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Comparative Analysis of a Novel Robust Fuzzy Control Algorithm, MPC and PID Controllers for an Uncertain Two-Link Planar Manipulator Robot with External Disturbances

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This paper presents a novel robust fuzzy controller for a planar manipulator robot. Also, model predictive control and proportional–integral–derivative techniques are used to compare the results with the proposed method. The control system of manipulator robots must have some special features, which guarantee the stability, fast tracking, practicability of control signals, smooth control, etc. A comparative analysis can provide a clearer picture of the control system's performance. In this study, a comparative analysis is presented between: the novel robust fuzzy technique, model predictive control, and proportional–integral–derivative controllers for a two-link planar manipulator robot. Simulink/MATLAB toolbox is used to simulate the controllers. The results show that the proposed robust fuzzy method performs better and is more robust than other methods. The integral of the absolute value of the error (IAE) and integral of the time absolute value of the error (ITAE) performance indexes are employed for better and more logical comparison. Moreover, the control methods are compared with the essential control features such as accuracy, fast-tracking, robustness, etc., and for all the features, the proposed fuzzy method is better than others.

topics: robot, fuzzy, model predictive control (MPC), proportional–integral–derivative (PID) controller

1. Introduction

Control systems of manipulator robots have become popular due to the increasing demands for the smart functionality of robotics in Industry 4.0. The industrial demand is to make robots fast, efficient, and robust. This attracts the attention of researchers to develop new methods for robots. Recently, manipulator robots have been used in a lot of applications, such as industry [1–3], surgery [4, 5], school [6], society [7], etc. The control system in the manipulator robust has a critical role. Several approaches are developed in the literature for manipulator robots. In recent years, some control methods have been combined with fuzzy logic. For example, in [8] a robust adaptive fuzzy tracking controller is proposed by utilizing the recursive back-stepping approach for non-affine stochastic nonlinear switched systems.

In [9], a novel adaptive fuzzy terminal *sliding mode control* (SMC) technique has been used to design a robust controller for uncertain systems in the presence of disturbances. The results revealed that the fuzzy technique provides faster and more accurate tracking performance compared to the non-fuzzy control method. The fuzzy logic controller is used as the main controller in [10]. In [11], it is used as a part of the controller estimator. Some examples of systems controlled using fuzzy logic are:

(i) fuzzy logic and *internet of things* (IoT) for water and energy saving [12],

(ii) DC/DC converters designed for non-minimum-phase [13],

(iii) *permanent magnet synchronous motor* (PMSM) speed control [14],
(iv) synchronization for two Chua systems [15],
(v) autonomous underwater robot [16],
(vi) impedance control for manipulator robots [17].

In [18], *model predictive control* (MPC) for two-link planar robot is presented using the feedback linearization control method. The nonlinear dynamic model of the robot is linearized, and MPC controller is applied to it. In [19], MPC is compared with a linear quadratic control method, and results showed that MPC outperforms linear quadratic control when applied to robotic manipulators. In [20], PID-based MPC is designed and tested for two-link vertical manipulator robot. In [21], MPC is tested for linearized dynamic manipulator robot in simulation. In [22], MPC for two-link robot is tested in simulation, and it is concluded that MPC can be used in robotic control application. In [23], performance of PID controller is investigated for tracking trajectory control of a two-link robotic manipulator. Moreover, this technique is tested in simulation. There is a literature review which examined PID, fuzzy, and sliding mode control approaches for two-link manipulator robots [24]. In [25], neuro fuzzy-based controller method is compared with the PID control method for sorting and placing balls using the six *degree of freedom* (DOF) robotic arm. Experimental tests showed that the neuro-fuzzy controller showed promising results. In [26], variant of PID controller, which is fractional order fuzzy-sliding-mode PID, has been compared with the integral order fuzzy-sliding-mode PD controller and tested in simulation for a two-link robotic manipulator. The nonlinear self-tuning controllers are also new control techniques that are suitable for robotic systems [27].

The main contribution of this paper is that it formulated the control problem for two-link planar robotic manipulator, and then solved it with three control methods: novel robust fuzzy, MPC, and PID. The control problem is the tracking of the desired trajectory of manipulator robot as a robust and fast controller. The simulation results of Simulink/MATLAB software show that the proposed fuzzy controller outperforms other control methods. The proposed robust fuzzy control method has the following features:

- smooth and fast tracking,
- high control accuracy,
- robustness against uncertainties and external disturbances,
- feedback-based output,
- is suitable for nonlinear applications,
- is smart in tracking the time-varying trajectories,
- uses only the robot joint's positions in the control law.

