ONE DOF ROBOT MANIPULATOR CONTROL THROUGH TYPE-2 FUZZY ROBUST ADAPTIVE CONTROLLER

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Abstract:
In this article, the one DOF robot manipulator control is assessed through second type robust fuzzy-adaptive controller. The objective is to obtain a tracking path with appropriate accuracy. The stability of the closed loop system is verified through Lyapunov stability theory and the efficiency of tracking is analyzed subject to the constraints and uncertainty. In order to design the fuzzy controller a set of if-then fuzzy rules are considered which describe the system input-output behavior. Simulation and the results of the experiments on the one DOF robots indicate the effectiveness of the proposed methods.

Keywords: *Robot manipulator, Lyapunov function, One-DOF robot, Adaptive-fuzzy controller, Robust*

1. Introduction

The robot manipulator control system has made advances in various areas like physical health, welding services, soldering, packing and working in hard environments. In order to apply the robots in an appropriate manner, their respective equations must be obtained which may lead to more appropriate control. In this control system, the effects due to uncertainty and external disturbance must be considered in the controller design. Most manipulator systems are fixed on a platform. The most essential challenge in this context is the estimation of the robot manipulator parameters. Due to the high volume of the computations and their complexity, controlling robots is a difficult task. Flexibility in joints is a factor leading to the complexity of the robotic systems. Most of the robot control methods are based on robot joints' voltage control strategy; hence, these control methods are complex. In order to overcome this challenge, the robot motor torque' control strategy is applied.

Different structure of adaptive controller is utilized to control of one DOF robot manipulator due to existing uncertainty parameters. In [5], an adaptive control of a mechanical manipulator with parametric uncertainty and displacement constraints is suggested. Here, control and acceleration constraints are combined and converted into common input constraints. In [12], an adaptive-neural control is developed to obtain tracking when the issue of displacement constraints is addressed by considering the normal input saturation effect. The bound in all closed loop signals is monotone through Lyapunov stability analysis. In [13], a combining adaptive-fuzzy output feedback control design approach is proposed for a specific class of nonlinear multi input-multi output systems with variable delays and input saturation constraint. This proposed control schematic does not need the extraction of dynamic equation in robot. In [8], the robust-adaptive control rules are proposed in the intended schematics to reduce the effect of error caused by approximation. Thus, the adaptive impedance control for n-link robot manipulator with input saturation is developed through neural networks. An adaptive fuzzy logic is designed to estimate sliding mode control parameters in order to prevent chattering effect [3]. Real-virtual control inputs are inferred by solving a set of dynamic equations.

In [2, 18], an adaptive backstepping control is applied to n-degree of freedom robotic manipulator. This suggested controller promise the system stability against nonlinearities and uncertainties. Thus, an adaptive back stepping controller is suggested based on support vector machine with the least square for accurate positioning of robot manipulator which can compensate for static effect and uncertainty available in dynamism [9].

An essential capability is the universal approximation of the fuzzy system. In order to approximate the uncertainty of the system, a radical based saturated input is applied through designing and auxiliary system. In [4], controlling the fuzzy logic as a design view point is developed as a free control model. A new robust control is suggested for mechanical manipulator through adaptive uncertainty estimator based on Taylor first order series. In this state, the controller does not need constraint function. One of the drawbacks of this method could be the inappropriate tracking in presence of external disturbances.

Due to specific features like time-varying, cross-coupling effect and being of high order of robot models is a complex issue in the given systems. Intelligent methods like combined fuzzy methods are appropriate choice for these systems. In [6], a fuzzy sliding mode with nonlinear observer for the robot manipulator is suggested, where it leads to an accurate tracking path in presence of disturbances. It is obvious that, all fuzzy systems are not applicable in fuzzy controllers and depend on the capability and efficiency of the fuzzy system.

