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Robust tracking control of robot manipulators with friction and variable loads without velocity measurement: A switched control strategy

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Abstract

This article addresses the adaptive-based robust output feedback tracking control for robot manipulators with friction and alternating unknown loads. A switched nonlinear system is first established to model the friction and parameter variations, caused by the load change. Under arbitrary load changings, an adaptive H_∞ tracking control strategy is proposed to ensure link position tracking, in the presence of uncertainties and external disturbances. Then, for bounded external disturbances, a novel robust adaptive output tracking control strategy is developed, which guarantees all the closed-loop signals are bounded and tracking error is driven to zero. Unlike some previous studies, the proposed algorithms do not require velocity measurements, and the unknown switched parameters and disturbances are neither required to be periodic nor to have known bounds. A simulation study is also given to demonstrate the analytically proved properties of the proposed schemes.

Keywords

Switched nonlinear system, robot manipulators, robust adaptive control, position tracking, output feedback

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Introduction

Over the past decades, the development of controllers for robot manipulator has attracted considerable attention due to their complex nonlinear dynamics and wide applications in industrial systems.[1–4] Various control methods, including proportional-integral-derivative control,[5,6] backstepping method,[7,8] and sliding mode control,[9–11] have been applied to robot manipulators in past decades. In order to improve the tracking performance, various methods have been developed and applied to robotic systems to drive the tracking error to zero.[12,13] Nevertheless, as the friction affects the tracking accuracy at low speed, considering friction is inevitable to achieve high accuracy motion control.[14–16] Accordingly, robot manipulators usually suffer from different uncertainties, such as unstructured dynamics, unknown loads, nonlinear friction, and external disturbances. Thus, it is difficult to find an exact dynamical model for a robot manipulator. In the work by Mohammadi et al.,[17] a disturbance observer has been suggested to tackle the disturbances, based on the immediate angular measurement of link position and velocity. Furthermore, the disturbance may be modelled as a constant direct current parameter, estimated along with the link position and velocity.[18]

Adaptive control, as a powerful strategy to deal with the uncertainties, is widely used for robot manipulators. In previous studies,[19–21] the uncertain parameters are assumed to be constant. In the work by Dumlu,[22] an adaptive and fractional sliding mode control approach for a 6-degree-of-freedom (DOF) robot manipulator has been investigated. This condition is only satisfied if the load of the manipulator is fixed, whereas in practice, a robot manipulator often needs to pick up and lay down some specific loads repeatedly. This causes the value to change among several unknown parameters. In conventional adaptive control, it is assumed that unknown parameters are constant. The jump in

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the value of robot parameters poses a new challenge for adaptive control of robot manipulators. By considering the robot manipulator as a switched system, the load variations can be described by subsystems, each one is activated by a switching signal over a period of time. In the work by Noghreian and Koofigar,[23] it has been proven that an uncertain switched system, under arbitrary switching, is stable if a common Lyapunov function (CLF) exists for all subsystems of the switched system. In the work by Wang and Zhao,[24] an adaptive switched controller has been designed for a nominal switched robot model, whose switching is dominated by the load. H_∞ tracking control problem has been studied for robot manipulators with changing loads in the work by Wang et al.,[25] while no friction has been considered and error convergence to zero has not been achieved.

Many robot controllers, in addition to joint position measurements, require joint velocity measurements, whereas most of robotic systems are only equipped with joint position measurement devices. To overcome this constraint, several researchers have presented link position tracking controllers, by estimating velocity information. With an exact robot model, an observer may be designed either for fault detection or tracking controller design.[26,27] To compensate the robot uncertainty, an adaptive link position controller without joint velocity measurements is suggested in the work by De Queiroz et al.[28] Also, intelligent output feedback controllers, based on fuzzy logic and neural networks, were proposed by Liu and Li[29] and Kim.[30] In addition, global output feedback tracking control of uncertain robot manipulators, using a nonlinear dynamic filter, is provided in the work by Zhang et al.[31]

