.\ m^2$

DC motor's parameters and values as in Table 1 are substituted in the model transfer function in Equation (1), gives

$$G(s) = \frac{\theta(s)}{E(s)} = \frac{0.01826}{3.378\ x\ 10^{-7}s^3 + 1.848\ x\ 10^{-4}s^2 + 5.673\ \text{x}\ 10^{-4}s}$$

Thus, Equation (2) will be used throughout the simulation performance evaluation.

3.2 Controller Design

A PID controller and a fuzzy logic controller (FLC) are constructed for the system in MATLAB Simulink and combine with the transfer function of the plant model. To develop the PID controller, the integral gain (Ki), derivative gain (Kd), and proportional gain (Kp) were all calculated using the root locus approach and fine-tuned using the Ziegler-Nichols technique. In the meanwhile, a rule-based methodology that considers system behavior or expert knowledge is used to generate the FLC. The design entails choosing the right inference and defuzzification methods, fine-tuning the membership functions, and figuring out the ideal number of rules that suits the system.

PID Controller

The Ziegler-Nichols tuning method is used to fine-tune the gains for the proportional, integral and derivative functions of the PID after they have been set using the root locus
approach. The system is trained to acquire the plant's openloop response by applying a step input signal. To begin with the Ziegler-Nichols method, the integral (K_i) and derivative (K_d) gains are then adjusted to zero. After that, the proportional gain (K_p) is increased until the system begins to exhibit instability. K_{max}, the greatest value of K_p, indicates the point at which the system is approaching instability; this frequency is known as the oscillation frequency (f_o). Using this tuning procedure, the K_i and K_d are then set as functions of f_o, and the K_p is backed off by a predetermined amount. The block diagram for the PID controller is made as seen in Figure 3.

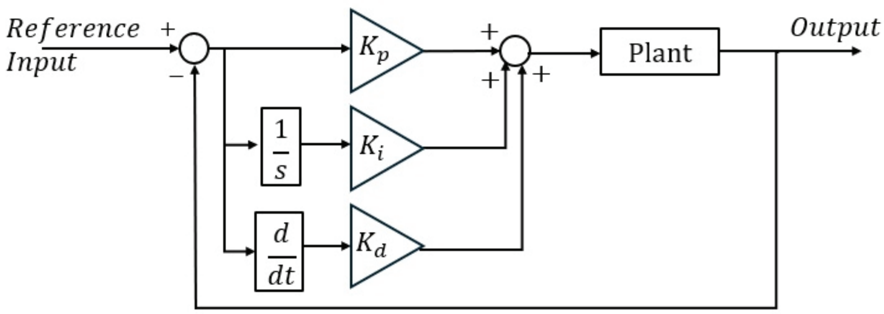


Figure 3. Block diagram of PID controller

Table 2 lists the values for the individual gains that are used in the PID controller for the one mass rotary system.

Table 2. Parameters of PID gains.

Parameter	Symbol	Value
Proportional gain	K_m	3.15
Integral gain	K_i	0.9
Derivative gain	K_d	0.485

Fuzzy Logic Controller

Fuzzy logic controller utilizes two input variables: receiving the error signal and the error change. The defuzzification process is utilized to determine the appropriate control action, and these variables evaluate the fuzzy control rules using compositional rules of inference. The error and change of error are the two input variables, and one output variable of the fuzzy logic controller. Figure 4 shows the block diagram of FLC.

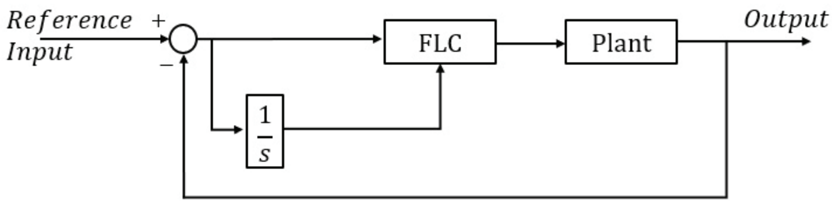


Figure 4. Block diagram of Fuzzy Logic Controller

The linguistic labels of the input variable, amplitude, are represented by trapezoidal membership functions in the fuzzy logic controller (FLC) used for the tracking control of the single mass rotary system. The membership functions, which capture amplitude variations and allow the FLC to make precise control decisions, which include Negative Large (NL), Negative Small (NS), Zero (ZE), Positive Small (PS), and Positive Large (PL). The selection of the trapezoidal membership functions is based on their effective handling of asymmetric or non-linear relationships. The fuzzy rules are combined, and the fuzzy output is determined using the Mamdani inference method.

