Model Reference Adaptive Control Strategy for Application to Robot Manipulators

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Abstract. The geometric nonlinearities, strong couplings, and the dependence on the inertia payload in the system dynamics of the robot manipulators lead to the difficulty in achieving good control performance. Conventional control methods cannot compensate for the payload variation effect. On the other hand, the mathematical model of the robot systems is extremely complicated and consumes an excessive amount of time in computing the robot dynamics. Moreover, deriving an exact mathematical model of the manipulator is very difficult. To handle the above issues, the model reference adaptive controller for motion control applied to robot manipulators is presented in this paper. The control law is based on the decentralized linear joint control strategy. In this approach, the control law does not require the exact model of the joint. Experiments are conducted on the 4-DOF robot manipulator to demonstrate the practicality and feasibility of the proposed control scheme, and the results are compared to those of the Ziegler-Nichols method-based PID controller and those of the model-independent controller based on time-delay estimation technique. The comparison results show that the control performance of the proposed scheme is better than that of the other controllers.

Keywords: Motion control · Decentralized control · Model reference adaptive control (MRAC) · Time-delay estimation (TDE)

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1 Introduction

The user-oriented demand of robot manipulators used in small industries such as painting and welding work is increasingly remarkable in the last few decades. The basic requirement of motion control for this kind of applications is usually described as follows, given the prescribed trajectory, a well-known mathematical model of the robot system and its interactions with surroundings, design a control law that generate the control signals to the actuators to reconstruct accurately the motion. However, control system design for such robot systems there are some obstacles such as uncertainties in parameter identification, natural nonlinearities in the system dynamics, variations of the system parameters due to the posture change of the robot, and the effect of external disturbances. There has been much effort in developing robust advanced control techniques to obtain acceptable control performance. These robust advanced control techniques can be listed as the conventional computed-torque control [1], sliding mode control [2, 3], and adaptive control [4]. However, the aforementioned controllers are the model-based control methods which require the complicated calculations of the high nonlinearity terms of the robot dynamics equations. Henceforth, it is not easy to apply these conventional model-based control techniques for practical implementation. To realize the simplicity in estimating system dynamics parameters, fuzzy logic control [5] and neural network [6] are incorporated to approximate unknown functions. By introducing these intelligent control techniques, neither offline identification nor prior knowledge of the perfect model of the manipulator is required. However, such implementation of intelligent control methods is hindered because they introduce many design parameters and complicated rules which may heavily affect the overall control performance. Therefore, intelligent-based control techniques may be not a good solution.

As a simple alternative choice to the aforementioned techniques, the model reference adaptive control method was proposed for control of robot manipulators in the 1980s. The first idea to apply model reference adaptive control to manipulators was introduced by Dubowsky and DesFores [7]. In [8], the MRAC method for a dynamically uncertain hydraulic robot for position tracking was implemented. The authors employed a recursive parameter estimator for the parameter estimation. Although the tracking performance obtained from MRAC method was better than that of a PID control system, there was an issue was that a small fluctuation exists at the beginning of the movement. The authors [9] illustrated the application of the MRAC method for tracking the endpoint of a flexible joint manipulator which was used in space exploration. Some numerical simulations pointed out that the adaptive control strategy could maintain the stability and good tracking performance in spite of large uncertainties in the joint stiffness coefficients. A nonlinear model reference adaptive controller working together with impedance control approach was proposed in [10] for asymptotic tracking control of the robot end-effector in physical human-robot interaction issue. A novel enhanced human-robot interaction system based on model reference adaptive control was presented in [11]. In this paper, the control system was included two control loops, the one is a robot-specific inner integrated the neural network, it was utilized to learn the robot dynamics online and make the robot behaves as the prescribed impedance model, while the other one is the task-specific loop which took the human dynamics into account and updated the desired impedance model in order to obtain the desired characteristics for the human-robot task performance. A model-free model reference adaptive fuzzy sliding mode control was proposed to control a 5-DOF robot manipulator in [12]. The proposed method coped with the implementation problem in a multivariable robotic system. The shortcoming idea comes from the paper is that the controller drove the system state variables to reach a user-prescribed sliding surface and then slid along it to approach the desired reference model. Experimental results showed that the controller has good control performance, stability, and robustness. The authors in [13] presented an adaptive global asymptotic stable control method for compensating the friction and disturbance effects on the manipulators. The control system combined MRAC and exact linearization. In order to control the system to track the desired reference model response, the disturbance compensation scheme was employed to counteract the modeling error, disturbance, and noise. Simulation results were shown to verify the effectiveness of the proposed method. The MRAC PID controller for controlling a compliant flexures-based XY micro-positioning stage was presented in [14], in which the control parameters were systematically tuned based on intuitive desired performance and robustness. Experimental results indicated that the designed controller performed the expected performance.