2. Problem statement

2.1. Dynamic model

Figure 1 shows the two-link planar manipulator robot that is studied in this paper. The nonlinear model of the manipulator robot is used to apply the PID and robust fuzzy controllers, and the linearized model is used to apply the MPC. The nonlinear dynamic model of the two-link manipulator robot has been presented in [28] as follows

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = u(t) + \tau_d, \tag{1}$$

where $q, \dot{q}, \ddot{q} \in \mathbb{R}^2$ refer to the angular position, velocity, and acceleration of the robot, respectively; $M(q) \in \mathbb{R}^{2\times 2}$ is a symmetric and positive-definite inertia matrix; $C(q,\dot{q}) \in \mathbb{R}^{2\times 2}$ is the centrifugal and Coriolis matrix. Further, $G(q) \in \mathbb{R}^2$ is the gravity term, $u(t) \in \mathbb{R}^2$ is the control input (torque input) vector of the robot, and $\tau_d \in \mathbb{R}^2$ is a model of the uncertainties and external disturbances vector. By choosing the system state as $x = [x_1, x_2, x_3, x_4]^{\mathrm{T}} = [q_1, \dot{q}_1, q_2, \dot{q}_2]^{\mathrm{T}} \in \mathbb{R}^{4\times 1}$ the dynamical model can be expressed by the following equation

$$\begin{cases} \dot{x}_{2j-1} = x_{2j}, \\ \dot{x}_{2j} = \dfrac{1}{m_{jj}} \begin{pmatrix} u_j(t) - m_{12}\ddot{q}_{j'} - c_{1j}x_2 \\ -c_{2j}x_4 - g_j + \tau_{d_j} \end{pmatrix}, \end{cases} \tag{2}$$

where $j = (1,2)$, $j' = (2,1)$, and the elements of the matrices are presented as

$$M = \begin{pmatrix} m_{11} & m_{12} \\ m_{12} & m_{22} \end{pmatrix};$$

$$\begin{cases} m_{11} = p_1 + p_2 + 2p_3\cos(x_3) - 2p_4\sin(x_3), \\ m_{12} = p_2 + p_3\cos(x_3) - p_4\sin(x_3), \\ m_{22} = p_2. \end{cases} \tag{3}$$

The values of the parameters are: $p_1 = 0.0398$, $p_2 = 0.0026$, $p_3 = -0.0015$, $p_4 = 0.0081$, while the values of the matrices of the centrifugal and Coriolis and gravity vector are, respectively,

$$C = \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix}; \quad \begin{cases} c_{11} = -2bx_4, \\ c_{12} = -bx_4, \\ c_{21} = bx_2, \\ c_{22} = 0, \\ b = p_3\sin(x_3) + p_4\cos(x_3), \end{cases}$$

$$G = \begin{bmatrix} g_1 \\ g_2 \end{bmatrix}; \quad \begin{cases} g_1 = f_{v_1}x_2 + f_{c_1}\operatorname{sign}(x_2), \\ g_2 = f_{v_2}x_4 + f_{c_2}\operatorname{sign}(x_4). \end{cases} \tag{4}$$

The parameter values are $f_{v_1} = 0.534684$, $f_{v_2} = 0.001$, $f_{c_1} = 0.81958$, $f_{c_2} = 0.002$. The nonlinear model presented in (2) is linearized around the operating points. The linearized model is presented as follows

$$\begin{cases} \dot{x} = Ax + Bu + Ed, \\ y = Cx + Du, \end{cases} \tag{5}$$

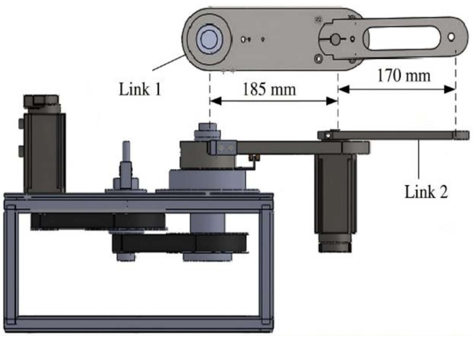

Fig. 1. Two-link planar manipulator robot [28].

where $x \in \mathbb{R}^4$ is the system's states vector, $u \in \mathbb{R}^2$ is the control inputs vector, $d \in \mathbb{R}^2$ is the model of the uncertainties and external disturbances vector, and $y \in \mathbb{R}^{4\times1}$ is the output's vector. The elements of the matrices are as follows