An appropriate observer is provided to estimate the accurate disturbances through recursive algorithm. Thus, a modified fuzzy algorithm with an extra integral agent is introduced to eliminate the static error state in the manipulator [17]. Also, this approach using supervisory fuzzy control is utilized to control of 3-DOF planar robot manipulator. In [14], a sliding mode controller is designed for robot systems through wavelet networks. Proposed training algorithms can align online parameters based on their weights, [7], where the manipulator tracking neural network with dead constraint input and output are suggested. In [11], a robust-adaptive power and replacement control schematic is proposed for n-link robot manipulator.

In [10], a fuzzy switching is applied through model adaptive control (MRAC) in manipulator robot. In [15], the sliding mode control with a robust control scheme is implemented for the joint angular position control of a 6-DOF PUMA robot. In [1], the fractional-order controller with fuzzy type-2 compensator is utilized for two-DOF robot manipulator. Moreover, an adaptive fractional-order sliding mode controller is applied for two-DOF gimbal system [16]. An adaptive neural network control is applied for robot manipulator with nonlinear uncertainties and environment disturbances [22]and [23]. In [20], a fuzzy neural network control through dynamical model-based method is employed for single-link flexible robot manipulator. In [21], a robot control scheme is implemented to recognize the unknown robot kinematic and dynamic robot manipulator parameters with convergence rate.

The remainder of this paper is organized as follows. Section 2 describes the dynamic of one-DOF robot manipulator. The proposed robust second type fuzzy-adaptive controller is presented in Section 3. The performance of the proposed robust second type fuzzy-adaptive controller is demonstrated by simulation given in Section 4. Finally, Section 5 concludes the paper.

2. One-DOF Robot Manipulator Dynamics

Robotic systems are highly nonlinear, uncertain, coupling and multi-input multi-output dynamic systems, in nature. In order to control such system, the isolation control method is adopted which converts a multi input-multi output system to a single input-single output one. This control method in many modern robots is used due to simplification of the computations and reduction of software costs. In order to control the robot, each joint must be controlled in a separate manner. In this method, all the effects caused by cross-couple are considered as uncertainty which is compensated by the controllers. The simplified schematic of one DOF robot manipulator is illustrated in Figure 1.

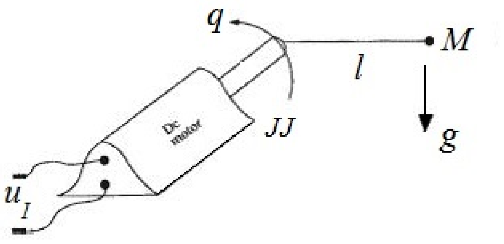

Fig. 1. Schematic of one DOF robot manipulator

The state space representation of one DOF robot manipulator together with actuator dynamics are presented as follows

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = x_3 \\ \dot{x}_3 = x_4 \\ \dot{x}_4 = -(\frac{Mgl}{I^* \cos(x_1)} + \frac{K}{I} + \frac{K}{J})x_3 + \\ \qquad \frac{Mgl}{I}(x_2^2 - \frac{K}{J})\sin(x_1) + \frac{K}{I * J}u \end{cases} \tag{1}$$

where x_1 , x_2 and x_3 are position, velocity and acceleration of robot manipulator, respectively. x_4 is the current of motor and u is controlling voltage. M is body mass, l is the length of robot arm, g is the fixed gravity; I and J are the inertial momentum.

Regarding these equations, this fourth-order state space can be written in the form state vector and output as following:

$$\begin{cases} y^{(4)}(t) = f(x) + bu \\ X = [x_1, x_2, x_3, x_4]^T \\ y = x_1 \end{cases} \tag{2}$$

where $f(x)$ and b are unknown function and parameter, respectively.