To the best of our knowledge, robust tracking control problem of robot manipulators with friction and variable loads, without velocity measurements, has been rarely studied before. Therefore, in this article, a switched nonlinear system is first adopted to model robot manipulators with friction and jumping parameters. A high-gain observer is also produced to compensate for the lack of velocity measurement. Then, two adaptive-based robust controllers are proposed to ensure asymptotic link position tracking, despite the switched parametric uncertainty, external disturbances, and the absence of link velocity measurements. The article is organized as follows. In the next section, the switched robot model containing friction and changing loads is proposed. In section "Design of robust adaptive output feedback controller," the output feedback controllers are developed for robot manipulator subject to square-integrable and bounded and external disturbances, under arbitrary switching. A simulation example is introduced in section "Simulation study" to demonstrate the effectiveness of the proposed methods. Finally, the concluding remarks and contributions are summarized in section "Conclusion."

Notations

In the following, $\mathbb{R}^n$ represents the n-dimensional Euclidean space, denotes the natural numbers, $|.|$ represents the absolute value of a scalar, and $||\cdot||$ refers to the induced 2-norm of a vector or a matrix. Moreover, for a $n \times 1$ vector E, $E \in L_\infty[0,\infty)$ if $||E(t)|| < \infty, t \in [0,\infty)$ and $E \in L_2[0,T]$ if $\int_0^T ||E(t)||^2 dt < \infty$, $T \in [0,\infty)$.

System description and preliminaries

Consider the Euler–Lagrange equations of an n DOF robot manipulator as[32]

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = \tau - F(q,\dot{q}) + \omega(t) \quad (1)$$

where $q, \dot{q}, \ddot{q} \in \mathbb{R}^n$ denote the vectors of link position, velocity, and acceleration, respectively; $\tau \in \mathbb{R}^n$ represents the control torque; $\omega(t)$ is the disturbance input; $M(q) \in \mathbb{R}^{n\times n}$, $C(q,\dot{q}) \in \mathbb{R}^n$, and $G(q) \in \mathbb{R}^n$ are inertia matrix, centrifugal, and Coriolis forces matrix and gravitational forces vector, respectively. Furthermore, the friction vector $F(q,\dot{q}) \in \mathbb{R}^n$ which includes Coulomb friction, static friction, viscous friction, and the Stribeck effect can be modelled as[33]

$$F(q,\dot{q}) = \begin{bmatrix} \mathrm{sgn}(\dot{q}_1)\left(\alpha_{01} - \alpha_{11}|\dot{q}_1|^{\frac{1}{2}} + \alpha_{21}|\dot{q}_1|\right) \\ \vdots \\ \mathrm{sgn}(\dot{q}_n)\left(\alpha_{0n} - \alpha_{1n}|\dot{q}_n|^{\frac{1}{2}} + \alpha_{2n}|\dot{q}_n|\right) \end{bmatrix} \quad (2)$$

where α_{ij}, $i = 0,1,2$ are the friction parameters of the jth joint. The friction model (equation (2)) is written here as

$$F(q,\dot{q}) = \begin{bmatrix} \mathrm{sgn}(\dot{q}_1) & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & \mathrm{sgn}(\dot{q}_n) \end{bmatrix} \begin{bmatrix} 1 & -|\dot{q}_1|^{\frac{1}{2}} & |\dot{q}_1| & 0 & \cdots & 0 \\ & & & \ddots & & \\ 0 & \cdots & 0 & 1 & -|\dot{q}_n|^{\frac{1}{2}} & |\dot{q}_n| \end{bmatrix} \begin{bmatrix} \alpha_{01} \\ \alpha_{11} \\ \alpha_{21} \\ \vdots \\ \alpha_{0n} \\ \alpha_{1n} \\ \alpha_{2n} \end{bmatrix} = f(\dot{q})\alpha \quad (3)$$

In practice, robot manipulators have to frequently pick up and lay down certain loads. Also, the friction character can be affected by the changing loads. This causes the system parameters to be changed between several unknown constants. Such evidences motivate to adopt a switched model of the robot manipulator

$$M_\sigma(q)\ddot{q} + C_\sigma(q,\dot{q})\dot{q} + G_\sigma(q) + F_\sigma(q,\dot{q}) = \tau + \omega(t) \tag{4}$$

where $\sigma : [0,\infty) \mapsto \Lambda = \{1,\ldots,N\}$ denotes a piecewise constant right continuous switching signal, and $N \in \mathbb{N}$ is the number of subsystems, specified by number of different loads.