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -2.70\times10^6 & -4.07\times10^{-8} & 1.92\times10^4 \\ 0 & 0 & 0 & 1 \\ 0 & 7.90\times10^6 & 2.60\times10^{-7} & -1.33\times10^5 \end{bmatrix},$$

$$B = \begin{bmatrix} 0 & 0 \\ 33.064 & -96.453 \\ 0 & 0 \\ -96.453 & 6.6598 \end{bmatrix}, \quad C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$D = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, \quad E = \begin{bmatrix} 0 & 0 \\ 38.1679 & 0 \\ 0 & 0 \\ 0 & 384.615 \end{bmatrix}. \tag{6}$$

2.2. Control goals

This paper aims to control the two-link planar manipulator robot by PID, MPC, and a novel fuzzy algorithm. The PID and fuzzy controllers will be applied to the nonlinear model, and MPC will be applied to the linearized model.

The control problem is tracking of the desired trajectories in the presence of external disturbances. The models are also uncertain, so the controller should be robust against the uncertainties and external disturbances. The control techniques are compared in two feature and numerical phases. For the comparison in the feature phase, the controllers are compared while considering some important and essential features, which are specific for the manipulator robots. In the numerical phase, the following performance indexes are defined and used to compare the control methods

$$\begin{cases} \mathrm{IAE}_{e_i} = \int \mathrm{d}t\ |e_i|, \\ \mathrm{ITAE}_{e_i} = \int \mathrm{d}t\ |e_i|, \end{cases} \tag{7}$$

TABLE I

Fuzzy roles for output 1.

Input 1,2	VS	S	M	H	VH
VS	VS	S	M	H	VH
S	VS	S	M	H	VH
M	S	S	M	H	VH
H	S	M	H	H	VH
VH	M	M	H	VH	VH

VS = very small, S = small, M = medium, H = high, VH = very high

TABLE II

Fuzzy roles for output 2.

Input 1,2	VS	S	M	H	VH
VS	VS	M	S	M	VH
S	S	H	M	VS	S
M	VS	S	S	VS	M
H	S	M	H	H	VS
VH	H	M	VH	VH	VH

VS = very small, S = small, M = medium, H = high, VH = very high

where $e_i = x_i - x_{i_d}$, $i = (1,2,3,4)$, with the desired trajectory x_{i_d}. Hence, the goal of this study is to design a novel robust fuzzy control system to track the desired trajectories in the presence of uncertainties and external disturbances.

3. Controller design

3.1. Robust fuzzy controller

The proposed control system is a type of fuzzy controller. The proposed control law is designed as follows

$$u_j = -K_{2j-1}\, e_{2j-1}; \quad j = 1,2, \tag{8}$$

where K_{2j-1} are the outputs of the fuzzy system. This control law uses only the robot joint's positions (no velocities and accelerations), which means that in the practical studies we need to pay lesser cost due to the only requirement being the position sensors. The control parameters K_{2j-1} should be tuned by the fuzzy system. The proposed fuzzy system is Mamdani. For the purpose of designing the fuzzy controllers, we must design membership functions and fuzzy roles. The proposed fuzzy roles are presented in Tables I and II.

The proposed fuzzy control system consists of four inputs and two outputs, where output 1 = K_1, output 2 = K_3 are control parameters. In turn, the inputs are the system's states as input 1 = x_1, input 2 = $\dot{x}_1$, input 3 = x_3, input 4 = $\dot{x}_3$. The proposed membership functions are as presented in Figs. 2 and 3.

In Sect. 4, a scenario is considered to simulate and compare the control methods.

3.2. MPC controller

Model predictive control (MPC) algorithms are gaining popularity, especially their applications in chemical processes industries. These algorithms use a model of the controlled system in the state-space form. The model is applied to predict future values of the output signals, whereas an optimisation procedure (e.g., quadratic programming — QP) can be implemented to calculate the controls within a certain fixed horizon into the future.