However, most of the above-mentioned papers either just gave the simulation results, or extreme difficulty to carry out the control system due to the heavy calculations of the nonlinear terms of the robot dynamic equations. In this paper, an independent joint controller using the direct model reference adaptive control method is proposed for the position tracking control problem applied to robot manipulators. To do this task, the process is described as follows: Firstly, in order to cope with the difficulty in deriving the nonlinear mathematical model of the robot system, the second-order, linear time-invariant model is employed as the reference model for each joint of the manipulator. Secondly, the adaptive control algorithm based on the reference model is developed to assure the stability of the system and obtain good control performance. Finally, the efficiency and the performance of the proposed control method are validated through experiments on a 4-DOF robot arm, and the results are compared with those of the Ziegler-Nichols method-based PID controller and the ones of the model-independent controller based on time-delay estimation technique.

The rest of the paper is structured as follows: The system modeling and problem statement are presented in Sect. 2. Controller design is derived in Sect. 3. Section 4 shows experimental results and discussion. The conclusion and future work are summarized in Sect. 5.

2 System Modeling

2.1 Problem Statement

Consider the standard form of the dynamic equations of an n-DOF robot manipulator:

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}}) + \mathbf{G}(\mathbf{q}) + \mathbf{F}(\mathbf{q},\dot{\mathbf{q}}) + \boldsymbol{\tau}_{\mathbf{d}} = \boldsymbol{\tau} \tag{1}$$

where $\mathbf{q}, \dot{\mathbf{q}}\, \ddot{\mathbf{q}} \in R^n$ stand for the joint position, velocity, and acceleration, respectively; $\mathbf{M}(\mathbf{q}) \in R^{nxn}$ is the positive definite inertia matrix; $\mathbf{C}(\mathbf{q},\dot{\mathbf{q}}) \in R^{nx1}$ stands for the Coriolis (centrifugal) vector; $\mathbf{G}(\mathbf{q}) \in R^n$ the gravitational vector; $\mathbf{F}(\mathbf{q},\dot{\mathbf{q}}) \in R^n$ denotes the friction forces; $\boldsymbol{\tau}_{\mathbf{d}} \in R^n$ is the disturbance torques; and $\boldsymbol{\tau} \in R^n$ is the joint torque. Basically, this equation is a set of strong coupling and high nonlinearity differential equations which lead to the control design and practical implementation based on Eq. (1) are extremely complicated. In this study, we present a simple method for mathematical modeling of joints on a robot system. Our studied system is a 4-DOF robot system (RRRR) in which each joint is driven by a permanent magnet DC motor with a reduction gear, and an incremental encoder to sense angular displacement is attached to each joint. The following section will precisely describe the method.

2.2 Mathematical Modeling

As well known, the robot dynamics is highly nonlinear and strongly coupled due to the nonlinear terms and the disturbance terms. A more practical controller design solution is to decide the control inputs to the actuators that drive the corresponding joints. Nowadays, most industrial manipulators utilize DC motors with high gear ratio as the joint.

The dynamic equation of a joint of such a robot manipulator can be written as:

$$J_m\ddot{\theta} + B_m\dot{\theta} = K_a v_a - K_g \tau_L \tag{2}$$

where J_m the total inertia of rotor and gear, B_m viscous friction coefficient, v_a applied voltage, K_a voltage constant, K_g gear ratio, τ_L is the load torque caused by the joint of the robot arm, θ joint angular position. In the structure of an n-DOF manipulator, τ_{Li} at the i^{th} joint can be expressed as in Eq. (1) as follows:

$$\tau_{Li} = \sum_{j=1}^{n} m_{ij}(\mathbf{q})\ddot{q}_j + c_i(\mathbf{q},\dot{\mathbf{q}}) + g_i(\mathbf{q}) + f_i(\dot{\mathbf{q}}) + \tau_{di} \tag{3}$$

It should be noted that the typical values of gear ratios range from 30:1 to 300:1. Subsequently, the nonlinear terms in the dynamic equations and coupling interactions among the joints are noticeably reduced. This fact allows designers to design controllers for joints individually based on Eq. (2) with external interactions can be considered as a disturbance. The studied system structure is illustrated schematically in Fig. 1(a) in which the positive direction is indicated by the arrows, whereas the system for the experiments is shown in Fig. 1(b).