In this article, the control objective is to design a robust link position tracking controller for the uncertain robot model (equation (4)), assuming the load can be arbitrarily changed and velocity measurements are not available. To this end, the following assumptions are considered for the system.

Assumption 1. The dynamic of robot manipulator model (equation (1)) can be linearly parameterized, that is, there exist regression matrix $Y(q,\dot{q},\ddot{q}) \in \mathbb{R}^{n\times m}$ and unknown constant system parameters vector $\theta_\sigma \in \mathbb{R}^m$ such that[24]

$$M_\sigma(q)\ddot{q} + C_\sigma(q,\dot{q})\dot{q} + G_\sigma(q) = Y(q,\dot{q},\ddot{q})\theta_\sigma \tag{5}$$

Therefore, one can rewrite equation (4) as

$$W(q,\dot{q},\ddot{q})\phi_\sigma = \tau + \omega(t) \tag{6}$$

where $W(q,\dot{q},\ddot{q}) = [Y(q,\dot{q},\ddot{q}), f(\dot{q})] \in \mathbb{R}^{n\times(m+3n)}$ contains known functions of link position, velocity, and acceleration and $\phi_\sigma = [\theta_\sigma^T, \alpha_\sigma^T]^T \in \mathbb{R}^{3n+m}$ includes unknown switching parameters determined by loads.

Assumption 2. The switching parameter vector ϕ_σ belongs to a compact set $\Omega = \{\phi_k : \|\phi_k\| \le \varphi, \forall k \in \Lambda\}$, in which $\varphi > 0$ is an unknown constant parameter.

Design of robust adaptive output feedback controller

Define the tracking error vector as $E = [e^T, \dot{e}^T]^T$, where $e = q - q_d \in \mathbb{R}^n$ is the error vector for a smooth desired link trajectory $q_d \in \mathbb{R}^n$. Consider

$$\tau = M_0(\ddot{e} + k_v\dot{e} + k_p e) - \tau_r \tag{7}$$

where $M_0 \in \mathbb{R}^{n\times n}$ is a positive-definite matrix, $k_p \in \mathbb{R}^{n\times n}$ and $k_v \in \mathbb{R}^{n\times n}$ are the proportional and derivative gain matrices, respectively, and τ_r is the robust control to be designed. Substituting equation (7) into equation (6), the state–space model of the error dynamic is obtained as

$$\dot{E} = \begin{bmatrix} 0_n & I_n \\ -k_p & -k_v \end{bmatrix} E + \begin{bmatrix} 0_n \\ I_n \end{bmatrix} M_0^{-1} (\tau_r + W(q,\dot{q},\ddot{q})\phi_\sigma + \omega(t)) \tag{8}$$

where 0_n and I_n denote n dimension zero matrix and identity matrix, respectively. Furthermore, by defining $d(t) = M_0^{-1}\omega(t)$ as new disturbance, $\Psi(q,\dot{q},\ddot{q}) = M_0^{-1}W(q,\dot{q},\ddot{q})$, $A = \begin{bmatrix} 0_n & I_n \\ -k_p & -k_v \end{bmatrix}$, $B = \begin{bmatrix} 0_n \\ I_n \end{bmatrix}$, and choosing k_p and k_v such that A is Hurwitz, one can rewrite equation (8) as

$$\dot{E} = AE + B(M_0^{-1}\tau_r + \Psi(q,\dot{q},\ddot{q})\phi_\sigma + d(t)) \tag{9}$$