3. Second-Type Adaptive Fuzzy Controller Design

Fuzzy logic systems are applied for the unknown nonlinear approximation functions in the system. Hence, a smooth function is applied for approximation of input saturation and an adaptive-fuzzy observer is designed to solve the problem of unmeasured cases. By applying the adaptive fuzzy dynamic level control technique and previous error between the observer model and parallel series-estimation model, a new fuzzy control with adaptive rules of combining parameters is adopted based on Lyapunov rule. The fuzzy controllers are nonlinear which are designed according to fuzzy logic. The fuzzy control based on the model guarantees the closed loop stability with the least computation and analyzes the robustness and efficiency of the closed loop system.

The robot performance in a structured environment consists of constraints like acceleration and position ones. In order to reduce the fuzzy rules, dynamic features of robots and uncertainty function analysis are taken into account. The membership functions of type one fuzzy system are selected according to human knowledge. In the type two fuzzy systems, the membership degree therein is a fuzzy digit with more capability and flexibility compared to type one fuzzy system. A type two fuzzy set, in general, is described as follows.

$$\tilde{A} = \int_{x \in X} \left[\int_{u \in U_x} \frac{f_x(u)}{u} \right] / x \tag{3}$$

where $\tilde{A}$ is a type-2 fuzzy system, U_x is set degrees of membership, x is primary variable, u is secondary variable and $f_x(u)$ is secondary membership function. A fuzzy logic system consists of fuzzy rule base, fuzzy inference engine and defuzzification mechanism. Type-2 fuzzy rules can be written as follows which in this regard, x is input vector, $\mu_j^i(j = 1, ..., n)$ is type-2 fuzzy sets and y^i is the center of a type-2 membership function.

$$\textbf{if } x_1^i \textbf{ is } \tilde{\mu}_1^i, ..., x_n^i \textbf{ is } \tilde{\mu}_n^i \textbf{ then } y \textbf{ is } y^i,\ (i = 1, ..., m) \tag{4}$$

A type-2 fuzzy system structure is similar to a type-1 fuzzy system, which has one extra order reduction block. This block is a modified defuzzification of type-1 fuzzy which converts the type-2 fuzzy set output of inference engine into a type-1 fuzzy set.

$$y(x) = [y_l, y_r] = \bigcup_{f^i \in F^i(x)} \frac{\sum\limits_{i=1}^{M} f^i y^i}{\sum\limits_{i=1}^{M} f^i} \tag{5}$$

where y_r and y_l are the output values for right and left functions, respectively. $\underline{f}^i(x)$ and $\overline{f}^i(x)$ are lower and upper limitations of the output function as follows [20]

$$\underline{f}^i(x) = \underline{\mu}_{\tilde{x}_1^i}(x_1) \times \cdots \times \underline{\mu}_{\tilde{x}_p^i}(x_p) \tag{6}$$

$$\overline{f}^i(x) = \overline{\mu}_{\tilde{x}_1^i}(x_1) \times \cdots \times \overline{\mu}_{\tilde{x}_p^i}(x_p) \tag{7}$$

where $\underline{f}^i(x)$ and $\overline{f}^i(x)$ are upper and lower limitations of the membership function, respectively. y_r and y_l in above equations are calculated through equations (8) and (9).

$$y_l = \frac{\sum\limits_{i=1}^{l} \overline{f}^i y_l^i + \sum\limits_{i=l+1}^{M} \underline{f}^i y_l^i}{\sum\limits_{i=1}^{l} \overline{f}^i + \sum\limits_{i=l+1}^{M} \underline{f}^i} \tag{8}$$

$$y_r = \frac{\sum\limits_{i=1}^{r} \underline{f}^i y_r^i + \sum\limits_{i=l+1}^{M} \overline{f}^i y_r^i}{\sum\limits_{i=1}^{r} \underline{f}^i + \sum\limits_{i=l+1}^{M} \overline{f}^i} \tag{9}$$

where y_r and y_l are obtained through Kernick-Mandel approach [12].