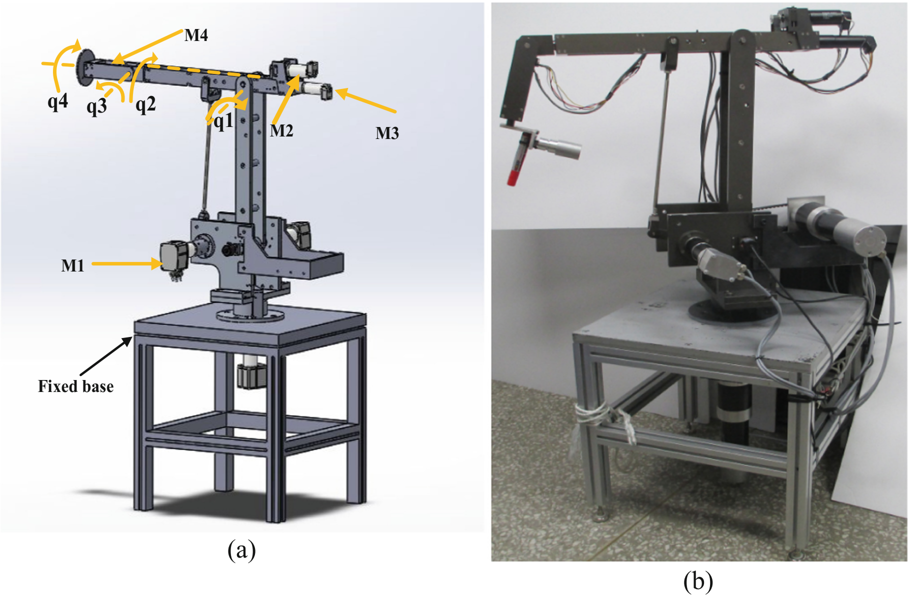

Fig. 1. System demonstration: (a) schematic structure, (b) real system for experiments

3 Model Reference Adaptive Controller Design

3.1 Overview of Adaptive Control

Since the fact that the modeling of the joint in a robot system has some unknown parameters such as friction, moment of inertia, couplings, etc. To identify the system parameters, it takes a great deal of time, some special hardware and software equipment, and experimental studies to analyze the dynamic characteristics of the joint model. On the other hand, there are large variations in the system dynamics of the robot due to the posture change during the operation, carrying different payloads, the effect of Coulomb friction, etc. Adaptive control, since has been widely deployed to handle the above issues. Among many adaptive control methods, the direct MRAC method based on the Lyapunov stability theory is one of the main schemes widely utilized. The interesting thing in this method is that the control scheme directly adjusts the control parameters in the controller under the condition that the plant parameters are poorly known, uncertain, or even unknown.

3.2 Model Reference Adaptive Controller Design

The control objective is to determine the control inputs for the model reference adaptive control system such that the plant position output tracks a reference model position output. In addition, a reference model is chosen for the reference outputs to track the desired reference inputs.

Consider Eqs. (2) and (3), the dynamic equations of the i^{th} joint of the robot system can be formulated as second-order differential equations, and in general, can be formed as follows:

$$\alpha_{0i}\ddot{\theta}_i + \alpha_{1i}\dot{\theta}_i + \alpha_{2i}\theta_i = \beta_{0i}u_i \tag{4}$$

where $i = 1 \div 4$ indicates the corresponding joint; α_{0i}, α_{1i}, α_{2i} are uncertain parameters; u_i applied voltage, β_{0i} voltage constant coefficient. Equation (4) can also be written in matrix form as:

$$\begin{cases} \dot{\mathbf{x}}_i = \mathbf{A}_i\mathbf{x}_i + \mathbf{b}_i u_i \\ y_i = \mathbf{c}_i\mathbf{x}_i \end{cases} \tag{5}$$

where $\mathbf{x}_i = [\theta_i \, \dot{\theta}_i]^T$ state variable vector of the i^{th} joint, θ_i, $\dot{\theta}_i$ angular position and angular velocity output, u_i the control input, $\mathbf{c}_i = [1 \;\, 0]$, and unknown constant matrices $\mathbf{A}_i \in R^{2x2}$, $\mathbf{b}_i \in R^{2x1}$ are given as follows:

$\mathbf{A}_i = \begin{bmatrix} 0 & 1 \\ -\alpha_{2i}/-\alpha_{0i} & -\alpha_{1i}/-\alpha_{0i} \end{bmatrix}$, $\mathbf{b}_i = \begin{bmatrix} 0 \\ \beta_{0i}/\alpha_{0i} \end{bmatrix}$, and $y_i = \theta_i$ is the position output.