In this paper, two rule tables with distinct membership functions for the FLC were created, and the output results were compared to determining which rule table would be chosen in the end. Tables 3 and 4 display the rule table that was utilized to develop the project. The outcome of the result will depend on the number of membership functions.

Table 3. Rule table of FLC (3x3).

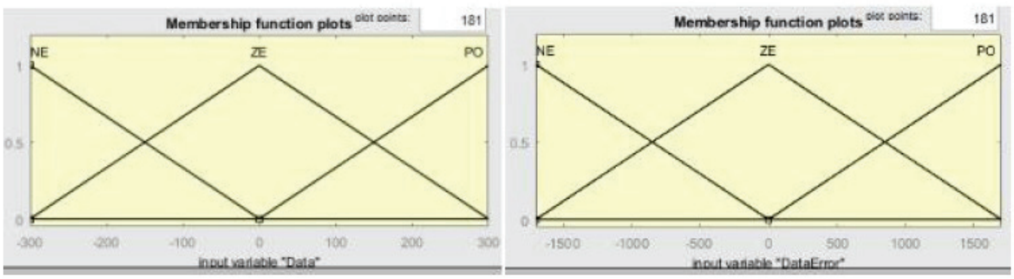
DE\E	**NE**	**ZE**	**PO**
NE	NE	NE	ZE
ZE	NE	ZE	PO
PO	ZE	PO	PO

Table 4. Rule table of FLC (5x5).

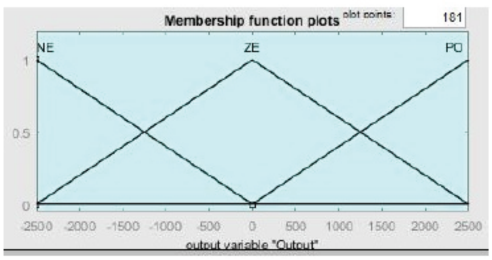
DE\E	NL	NS	ZE	PS	PL
NL	NL	NL	NL	NS	ZE
NS	NL	NL	NS	ZE	PS
ZE	NL	NS	ZE	PS	PL
PS	NS	ZE	PS	PL	PL
PL	ZE	PS	PL	PL	PL

Generally, FLC functionality is significantly influenced by the size of the rule table and the membership function. The mapping of inputs to fuzzy sets is determined by the membership function, which also specifies the extend of an input's membership to a linguistic label. The membership function's dimensions, width, and parameters have a direct impact on the system's overall performance and control behavior. The rule table, on the other hand, outlines the control actions in accordance with the combinations of fuzzy sets and the associated linguistic labels. A larger rule table provides finer-grained control decisions and considers a wider range of input combinations; therefore, it enables more accurate control. But larger rule table also means that the controller must work harder and use more computing power.

Hence, to achieve the desired control performance, it is crucial to carefully design the membership functions and select a suitable rule table size to strike a compromise between accuracy and computing efficiency. Figures 5 and 6 show the tuned FLC for membership function (MF) 3x3 and 5x5 accordingly using MATLAB Simulink R2015b.

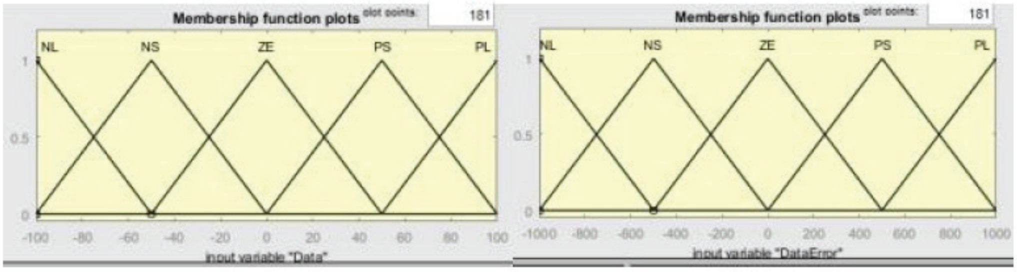


(a)

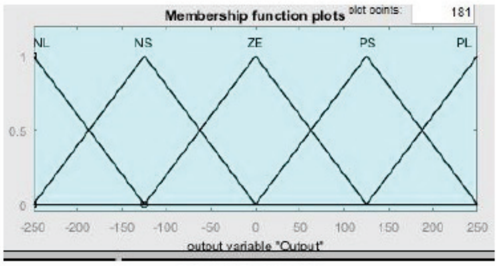


(b)