MPC for continuous time, being a linear model, with additive disturbance is presented as follows

$$\begin{cases} x(t+1) = A\,x(t) + B\,u(t) + E\,d(t), \\ y(t) = C\,x(t), \end{cases} \tag{9}$$

where $x \in \mathbb{R}^{4\times 1}$ is a state of the system, $u \in \mathbb{R}^{2\times 1}$ is system input, and $d \in \mathbb{R}^{2\times 1}$ is disturbance and time $t \geq 0$. Also, $A \in \mathbb{R}^{n\times n} B \in \mathbb{R}^{n\times m}$, $C \in \mathbb{R}^{p\times n}$, and $E \in \mathbb{R}^{n\times q}$ are system matrices with n, m, p, and q are the number of the system's states, control inputs, system output, and external disturbances, respectively. The objective of a control system is to track the desired trajectory, and the controller is evaluated periodically with sampling time $t_s > 0$. The receding horizon approach is used to implement the open-loop optimization problem. The cost function J is described as

$$J = \int_0^T \mathrm{d}t\, \left(x^{\mathrm{T}} Q\, x + u^{\mathrm{T}}\, R\, u\right), \tag{10}$$

where u is system input, and x is system state. Also, Q and R are semi-definite matrices and T is terminal time of optimization.

Moreover, the prediction of the system's output j-steps ahead is given by

$$\hat{y}\,(t+j|t) = CA\,\hat{x}(t|t) + \sum_{N=1}^{j} CA^{j-N} B\, u(t+N-1) + \sum_{N=1}^{j} CA^{j-N} E\, d(t+N-1), \tag{11}$$

where $\hat{x}(t|t)$ denotes the estimation of the system state at time t. If the state of the system is known (measured), then the estimate becomes equivalent this this measured state ($\hat{x}(t|t) = x(t) = x_t$). Let us consider the following quadratic cost function

$$J_t = \sum_{i=n}^{t+N} \left[y(i+1) - r(i+1)\right]^{\mathrm{T}} \Lambda_e \left[y(i+1) - r(i+1)\right] + \left(u(i)^{\mathrm{T}} \Lambda_u u(i)\right), \tag{12}$$

where Λ_e and Λ_u are the weight matrices, and $r(t)$ denotes the set-point (reference) signal.

Note 1: It is assumed that the reference signal is known within the time horizon from $t+1$ to $t+N$. The cost function can be written using vector notation as follows

$$\tilde{J}_t = \left(\hat{Y}_{t,N} - R_{t,N}\right)^{\mathrm{T}} \Lambda_e \left(\hat{Y}_{t,N} - R_{t,N}\right) + U_{t,N}^{\mathrm{T}} \Lambda_u U_{t,N}. \tag{13}$$

The optimisation problem formulated above has an analytical solution. It can be evaluated by solving a corresponding Riccati equation. The control signal vector is as follows

$$U_{t,N} = (S_{t,N}^{\mathrm{T}} \Lambda_e S_{t,N} + \Lambda_u)^{-1} S_{t,N}^{T} \Lambda_e (R_{t,N} - F_{t,N} - T_{t,N}), \tag{14}$$

where other matrices are as follows

$$S_{t,N} = \begin{bmatrix} CB & \cdots & O \\ \vdots & \ddots & \vdots \\ CA^N B & \cdots & CB \end{bmatrix} \tag{15}$$

and

$$F_{t,N} = \begin{bmatrix} C \\ \vdots \\ CA^N \end{bmatrix} A\,\hat{x}, \tag{16}$$

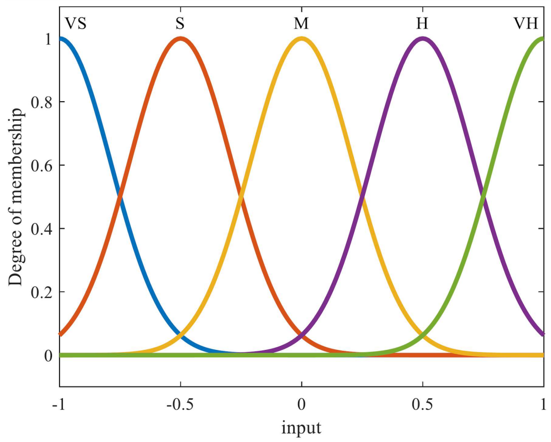

Fig. 2. Input membership functions.

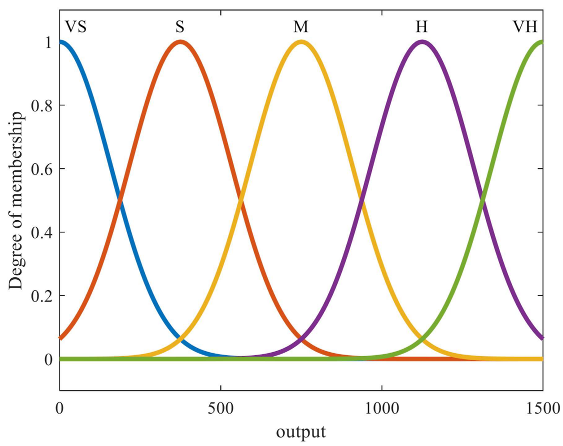

Fig. 3. Output membership functions.