As mentioned earlier, in this brief, the control strategy of the system is developed based on the decentralized control technique. For the purpose of position tracking control, a linear time-invariant, second-order reference model for the i^{th} joint is given as:

$$\begin{cases} \dot{\mathbf{x}}_{mi} = \mathbf{A}_{mi}\mathbf{x}_{mi} + \mathbf{b}_{mi}r_i \\ y_{mi} = \mathbf{c}_{mi}\mathbf{x}_{mi} \end{cases} \tag{6}$$

where $\mathbf{x}_{mi} = [\theta_{mi} \, \dot{\theta}_{mi}]$ is the state vector of the reference model of the i^{th} joint, θ_{mi} and $\dot{\theta}_{mi}$ are the reference model angular position and angular velocity output, respectively; r_i is the reference input; $y_{mi} = \theta_{mi}$ is the angular position output; $\mathbf{A}_{mi}$ and $\mathbf{b}_{mi}$ are the reference model system matrix and control distribution vector which can be easily determined through the minimum set of parameters comprising of the undamped natural frequency ω_{ni}, and the damping ratio ξ_i.

The model reference adaptive controller for position tracking control is developed based on the following assumptions:

- Given a known Hurwitz matrix $\mathbf{A}_{mi} \in R^{2x2}$ and known vector $\mathbf{b}_{mi}$, there exists an unknown ideal gain vector $\mathbf{k}_i \in R^{1x2}$ and an unknown ideal gain constant ϕ_i such that the following equations are held

$$\begin{cases} \mathbf{A}_i + \mathbf{b}_i\mathbf{k}_i = \mathbf{A}_{mi} \\ \mathbf{b}_i\phi_i = \mathbf{b}_{mi} \end{cases} \tag{7}$$

- There exists a symmetric positive definite matrix $\mathbf{P}_i$ such that the following equation is satisfied:

$$\mathbf{A}_{mi}^T \mathbf{P}_i + \mathbf{P}_i \mathbf{A}_{mi} = -\mathbf{Q}_i \tag{8}$$

where $\mathbf{Q}_i$ is a symmetric positive definite matrix, and p_{ij} is the $ij - th$ element of the matrix $\mathbf{P}_i$ with $i,j = 1 \div 2$.

The control input can be designed as follows:

$$u_i = \hat{\mathbf{k}}_i \mathbf{x}_i + \hat{\phi}_i r_i \tag{9}$$

where $\hat{\mathbf{k}}_i$, $\hat{\phi}_i$ are the estimated parameters of the unknown ideal gains $\mathbf{k}_i$ and ϕ_i. These estimated parameters are updated online according to adaptation laws in Theorem 1 in the following.

Define the tracking error as

$$\mathbf{e}_i = \mathbf{x}_i - \mathbf{x}_{mi} \tag{10}$$

then, subtracting (6) from (5), combining with (7) lead to the error dynamics as

$$\begin{aligned} \dot{\mathbf{e}}_i &= \dot{\mathbf{x}}_i - \dot{\mathbf{x}}_{mi} = \mathbf{A}_i \mathbf{x}_i + \mathbf{b}_i u_i - \mathbf{A}_{mi} \mathbf{x}_{mi} - \mathbf{b}_{mi} r_i \\ &= \mathbf{A}_{mi} \mathbf{e}_i + \mathbf{b}_i (\tilde{\mathbf{k}}_i \mathbf{x}_i + \tilde{\phi}_i r_i) \end{aligned} \tag{11}$$

where $\tilde{\mathbf{k}}_i = \hat{\mathbf{k}}_i - \mathbf{k}_i$, $\tilde{\phi}_i = \hat{\phi}_i - \phi_i$

Theorem 1. The MRAC system defined by (4)–(6) is stable provided that the system control input in (9) and adaptation laws are given as

$$\dot{\hat{\mathbf{k}}}_i^T = -\gamma_{1i} \mathbf{e}_i^T \mathbf{P}_i \mathbf{b}_i \mathbf{x}_i \, , \dot{\hat{\phi}}_i = -\gamma_{2i} \mathbf{e}_i^T \mathbf{P}_i \mathbf{b}_i r_i \tag{12}$$

where $\hat{\mathbf{k}}_i$, $\hat{\phi}_i$ are estimated parameters and γ_{1i}, γ_{2i} are positive gain constants.

Proof of Theorem 1. To demonstrate the stability of the controller, a Lyapunov function candidate is defined as follows:

$$V_i = \mathbf{e}_i^T \mathbf{P}_i \mathbf{e}_i + \frac{1}{\gamma_{1i}} \tilde{\mathbf{k}}_i \tilde{\mathbf{k}}_i^T + \frac{1}{\gamma_{2i}} \tilde{\phi}_i^2 \geq 0 \tag{13}$$

Consider Eqs. (8), (11)–(13), taking the time derivative of V_i, yields:

$$\dot{V}_i = -\mathbf{e}_i^T Q_i \mathbf{e}_i + 2\tilde{\mathbf{k}}_i \left(\frac{\dot{\hat{k}}_i^T}{\gamma_{1i}} + \mathbf{e}_i^T \mathbf{P}_i \mathbf{b}_i \mathbf{x}_i\right) + 2\tilde{\phi}_i \left(\frac{\dot{\hat{\phi}}_i}{\gamma_{2i}} + \mathbf{e}_i^T \mathbf{P}_i \mathbf{b}_i r_i\right) \tag{14}$$

Next, inserting the adaptive laws (12) into (14), the time derivative becomes

$$\dot{V}_i = -\mathbf{e}_i^T Q_i \mathbf{e}_i \leq 0 \tag{15}$$

This implies that $\mathbf{e}_i$, $\hat{\mathbf{k}}_i$, $\hat{\phi}_i$ are bounded from (13) and (15). Thus, the stability condition of the closed-loop system is satisfied.