$$y_r = \sum_{i=1}^{R} \underset{-r}{q^i} y_r^i + \sum_{i=R+1}^{M} \bar{q}_r^i y_r^i = \theta_r^T \xi_r \tag{10}$$

$$y_l = \sum_{i=1}^{R} \bar{q}_l^i y_l^i + \sum_{i=l+1}^{M} \underset{-l}{q^i} y_l^i = \theta_l^T \xi_l \tag{11}$$

The reduce order block is calculated through Defuzzifierr block.

$$y(x) = 0.5(y_l + y_r) = 0.5(\theta_l^T \xi_1 + \theta_r^T \xi_r) \tag{12}$$

Fuzzy logic system can be utilized to approximate uncertain nonlinear function. In adaptive-fuzzy control system design, the object is to design a feedback controller $U = u(x|\theta)$ based on fuzzy system and an adaptation rule to adjust the parameter vector θ so that system output (y) tracks desired output (y_m) as well as the time derivatives are bounded. The block diagram of second-type fuzzy system is illustrated in Figure 2. Accordingly, the following feedback control law can be considered:

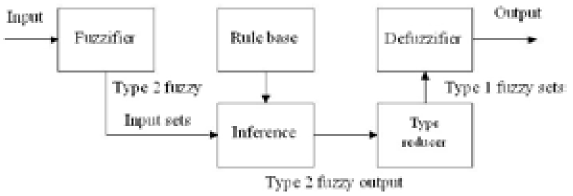

Fig. 2. The block diagram of second-type fuzzy system

$$U = [-f(X) + y_m + K^T e] \tag{13}$$

where y_m is the output of reference model, K is the parameters vector and e is the signal error. To make the system robust against external disturbances and uncertainties, term u_c can be added to the control law (12) as follow which is the H_∞ control term.

$$U = [-f(X) + y_m + K^T e + u_c] \tag{14}$$

where, robust term u_c is calculated as follow [19]:

$$u_c = -\frac{1}{r} B^T P e \tag{15}$$

where e denotes the output error $(e = y - y_m)$. There exists a positive definite matrix P for given positive definite matrix Q which is the solution of the following matrix equation [24]

$$A^T P + PA = -Q \tag{16}$$

The error dynamics of the system can be obtained as follow:

$$e^{(n)} + k_1 e^{(n-1)} + ... + k_n e = 0 \tag{17}$$

The centers average is obtained using product inference engine, singular Fuzzifier and Defuzzifierr. Suppose $\overline{y}_f^{l_1 \ldots l_n}$ are free parameters which are collected together in

$$\theta_f \in R^{\prod\limits_{i=1}^{n} p_i},$$

that can rewrite as following. System knowledge (fuzzy if-then rules) has been involved in designing process

$$\hat{f}(X|\theta_f^*)$$

through initial parameters $\theta_f(0)$.

$$\hat{f}(X|\theta) = \theta_f^T \xi(X) \tag{18}$$

where, parameters in θ_f change during online functions. These parameters are considered as primary. In this case, the modification rule for θ_f is designed in a manner that the tracing error of e is reduced. By replacing the control law (13) in system dynamics (1), the closed loop fuzzy control system is obtained as follows

$$\dot{e} = -K^T e + [\hat{f}(X|\theta_f) - f(X)]U_I \tag{19}$$

The block diagram of adaptive-fuzzy control is illustrated in Figure 3. In this block diagram, y_m, u_I , e_I , θ_f and $\theta_f(0)$ are reference input, control signal, error signal, estimation parameters vector and initial condition for state estimation, respectively. To guarantee the system stability and derive adaptation laws, the following Lyapunov function candidate is considered:

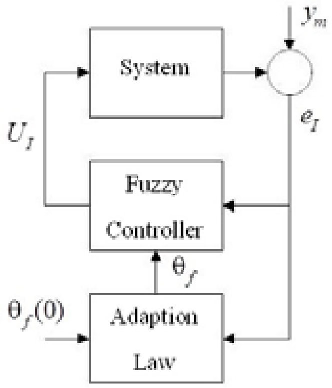

Fig. 3. Adaptive fuzzy control block diagram

$$V = \frac{1}{2}e^T Pe + \frac{1}{2\gamma}(\theta_f - \theta_f^*)^T(\theta_f - \theta_f^*) \tag{20}$$

where γ is a positive constant and P is the positive definite matrices. The time derivative V will be as

$$\dot{V} = -\frac{1}{2}e^T Pe + \frac{1}{\gamma}(\theta_f - \theta_f^*)^T[\dot{\theta}_f + \gamma e^T Pb\xi(x)] \tag{21}$$

In order to minimize the tracking error (e) and the parameter error $\theta_f - \theta_f^*$, the adaptation rule must be selected in a manner which $\dot{V}$ is negative definite. Since, $-\frac{1}{2}e^T Pe$ is negative, the fuzzy systems may be selected in a manner that the approximation error is minimized.

The closed loop system is obtained with applying control law. Thus, error signal tends to zero $(e(t) \to 0)$ with selection of appropriate parameters for $(t \to 0)$. Hence, system output converges to actual output asymptotically. In an appropriate strategy the adaptation rule is provided as follows:

$$\dot{\theta}_f = -\gamma e^T Pb\xi(x) \tag{22}$$

The convergence velocity of system (γ) is determined through fuzzy control rules. This purposed approach can be utilized to linear or nonlinear model which is robust to uncertainties and disturbances.

4. Simulation Results

After designing the controller, the control system is implemented in Matlab-Simulink and the proposed controller is simulated. The system parameters are considered as follow:

$$\begin{aligned} &I = 0.01(kg/m^2), \quad J = 0.05(kg/m^2), \\ &M = 1(kg), \quad g = 9.8(n/kg), \quad l = 1(m) \end{aligned} \tag{23}$$

Also designing parameters are considered as $k_1 = 10$, $k_2 = 15$ and desired input $y_r = \sin(t)$. In equation (16), the identity matrix is obtained as:

$$P = \begin{bmatrix} 1.2 & 2.6 & 0.7 & 0.9 \\ 2.2 & 0.1 & 0.2 & 4.3 \\ 3.5 & 9.7 & 1.3 & 5.6 \\ 1.9 & 0 & 2.1 & 22 \end{bmatrix} \tag{24}$$

To evaluation and comparison type-2 adaptive-fuzzy and robust type-2 adaptive-fuzzy controller, the error index performance is considered as follow:

$$IP = \int e^2 dt \tag{25}$$

In the designed robot control system, the states response to the input are shown in Figures 4-7.