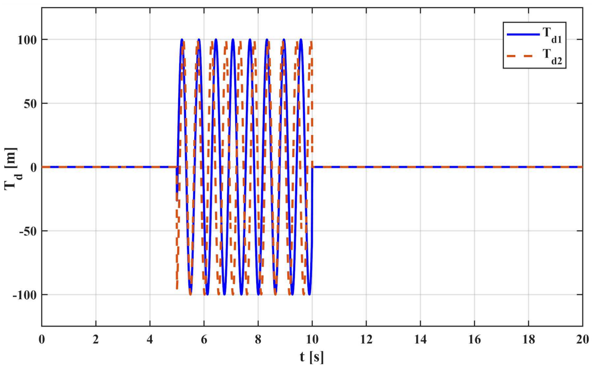

Fig. 4. Applied uncertainties and external disturbances models.

and

$$T_{t,N} = \begin{bmatrix} CE & \cdots & O \\ \vdots & \ddots & \vdots \\ CA^N E & \cdots & CE \end{bmatrix}. \quad (17)$$

MPC implementation is carried out in a MATLAB environment. The linearized model of the system is used in the proposed system. Gains of MPC controller are tuned by minimizing cost function values. After tuning, values are as follows "Prediction horizon" = 10, "Control horizon" = 8.

3.3. PID controller

Proportional–integral–derivative (PID) controller has a simple, easy, and flexible control structure. These controllers are widely used in industrial control applications due to their satisfactory performance. These control methods use less plant information and require minimum effort to tune controller parameters.

The mathematical relationship of PID controller is shown in equation

$$u(t) = K_P\, e(t) + K_I \int_0^t \mathrm{d}\tau\; e(\tau) + K_D \frac{\mathrm{d}e(t)}{\mathrm{d}t}, \quad (18)$$

where the error signal $e(t)$ is minimized by tuning the controller parameters K_P, K_I, K_D. The control signal $u(t)$ derives the plant model generated by the weighted sum of the proportional, integral, and derivative coefficients (denoted by subscripts P, K, D, respectively). The error signal $e(t)$ is the difference between the reference signal $x_d(t)$ and system's state $x(t)$.

Manual tuning of the gain of the controller is carried out. The input to the controller is the error signal, which is the difference between the desired robot position and the estimated robotic position. The filter coefficients (N) is the first order-filtering of the input signal, which reduces overshoots [29].

4. Results

Simulations are all done under the same condition in Simulink/MATLAB software, namely with the numerical solver ode4 (Runge–Kutta) of a sample time 0.01. To simulate control methods, presented systems in (2) (nonlinear model) and (5) (linear model) are used with the following uncertainties and external disturbances models

$$\begin{cases} \tau_{d_1}(t) = 100 \sin(10t), \\ \tau_{d_2}(t) = 100 \cos(12t). \end{cases} \quad (19)$$

These functions are applied to the system for from 5 to 10 s of simulation time. The results of uncertainties and external disturbances models are shown in Fig. 4. The presented models have high frequency and high amplitude. The proposed control method rejects this large-value disturbance.

The proposed fuzzy robust controller is tuned by the presented fuzzy system, the control parameters of which are shown in Fig. 5.

After applying the control methods, the simulation results are presented in Figs. 6–15. In Figs. 6–9 the curves of the system's states have been shown. In Figs. 10–13 the curves of the errors have been shown. Figures 14 and 15 show the curves of the control signals.

The Simulink/MATLAB toolboxes of the MPC and PID controlers have been selected for use in the system. The PID and MPC's control parameters are, respectively,

$$\begin{cases} u_1(t): \; K_{P_1} = 86.40, K_{I_1} = 518.48, K_{D_1} = 2.54, \\ \qquad\quad N_1 = 119.91002, \\ u_2(t): \; K_{P_2} = 13, \; K_{I_2} = 0, \; K_{D_2} = 9, \; N_2 = 9, \end{cases}$$

and

$$\begin{cases} \text{Prediction horizon} = 10, \\ \text{Control horizon} = 8. \end{cases}$$

As discussed in the previous sections, in this study, the control methods are compared; for the purpose of comparison, we need to use some performance indexes. The performance indexes defined in (7) are used for the comparison. The results of the calculation of the performance indexes are presented in Table III. The discussion of the figures and calculated performance indexes are presented in the next section.