3.3 Reference Motion Reconstruction Scheme

Seeing the control law (9), it has two inputs, namely the desired control voltage signal r_i and angular displacement θ_i; the output u_i that will be utilized to force the corresponding joint actuator to track the reference model output. However, instead of using the predefined voltage as the reference input, the desired motion trajectory is preferred for practical applications. Thus, from this point of view, once the reference–motion is given, the corresponding voltage should be generated. For generating the desired voltage, a simple mapping method is implemented via the inverse model of the reference model (6), which is expressed by the following transfer function:

$$G_{mi}^{-1}(s) = \frac{R_i(s)}{\theta_{di}(s)} = \frac{1}{\omega_{ni}^2}\left(s^2 + 2\xi_i \omega_{ni} s + \omega_{ni}^2\right) \tag{16}$$

where R_i and θ_{di} stand for the Laplace form of r_i and θ_{di}, respectively. For easy understanding, Fig. 2 illustrates the structure of the control system.

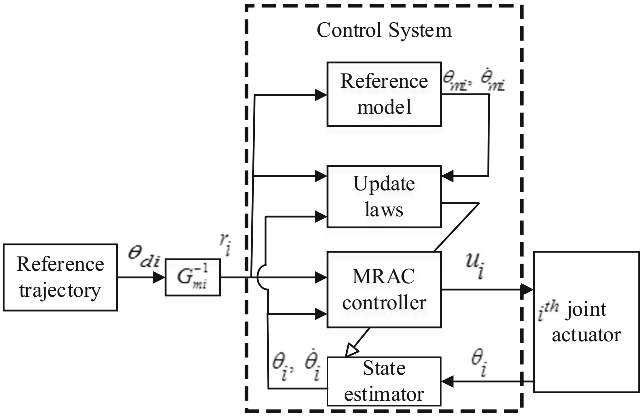

Fig. 2. The structure diagram of the control scheme.

4 Experimental Studies

In order to verify the effectiveness of the proposed control scheme in practical situations, some experiments on the 4-DOF robot manipulator developed in our laboratory as shown in Fig. 1(b) have been conducted. In the experiments, the robot arm is commanded to follow a low-speed sinusoidal trajectory, and afterwards a high-speed sinusoidal trajectory. Besides, two model-free based controllers namely PID and time-delay control (TDC) are utilized for comparing control performances. All parameters of the three controllers are summarized in Table 1.

4.1 Implementation of the Proposed Controller

In this paper, the reference model parameters for all joints are $\omega_{ni} = 16.5$ and $\xi_i = 0.9103$.

Based on the fact that the dynamic equation of the joint is a second-order differential equation, through simulation and an extensive of trial and error times, the plant parameters and the controller gains for all joints are determined.

4.2 Controllers for Comparison

PID Controller

In the PID control system, the controller has the general form as:

$$G_{PID}(s) = \left(K_P + \frac{K_I}{s} + K_D s \right) \tag{17}$$

In this paper, the controller gains are determined through the second experiment method proposed by Zeigler-Nichols.

TDE-Based Controller

In recent years, the control method based on time-delay estimation, especially applied to the robotic field, has attracted a great deal of attention from the robotic community due to its simplicity, efficiency, model-free, and robustness. Herein, the TDE-based nonsingular terminal sliding mode controller (TDE-NTSM) in [15] is applied. Basically, the control method does not require any complex numerical computation of the robot model, nor does it require any online estimation of robot dynamic parameters. The structure of the controller can be briefly expressed as follows:

$$\begin{aligned} v_{ai} &= v_{ai}(t-T) - M_i\ddot{\theta}_i(t-T) \\ &+ M_i\left[\ddot{\theta}_{di} + \frac{b_i}{a_i} c_i^{-1} \dot{e}_i^{2-a_i/b_i} + k_{swi}\,\mathrm{sgn}(s_i)\right] \end{aligned} \tag{18}$$

where v_{ai} is the current control input, $v_{ai}(t-T)$ the time-delayed control input, $\ddot{\theta}_i(t-T)$ the time-delayed value of acceleration, T the sampling time, M_i represents the equivalent inertia moment of the i^{th} joint, $\mathrm{sgn}(s_i)$ is the sign function then replaced by the signum-like function. More details about the controller can be found in [15].