Figure 5. FLC 3x3 Membership Function for (a) data and data error, and (b) output



(a)

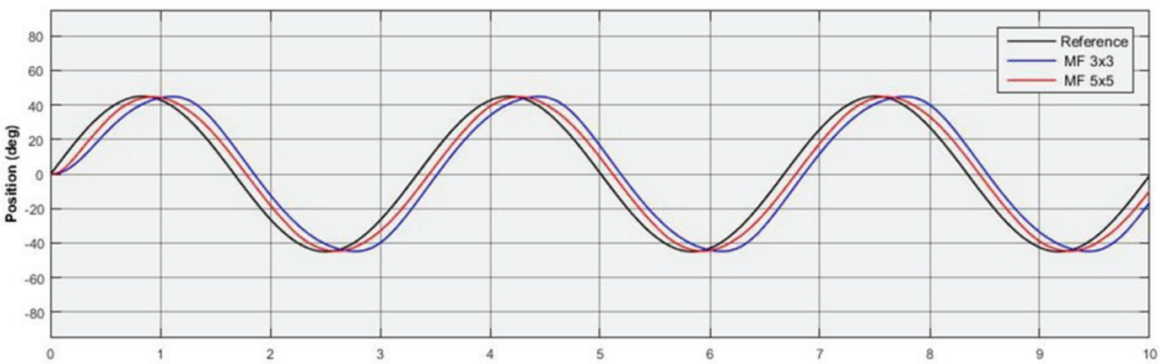


(b)

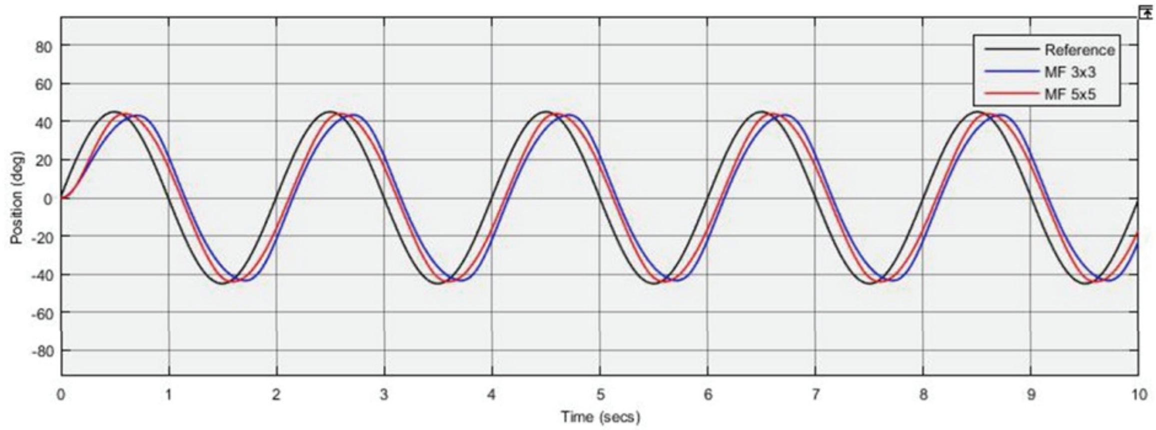
Figure 6. FLC 5x5 Membership Function for (a) data and data error, and (b) output

Results and Discussions

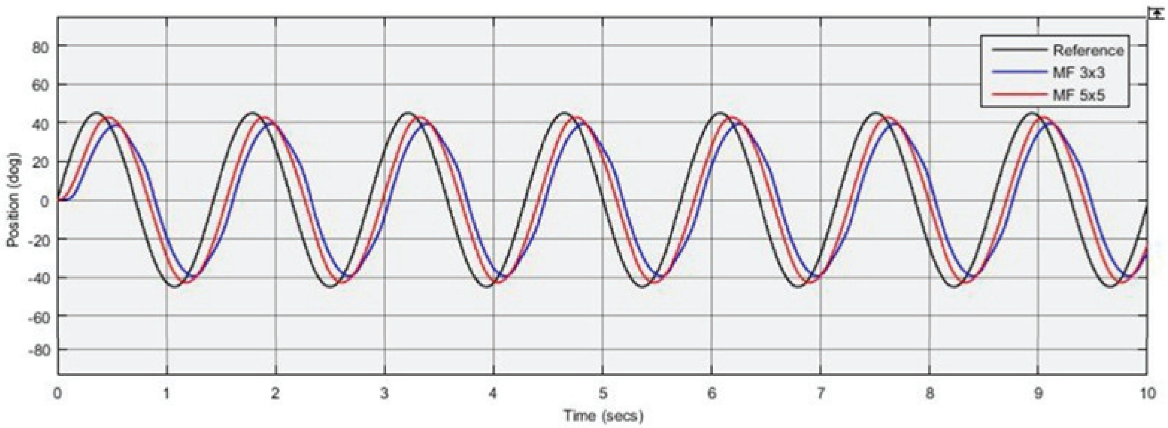
The tracking performances of the single mass rotary system is evaluated in simulation. A sinusoidal wave is used as reference input. The results were simulated at amplitude of 45°, at three different frequencies, 0.3 Hz, 0.5 Hz, and 0.7 Hz, respectively. Figure 7 illustrates the comparison between FLC with membership function 3x3 and 5x5 for 45°at three different frequencies. Based on the results, the tracking error for MF 5x5 is outstanding compared to using MF 3x3 throughout the variations of frequencies. Thus, MF 5x5 is selected to be compared with PID controller for further evaluations.