5. Discussion

The PID, MPC, and proposed robust fuzzy control methods have been simulated, and the simulations results were presented in the previous section. Also, the results of the calculations of the performance indexes were presented in Table III.

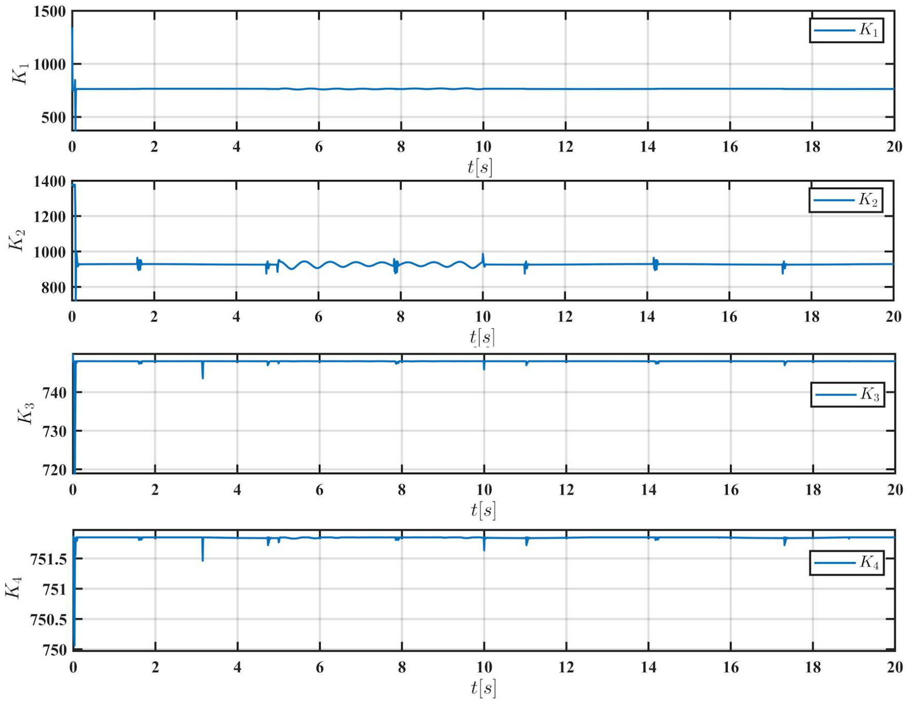

Fig. 5. Control parameters tuned by the proposed fuzzy system.

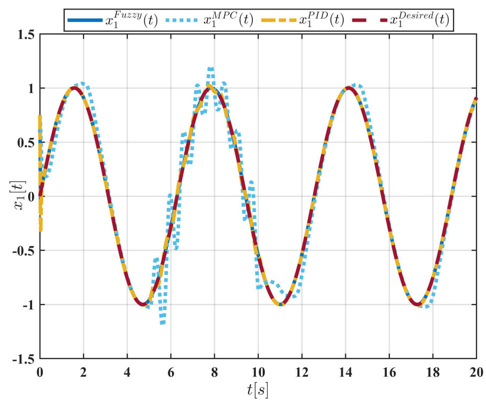

Fig. 6. Curve of the first state by the proposed fuzzy, MPC, and PID controllers.

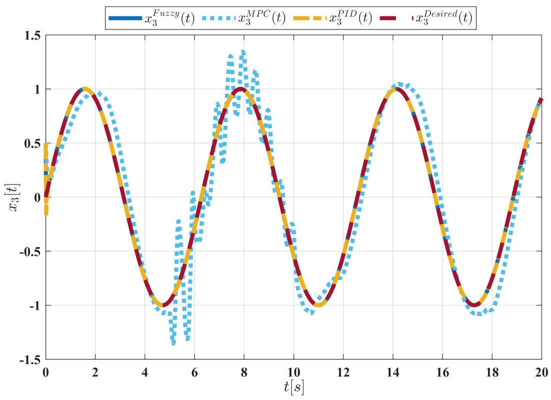

Fig. 8. Curve of the third state by the proposed fuzzy, MPC, and PID controllers.

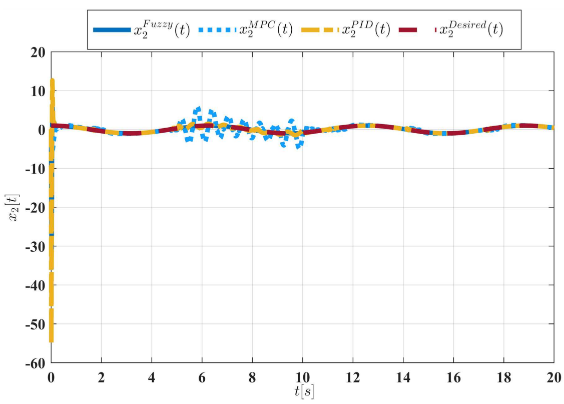

Fig. 7. Curve of the second state by the proposed fuzzy, MPC, and PID controllers.