4.3 Experimental Setup

All joints of the manipulator are driven by Maxon DC servo motors comes with drivers through a planetary gear. The maximum continuous torque are 0.192, 0.106, 0.0897, and 0.0279 Nm for joints 1, 2, 3, and 4, respectively. The reduction gear ratio of joints 1, 2, 3, and 4 are 53:1, 53:1, 51:1, and 33:1, respectively. The resolution of the angular sensors at joints 1, 2, 3, 4 are 0.03°, 0.0035°, 0.0035°, and 0.0055°, respectively. In addition, the National Instrument PXIe-8115 controller combined with PXIe-1078 chassis is adopted to implement the control schemes. The chassis is equipped with the data acquisition card PXIe-6363 and PXI-6221. The control algorithms are programmed using the NI LabVIEW 2009 software with the sampling time 0.01 s. The control signals sent to the driver boards of the motors are limited to ±5V.

4.4 Experimental Results

All joints of the manipulator are forced to track the following sinusoidal trajectory

$$q_i(t) = 30\sin(2\pi t/T)\ [\text{degree}] \tag{19}$$

where T denotes the period in second. Two different periods of 20 s and 10 s which denotes the slow speed and high speed are used. The experimental results are arranged in Figs. 3 and 4. Moreover, to make the comparison more precise, the root-mean-square errors (RMS) of the experimental data are listed in Tables 2 and 3.

Table 1. Plant model and controllers' parameters of the three control algorithms.

Control	Joint			
	1	2	3	4
PID	$K_P = 0.552$, $K_I = 0$, $K_D = 0.006$	$K_P = 0.17$, $K_I = 0$, $K_D = 0.004$	$K_P = 0.15$, $K_I = 0$, $K_D = 0.0039$	$K_P = 0.122$, $K_I = 0$, $K_D = 0.0015$
TDE-NTSM	$M = 4.2 \times 10^{-4}$ $a = 19$, $b = 15$, $c = 0.1$ $k_{sw} = 180$, $\delta = 5$	$M = 9.1 \times 10^{-5}$ $a = 21$, $b = 19$, $c = 0.08$ $k_{sw} = 180$, $\delta = 4$	$M = 9.7 \times 10^{-5}$ $a = 21$, $b = 19$, $c = 0.08$ $k_{sw} = 180$, $\delta = 2$	$M = 2.23 \times 10^{-5}$ $a = 9$, $b = 7$, $c = 0.95$ $k_{sw} = 180$, $\delta = 3$
MRAC	$\gamma_1 = 5 \times 10^{-3}$ $\gamma_2 = 1 \times 10^{-3}$ $p_{12} = 2 \times 10^{-2}$ $p_{22} = 5 \times 10^{-3}$	$\gamma_1 = 1 \times 10^{-3}$ $\gamma_2 = 5 \times 10^{-4}$ $p_{12} = 6 \times 10^{-3}$ $p_{22} = 8 \times 10^{-4}$	$\gamma_1 = 5 \times 10^{-3}$ $\gamma_2 = 1 \times 10^{-3}$ $p_{12} = 5 \times 10^{-3}$ $p_{22} = 8 \times 10^{-4}$	$\gamma_1 = 2 \times 10^{-3}$ $\gamma_2 = 5 \times 10^{-4}$ $p_{12} = 2 \times 10^{-3}$ $p_{22} = 1 \times 10^{-3}$

Table 2. RMS errors under low-speed commands [deg].

Control	Joint 1	Joint 2	Joint 3	Joint 4
PID	0.6125	0.4219	0.5584	0.5470
TDE-NTSM	0.3408	0.1695	0.2592	0.5023
MRAC	0.1960	0.1458	0.1701	0.1687

As shown in Figs. 3 and 4, all three controllers can drive the manipulator to accurately track the desired trajectory. In the model reference adaptive control method and the control method based on time-delay estimation, due to the control method do not use the robot dynamic model, they take a short period of time to update the controller gains, after a few seconds the control schemes can drive the manipulator to follow the trajectory very well. Moreover, especially in the MRAC scheme, if the controller's parameters are optimally tuned, it will absolutely take less time to adaptively update the control gains. Particularly, as illustrated in Tables 2 and 3, the proposed control shows the smallest RMS errors among the three controllers of joints under two different periods.

Table 3. RMS errors under high-speed commands [deg].