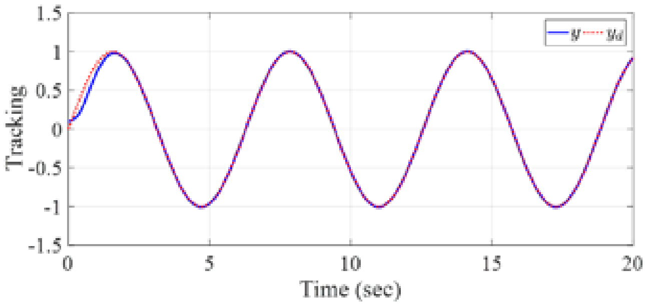

Fig. 4. Trajectory of x_1

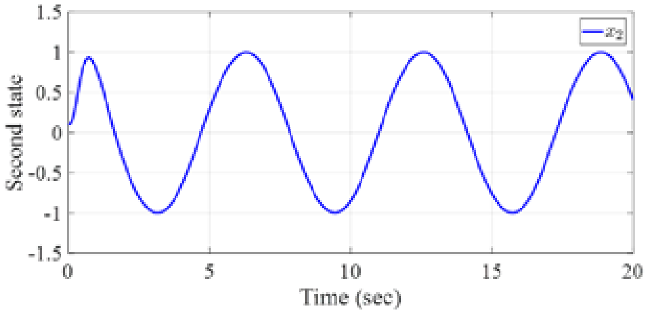

Fig. 5. Trajectory of x_2

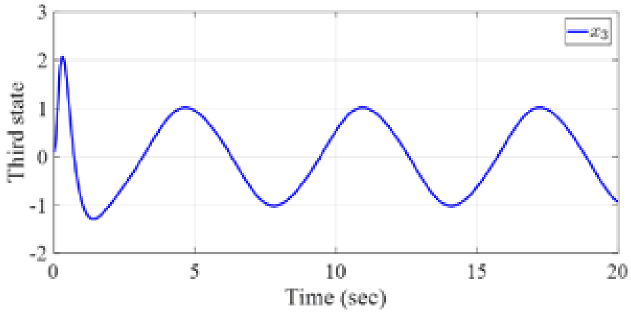

Fig. 6. Trajectory of x_3

Control signal which applied to the system is illustrated in Figure 8. Path tracking error for every state

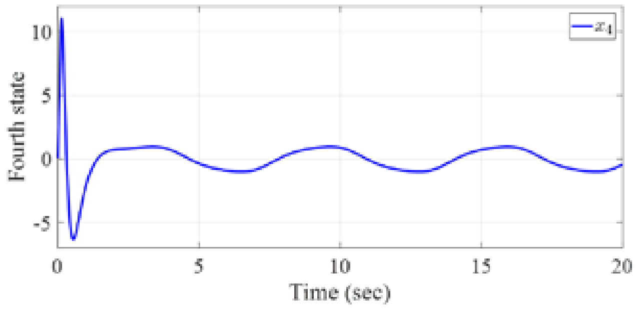

Fig. 7. Trajectory of x_4

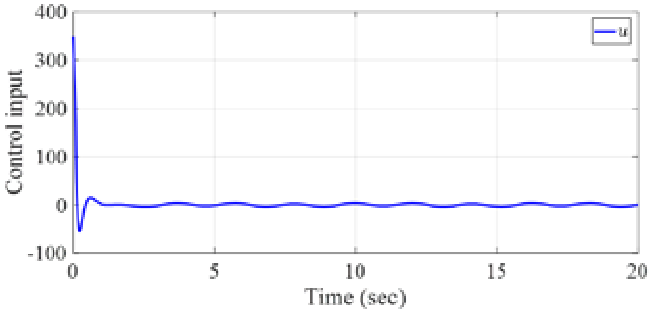

Fig. 8. Applied control signal to the system

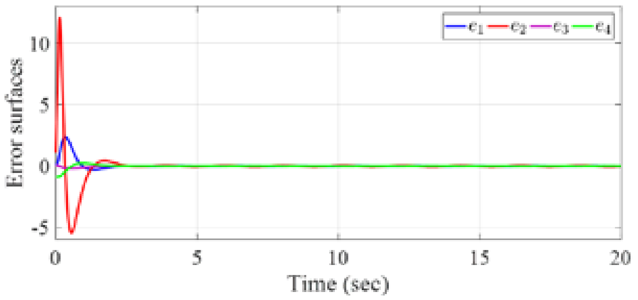

Fig. 9. Error signals in proposed control system

is shown in Figure 9. The value of performance index (25) for without (Test1) and with (Test2) robust controller are listed in Table 1.

Tab. 1. The inertial momentum values for two-axis gimbal system

Parameters	IP_1	IP_2	IP_3
Test1	0.64	1.53	4.32
Test2	0.23	0.95	2.12

Controlling the tracking of robots at high acceleration and accuracy is an essential issue in the realm of control. The fuzzy-adaptive controller accomplishes this issue by applying the features of the fuzzy systems and adaptive controllers. The Lyapunov theory method is applied as an efficient method in fuzzy-adaptive controller design.