(a)



(b)

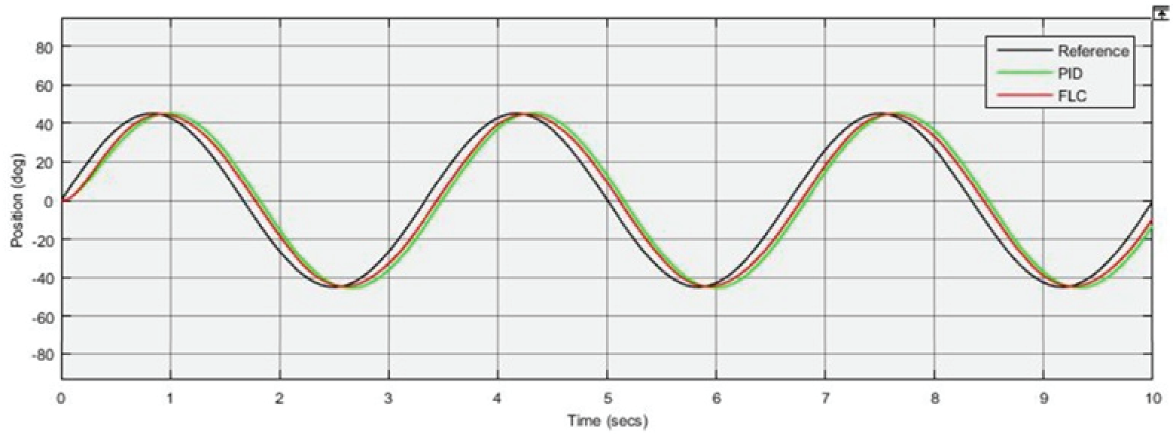


(c)

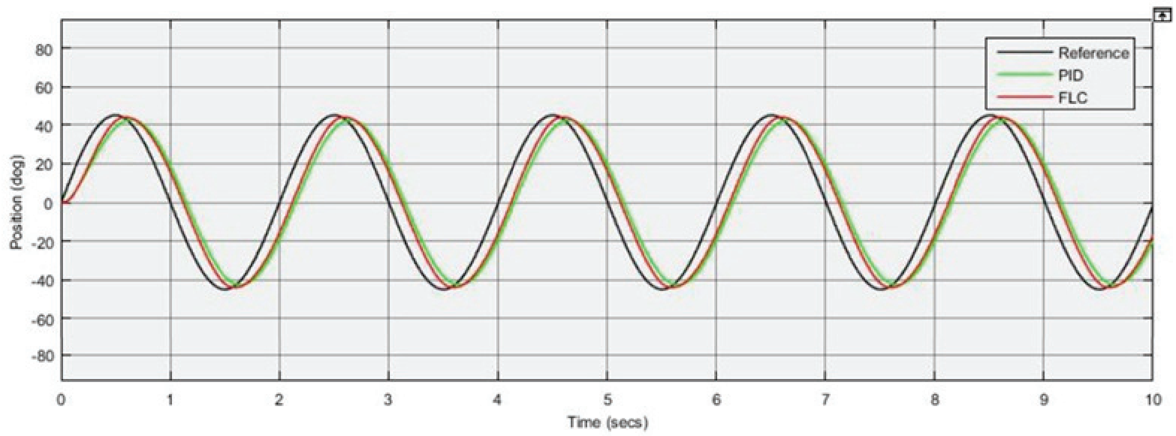
Figure 7. Comparison between FLC MF 3x3 and 5x5 at 45° for (a) 0.3 Hz, (b) 0.5 Hz, and (c) 0.7 Hz

The simulation findings demonstrated that, at an input amplitude of 45°, the FLC with MF 5×5 exhibits superior performance by producing substantially lower tracking errors compared to the MF 3×3 configuration. This performance is consistently observed across multiple operating conditions, specifically at excitation frequencies of 0.3 Hz, 0.5 Hz, and 0.7 Hz, thereby confirming the robustness of the MF 5×5 design in handling dynamic variations.