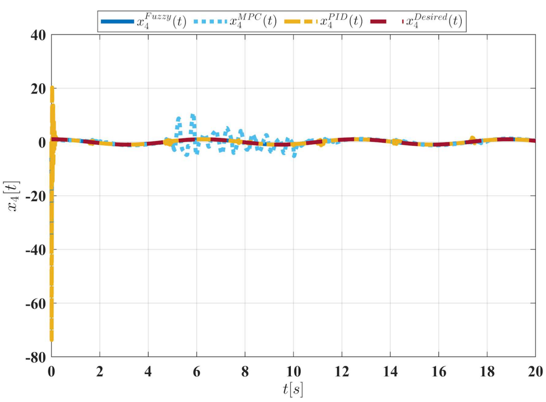

Fig. 9. Curve of the fourth state by the proposed fuzzy, MPC, and PID controllers.

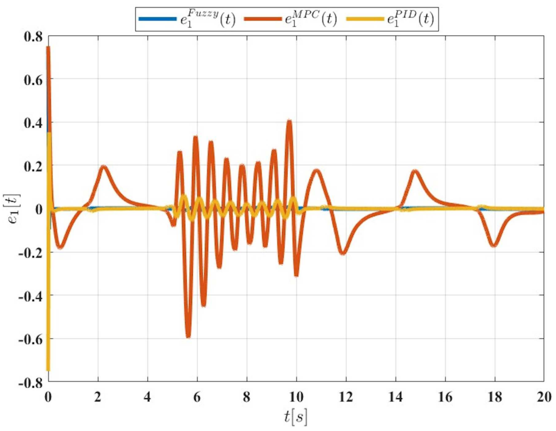

Fig. 10. Curve of the first error by the proposed fuzzy, MPC, and PID controllers.

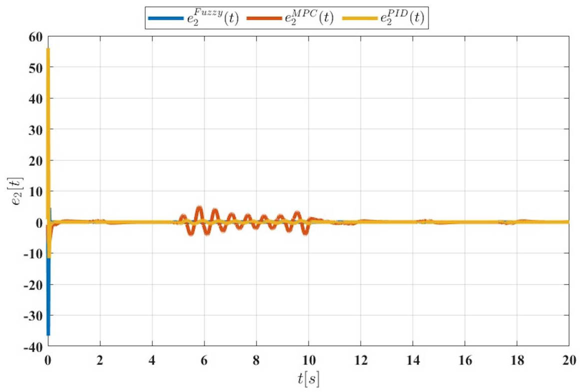

Fig. 11. Curve of the second error by the proposed fuzzy, MPC, and PID controllers.

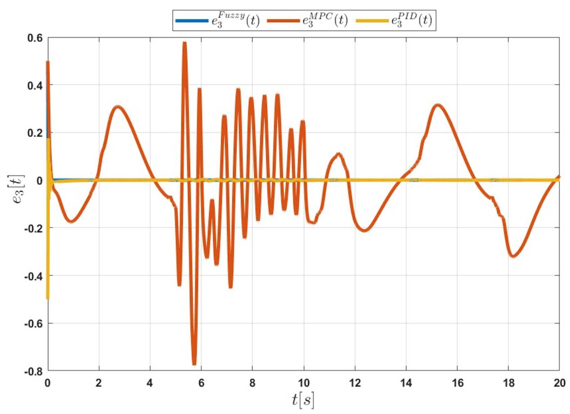

Fig. 12. Curve of the third error by the proposed fuzzy, MPC, and PID controllers.

Figures 6–15 show system's states track the desired trajectories faster and more robustly with proposed fuzzy controller rather than PID and MPC. Table IV compares the simulation results with different features.

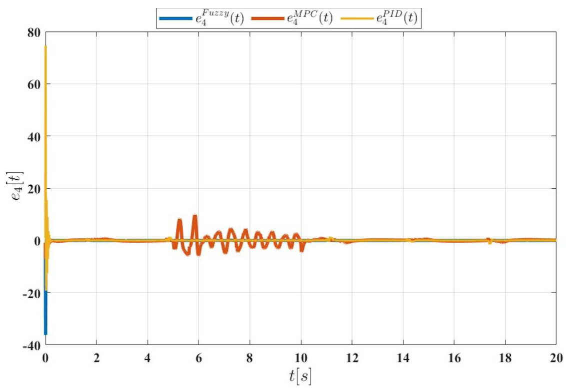

Fig. 13. Curve of the fourth error by the proposed fuzzy, MPC, and PID controllers.