5. Conclusion

In this paper, a type-2 fuzzy robust adaptive controller for one DOF robot manipulator is proposed. This proposed method is designed and simulated on the robot manipulator, based on control study. In comparison with the previous methods based on control study, this method is simpler, with less computation and higher efficiency, guaranteeing stability and robust against changes and uncertainty.

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REFERENCES

[1] A. T. Azar and F. E. Serrano, "Fractional Order Two Degree of Freedom PID Controller for a Robotic Manipulator with a Fuzzy Type-2 Compensator". In: A. E. Hassanien, M. F. Tolba, K. Shaalan, and A. T. Azar, eds., *Proceedings of the International Conference on Advanced Intelligent Systems and Informatics 2018*, 2019, 77–88.

[2] Byung Kook Yoo and Woon Chul Ham, "Adaptive control of robot manipulator using fuzzy compensator", *IEEE Transactions on Fuzzy Systems*, vol. 8, no. 2, 2000, 186–199, 10.1109/91.842152.

[3] W. Chang, S. Tong, and Y. Li, "Adaptive fuzzy backstepping output constraint control of flexible manipulator with actuator saturation", *Neural Computing and Applications*, vol. 28, no. 1, 2017, 1165–1175, 10.1007/s00521-016-2425-2.

[4] M. J. Er and S. Mandal, "A Survey of Adaptive Fuzzy Controllers: Nonlinearities and Classifications", *IEEE Transactions on Fuzzy Systems*, vol. 24, no. 5, 2016, 1095–1107, 10.1109/TFUZZ.2015.2501439.

[5] M. M. Fateh and M. Souzanchikashani, "Indirect adaptive fuzzy control for flexible-joint robot manipulators using voltage control strategy", *Journal of Intelligent & Fuzzy Systems*, vol. 28, no. 3, 2015, 1451–1459, 10.3233/IFS-141430.

[6] J. He, M. Luo, Q. Zhang, J. Zhao, and L. Xu, "Adaptive Fuzzy Sliding Mode Controller with Nonlinear Observer for Redundant Manipulators Handling Varying External Force", *Journal of Bionic Engineering*, vol. 13, no. 4, 2016, 600–611, 10.1016/S1672-6529(16)60331-1.

[7] W. He, A. O. David, Z. Yin, and C. Sun, "Neural Network Control of a Robotic Manipulator

With Input Deadzone and Output Constraint", *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 46, no. 6, 2016, 759–770, 10.1109/TSMC.2015.2466194.

[8] W. He, Y. Dong, and C. Sun, "Adaptive Neural Impedance Control of a Robotic Manipulator with Input Saturation", *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 46, no. 3, 2016, 334–344, 10.1109/TSMC.2015.2429555.

[9] X. Huang, H. Gao, J. Li, R. Mao, and J. Wen, "Adaptive back-stepping tracking control of robot manipulators considering actuator dynamic". In: *2016 IEEE International Conference on Advanced Intelligent Mechatronics (AIM)*, 2016, 941–946, 10.1109/AIM.2016.7576890.

[10] B. Kharabian, H. Bolandi, S. M. Smailzadeh, and S. K. Mousavi Mashhadi, "Fuzzy switching for multiple model adaptive control in manipulator robot", *Journal of Automation, Mobile Robotics and Intelligent Systems*, vol. Vol. 11, No. 1, 2017, 10.14313/JAMRIS_1-2017/7.

[11] C.-H. Lee and W.-C. Wang, "Robust adaptive position and force controller design of robot manipulator using fuzzy neural networks", *Nonlinear Dynamics*, vol. 85, no. 1, 2016, 343–354, 10.1007/s11071-016-2689-1.

[12] M. Li, Y. Li, S. S. Ge, and T. H. Lee, "Adaptive Control of Robotic Manipulators With Unified Motion Constraints", *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 47, no. 1, 2017, 184–194, 10.1109/TSMC.2016.2608969.