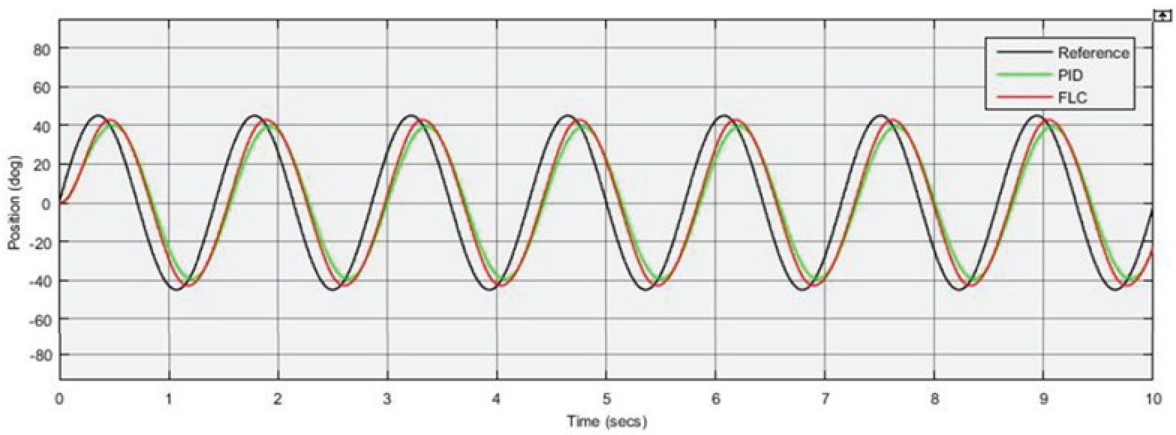
Figure 8 shows the comparison for tracking performances of PID and FLC controllers at 45° for 0.3 Hz, 0.5 Hz, and 0.7 Hz. Based on the simulation results obtained, FLC has shown better accuracy performances particularly at higher frequency.



(a)



(b)



(c)

Figure 8. Comparison tracking performances of PID and FLC controllers at 45° for (a) 0.3 Hz, (b) 0.5 Hz, and (c) 0.7 Hz in simulation

The observed reduction in tracking error suggests that the FLC MF 5×5 provides enhanced noise suppression and improved accuracy in trajectory following, which are critical factors for ensuring system stability and reliability. Given these consistent improvements, the MF 5×5 configuration is identified as the more effective control strategy and is therefore selected for subsequent comparative evaluations against the PID controller. This comparison is expected to provide deeper insights into the relative strengths and limitations of conventional control strategies versus advanced control approaches in precision tracking applications.

Conclusion

A fuzzy logic controller (FLC) was proposed for a single-mass rotary system driven by a DC motor and evaluated against a PID controller. The FLC adeptly converted input variables into control outputs utilizing the Mamdani inference method, rule base, and membership functions. Simulation findings indicated a diminished tracking error in comparison to PID under frequency variations of 0.3 Hz, 0.5 Hz, and 0.7 Hz at a position angle of 45°. The research validates the FLC's capacity for enhanced control efficiency. Subsequent research will investigate a wider range of angle variations and conduct experimental validation.

Acknowledgement

The authors wish to express their gratitude to Motion Control Research Laboratory (MCon Lab), Center for Robotics and Industrial Automation (CeRIA), Centre for Research and Innovation Management (CRIM), Fakulti Teknologi dan Kejuruteraan Elektrik (FTKE), and Universiti Teknikal Malaysia Melaka (UTeM) for supporting this research and publication. This research is supported by Universiti Teknikal Malaysia Melaka (UTeM) under the grant no. PJP/2021/FKE/S01818.

References

[1] Nor, R.M.; Rozali, S.M.; Horng, C.S. Positioning control and operational evaluation of a one mass rotary system using NCTF controller. International Journal of Engineering and Technology, 2018, 7(3), 111.