Control	Joint 1	Joint 2	Joint 3	Joint 4
PID	1.2380	0.8374	1.1138	0.9630
TDE-NTSM	0.9515	0.4391	0.5598	0.9557
MRAC	0.3156	0.1448	0.2724	0.2321

Furthermore, as shown in Fig. 3, when the desired trajectory become more quickly, the control performance has a degradation. Especially, the results obtained from the TDE-NTSM are significantly degraded by a high ratio as shown in Table 3 as compared with those in Table 2. This fact comes as a result because the time-delay estimation–based control techniques presume that the unknown nonlinear dynamics do not change much for a relatively small period of time.

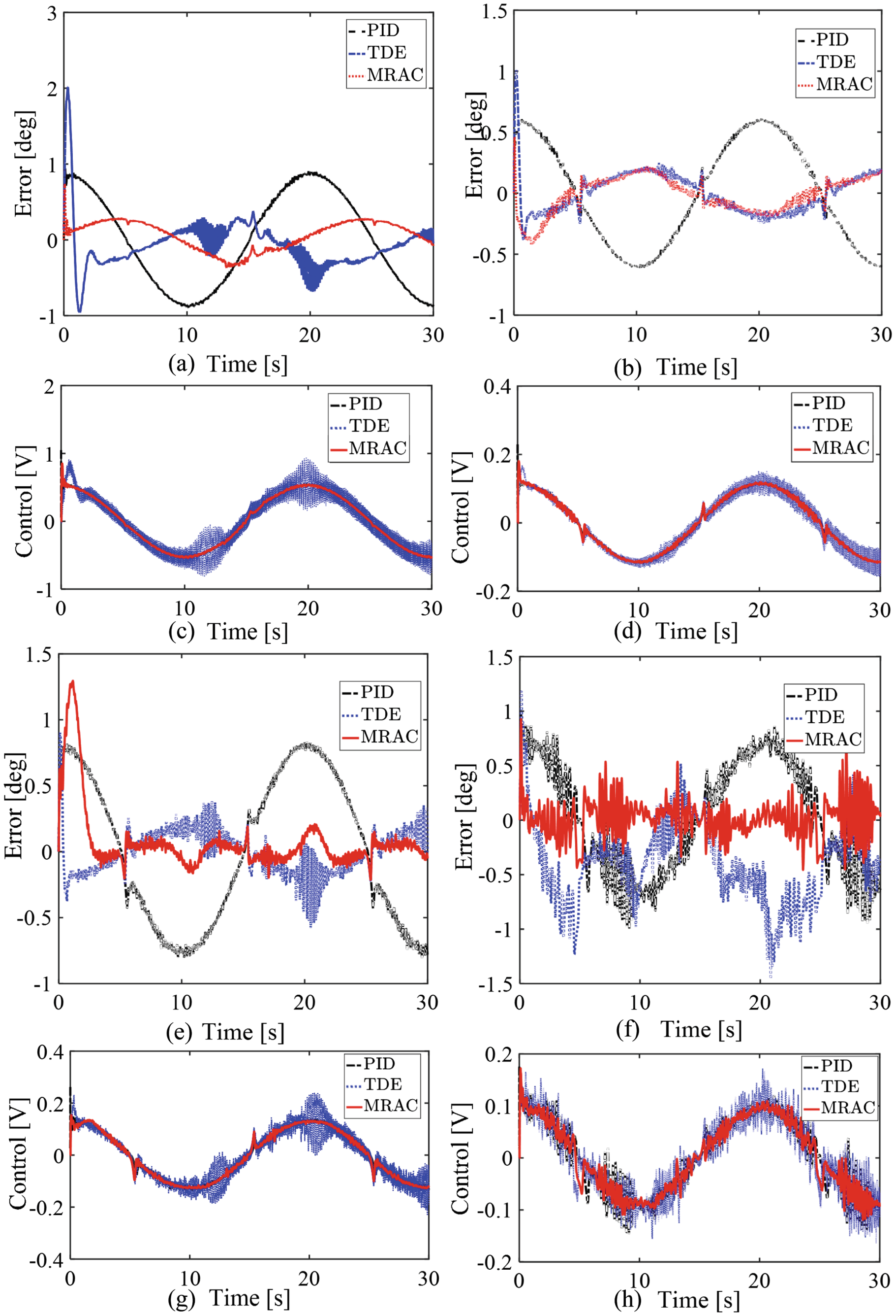

Fig. 3. Experimental results under low speed sinusoidal desired trajectory. (a), (b), (e), and (f) Tracking errors of joints 1, 2, 3, and 4, respectively. (c), (d), (g), and (h) Control inputs of joints 1, 2, 3, and 4, respectively.