TABLE III

Results of the performance indexes of three controllers.

Indexes	Proposed fuzzy	PID	MPC
IAE_{e_1}	0.0516	0.1844	0.7888
IAE_{e_2}	1.2341	3.0799	6.3274
IAE_{e_3}	0.0054	0.0346	0.4098
IAE_{e_4}	0.5925	2.7256	1.8284
$ITAE_{e_1}$	0.3640	1.2736	6.7910
$ITAE_{e_2}$	2.1127	12.6453	44.3817
$ITAE_{e_3}$	0.0100	0.1519	4.0461
$ITAE_{e_4}$	0.7368	8.8323	11.6603

TABLE IV

Comparison of three controllers.

Control methods	Proposed fuzzy	MPC	PID
robustness	high	low	medium
accuracy	high	low	medium
chattering	free	free	free
smooth control	yes	yes	yes
fast tracking	yes	yes	no
feedback	position	position, velocity	position, velocity
implementable	yes	yes	yes

Moreover, calculations in Table III shows that the accuracy of the fuzzy controller is better than of other two control methods (PID, MPC), However, the performance of PID is better than MPC. As a brief discussion, the features of the proposed fuzzy controller can be listed as follows:

- robustness against high-amplitude and high-frequency uncertainties and external disturbances (Figs. 6–9 and equation (19));
- high-accuracy control considering the performance indexes (Table III);

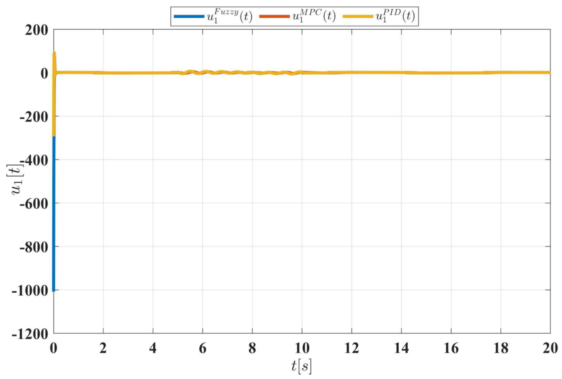

Fig. 14. Curve of the first control signal generated by the proposed fuzzy, MPC, and PID controllers.

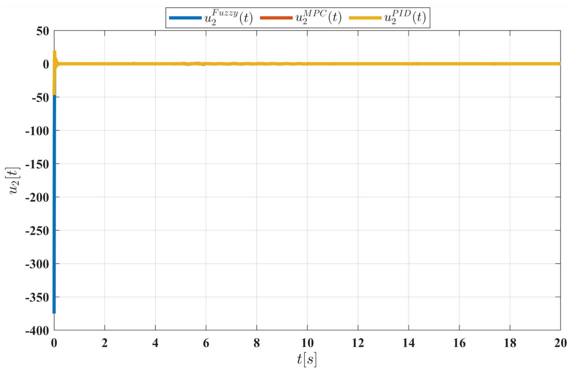

Fig. 15. Curve of the second control signal generated by the proposed fuzzy, MPC, and PID controllers.

- control signals are chattering-free (Figs. 14 and 15);
- smooth control, as the states do not have any unwanted overshoot and lower shots (Figs. 6–9);
- fast tracking, as the states track the desired trajectories quickly (Figs. 6–9);
- the control law uses only the positions of the robot (see (8));
- as the amplitude of the control signals is not very high (the control signals can be generated by the robot's motors), the controller is implementable (Figs. 14 and 15).

6. Conclusions

In this paper, a novel robust fuzzy controller has been developed to control a two-link planar manipulator robot. The robot has been controlled by the proposed method and two common PID and MPC control methods. A detailed comparative analysis was carried out to show the power of the proposed controller. One of the features of the proposed method was the robustness against high-amplitude and high-frequency uncertainties and external disturbances. One of the novelties of the controller was using only the joints' positions for fast, accurate, and smooth controlling of the robot. The control parameters generated by the fuzzy system are used in the control laws. The proposed control method can be used as an intelligent control system in different applications. For future works, it is suggested to minimize the fuzzy roles and optimize the amplitude of the membership functions.

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