[2] Deepshikha; Kumar, R. Comparative study of conventional controllers. International Journal of Electrical, Electronics and Data Communication 2014, 2(10), 44–48.

[3] Li, S.; Jiang, Q. Study on PID parameters tuning method based on MATLAB/Simulink. Proc. IEEE 3rd Int. Conf. Communication Software and Networks (ICCSN), Xi'an, China, May 2011, pp. 408–411, doi: 10.1109/ICCSN.2011.6014596.

[4] Fayek, H.M.; Elamvazuthi, I. Type-2 fuzzy logic PI (T2FLPI) based DC servomotor control. Journal of Applied Sciences 2012, 12(9), 879–885.

[5] Zadeh, L.A. Fuzzy sets. Information and Control, vol. 8, no. 3, pp. 338–353, Jun. 1965. doi: 10.1016/S0019-9958(65)90241-X.

[6] Dorf, R.C.; Bishop, R.H. *Modern control systems*, 12th ed. Upper Saddle River, NJ: Prentice Hall, 2010.

[7] Lin, S.-K. Designing control loops for linear and switching power supplies: A tutorial guide. Journal of Low Power Electronics and Applications 2013, 3(1), 1–8. doi: 10.3390/jlpea3010001.

[8] Geng, J.; Luo, Q. An open-closed-loop PID-type iterative learning control algorithm for uncertain time-delay systems. In 2005 International Conference on Machine Learning and Cybernetics, vol. 2, (pp. 1154–1159). doi: 10.1109/ICMLC.2005.1527117.

[9] Santoso, S.; Beaty, H.W. Standard handbook for electrical engineers, 27th ed. New York, NY, USA: McGraw-Hill Education, 2018.

[10] Hameed, W.I. Speed control of separately excited DC motor using fuzzy neural model reference controller. International Journal of Instrumentation and Control System 2012, 2(4), 27–39. doi: 10.5121/ijics.2012.2403.

[11] Pawlak, A.M. Sensors and actuators in mechatronics. 1st ed. Boca Raton, FL, USA: CRC Press, 2017, pp. 88–154, doi: 10.1201/9781315221632.

[12] Nor, R.M.; Chong, S.H. Positioning control of a one mass rotary system using NCTF controller. In 2013 IEEE International Conference on Control System, Computing and Engineering (ICCSCE), Penang, Malaysia (pp. 381–386). doi: 10.1109/ICCSCE.2013.6719994.

[13] Foo, J.E.; Chong, S.H.; Nor, R.M.; Loh, S.L. Positioning control of a one mass rotary system with CM-NCTF controller. Journal of Telecommunication and Electronics Computer Engineering (JTEC) 2016, 8(11), 125–129.

[14] Silva, F.A. Power electronics handbook, third edition (Rashid, M. H.; 2011) [Book News]. IEEE Industrial Electronics Magazine, 5(2), pp. 54–55. doi: 10.1109/MIE.2011.941117.

[15] Unbehauen, H. Control systems, robotics and automation. Oxford, U.K.: EOLSS Publishers, 2009, pp. 58–127.

[16] Pratumsuwan, P.; Thongchai, S.; Tansriwong, S. A hybrid of fuzzy and proportional-integral-derivative controller for electro-hydraulic position servo system. Energy Research Journal 2010, 1(2), 62–67. doi: 10.3844/erjsp.2010.62.67.

[17] Reyes-García, C.A.; Torres-García, A.A. Fuzzy logic and fuzzy systems. Biosignal Processing and Classification using Computational Learning and Intelligence: Principles, Algorithms, and Applications 2022, pp. 153–176, doi: 10.1016/B978-0-12-820125-1.00020-8.

[18] Åström, K.J.; Hägglund, T. PID controllers: Theory, design, and tuning, 2nd ed. Research Triangle Park, NC, USA: Instrument Society of America, 1995.

[19] Wu, H.; Luo, N.; Wang, C. Study on control strategy of the rotary synchronous fixed-length cutting system. Journal of Vibroengineering 2013, 15(2), pp. 713–725.

[20] Chotai, J.; Narwekar, K. Modelling and position control of brushed DC motor. In 2017 International Conference on Advances in Computing, Communication and Control (ICAC3).

[21] Piltan, F.; Sulaiman, N.; Ferdosali, P.; Rashidi, M.; Tajpeikar, Z. Adaptive MIMO fuzzy compensate fuzzy sliding mode algorithm: Applied to second order nonlinear system. International Journal of Engineering (IJE) 2011, 5(5), pp. 380–398