[13] Y. Li, S. Tong, and T. Li, "Hybrid Fuzzy Adaptive Output Feedback Control Design for Uncertain MIMO Nonlinear Systems With Time-Varying Delays and Input Saturation", *IEEE Transactions on Fuzzy Systems*, vol. 24, no. 4, 2016, 841–853, 10.1109/TFUZZ.2015.2486811.

[14] C. Lin, "Nonsingular Terminal Sliding Mode Control of Robot Manipulators Using Fuzzy Wavelet Networks", *IEEE Transactions on Fuzzy Systems*, vol. 14, no. 6, 2006, 849–859, 10.1109/TFUZZ.2006.879982.

[15] A. Medjebouri and L. Mehennaoui, "Adaptive Neuro-Sliding Mode Control of PUMA 560 Robot Manipulator", *Journal of Automation, Mobile Robotics and Intelligent Systems*, vol. Vol. 10, No. 4, 2016, 10.14313/JAMRIS_4-2016/27.

[16] A. Naderolasli and M. Tabatabaei, "Stabilization of the Two-Axis Gimbal System Based on an Adaptive Fractional-Order Sliding-Mode Controller", *IETE Journal of Research*, vol. 63, no. 1, 2017, 124–133, 10.1080/03772063.2016.1229581.

[17] S. R. Naghibi, A. A. Pirmohamadi, and S. A. A. Moosavian, "Fuzzy MTEJ controller with integrator for control of underactuated manipulators", *Robotics and Computer-Integrated Manufacturing*, vol. 48, 2017, 93–101, 10.1016/j.rcim.2017.03.006.

[18] N. Nikdel, M. A. Badamchizadeh, V. Azimirad, and M. A. Nazari, "Adaptive backstepping control for an n-degree of freedom robotic manipulator based on combined state augmentation", *Robotics and Computer-Integrated Manufacturing*, vol. 44, 2017, 129–143, 10.1016/j.rcim.2016.08.007.

[19] G. G. Rigatos, "Adaptive fuzzy control of DC motors using state and output feedback", *Electric Power Systems Research*, vol. 79, no. 11, 2009, 1579–1592, 10.1016/j.epsr.2009.06.007.

[20] C. Sun, H. Gao, W. He, and Y. Yu, "Fuzzy Neural Network Control of a Flexible Robotic Manipulator Using Assumed Mode Method", *IEEE Transactions on Neural Networks and Learning Systems*, vol. 29, no. 11, 2018, 5214–5227, 10.1109/TNNLS.2017.2743103.

[21] C. Yang, Y. Jiang, W. He, J. Na, Z. Li, and B. Xu, "Adaptive Parameter Estimation and Control Design for Robot Manipulators With Finite-Time Convergence", *IEEE Transactions on Industrial Electronics*, vol. 65, no. 10, 2018, 8112–8123, 10.1109/TIE.2018.2803773.

[22] S. Zhang, Y. Dong, Y. Ouyang, Z. Yin, and K. Peng, "Adaptive Neural Control for Robotic Manipulators With Output Constraints and Uncertainties", *IEEE Transactions on Neural Networks and Learning Systems*, vol. 29, no. 11, 2018, 5554–5564, 10.1109/TNNLS.2018.2803827.

[23] Q. Zhou, S. Zhao, H. Li, R. Lu, and C. Wu, "Adaptive Neural Network Tracking Control for Robotic Manipulators With Dead Zone", *IEEE Transactions on Neural Networks and Learning Systems*, 2019, 1–10, 10.1109/TNNLS.2018.2869375.

[24] M. M. Zirkohi, M. M. Fateh, and M. A. Shoorehdeli, "Type-2 Fuzzy Control for a Flexible- joint Robot Using Voltage Control Strategy", *International Journal of Automation and Computing*, vol. 10, no. 3, 2013, 242–255, 10.1007/s11633-013-0717-x.