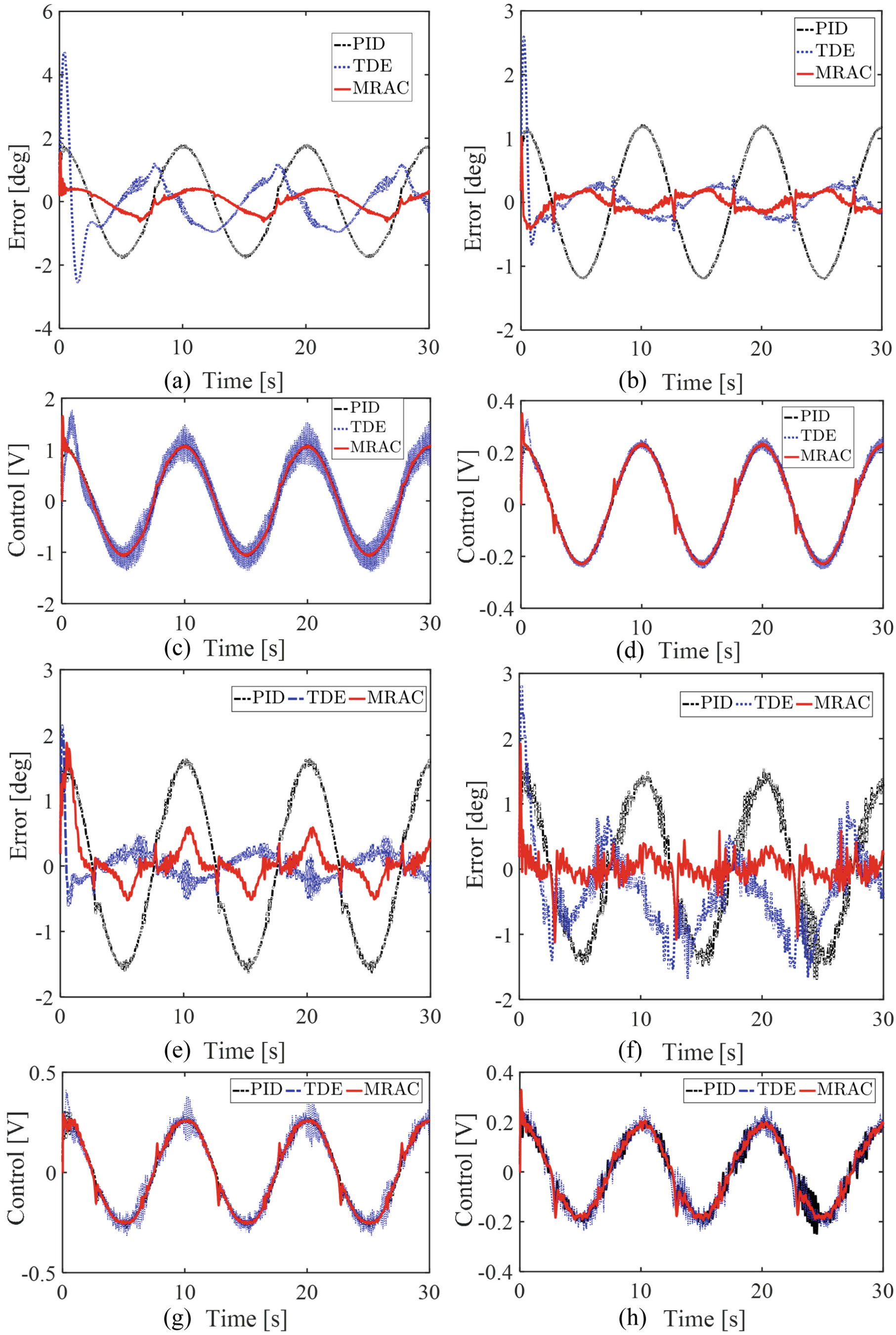

Fig. 4. Experimental results under high speed sinusoidal desired trajectory. (a), (b), (e), and (f) Tracking errors of joints 1, 2, 3, and 4, respectively. (c), (d), (g), and (h) Control inputs of joints 1, 2, 3, and 4, respectively.

5 Conclusion

In this study, we have proposed the decentralized adaptive control strategy using the MRAC method for motion control of robot manipulators. Due to high nonlinearities, strong couplings, and uncertainties in the robot dynamics, it is not easy to obtain the mathematical model of manipulators, thus, three control methods which do not require the exact model have been deployed. Especially, in the TDE–NTSM control method and the MRAC method, the stability of the closed-loop system is guaranteed based on the Lyapunov stability theory. It was verified through experiments that the proposed MRAC scheme can ensure better control performance than that of the conventional PID control and that of TDE-NTSM control despite the presence of unknown parameters and nonlinear uncertainties in the robot dynamics. For further work, in order to enhance the control performance as well as counteract the parameter variations during operation, adaptive control method combining with disturbance rejection techniques should be deployed.

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