Remark 1. In order to eliminate the need for velocity measurement, error E can be estimated using the high-gain observer below[34]

$$\begin{aligned} \dot{\hat{e}}_1 &= \hat{e}_2 + \frac{\kappa_1}{\varepsilon_1}(e_1 - \hat{e}_1) \\ \dot{\hat{e}}_2 &= \frac{\kappa_2}{\varepsilon_2}(e_1 - \hat{e}_1) \end{aligned} \tag{10}$$

where ε_i, $i = 1,2$ are small positive parameters, and $\kappa_i > 0$, $i = 1,2$ is chosen such that the roots of $s^2 + \kappa_1 s + \kappa_2 = 0$ have negative real parts.

Theorem 1. Consider the robot dynamic model (equation (4)), under arbitrary switching. The robust adaptive output feedback controller (equation (7)) with robust control torque

$$\tau_r = -M_0\left(\frac{1}{2\rho^2}B^T PE + \hat{\varphi}^2 \frac{\Psi^T\Psi B^T PE}{\Psi B^T PE\hat{\varphi} + \delta e^{-\upsilon t}}\right) \tag{11}$$

and adaptation law

$$\dot{\hat{\varphi}} = \gamma\Psi B^T PE \tag{12}$$

where P is a positive-definite symmetric matrix satisfying the Riccati-like inequality

$$A^T P + PA + Q + PB\left(\frac{1}{\rho^2}I - \frac{1}{r}I\right)B^T P \le 0 \tag{13}$$

and $\rho > 0$ is a damping level prescribed, $Q = Q^T > 0$ is a weighting matrix, $r > 0$ is the H_∞ control gain guarantees that

1. The tracking error is uniformly ultimately bounded (UUB), for all $d \in L_\infty[0,\infty)$.
2. The tracking error asymptotically converges to zero, for all $d \in L_2[0,\infty) \cap L_\infty[0,\infty)$.

In equation (11), δ and υ, are some small positive designed constants, and in equation (12), $\gamma > 0$ is the adaptation gain and $\hat{\varphi}$ is the estimate of φ.

Proof. Take the CLF candidate

$$V(E,\tilde{\varphi}) = \frac{1}{2}E^T PE + \frac{1}{2\gamma}\tilde{\varphi}^2 \tag{14}$$

where $\tilde{\varphi} = \varphi - \hat{\varphi}$ denotes the adaptation error. For any $k \in \Lambda$, the time derivative of V is given by

$$\dot{V} = \frac{1}{2}E^T(A^TP + PA)E + (\phi_k^T\Psi + \tau_r^T M_0^{-1} + d^T)B^TPE + \frac{1}{\gamma}\tilde{\varphi}\dot{\tilde{\varphi}} \tag{15}$$

substituting robust control law equation (11) into equation (15), for any $k \in \Lambda$, implies that

$$\dot{V} \leqslant \frac{1}{2}E^T(A^TP + PA)E + \phi_k^T\Psi B^TPE + E^TPB\left(d - \frac{1}{2\rho^2}B^TPE\right) - \hat{\varphi}^2\frac{E^TPB\Psi^T\Psi B^TPE}{\|\Psi B^TPE\|\hat{\varphi} + \delta e^{-\upsilon t}}\Bigg) - \frac{1}{\gamma}\tilde{\varphi}\dot{\hat{\varphi}} \tag{16}$$

Using inequality (13) one has

$$\dot{V} \leqslant -\frac{1}{2}E^TQE + \varphi\|\Psi B^TPE\| - \frac{1}{2}\left(\frac{1}{\rho}B^TPE - \rho d\right)^2 + \frac{1}{2}\rho^2\|d\|^2 - \hat{\varphi}\|\Psi B^TPE\| + \delta e^{-\upsilon t} - \frac{1}{\gamma}\tilde{\varphi}\dot{\hat{\varphi}} \tag{17}$$

substituting adaptation control law (equation (12)) yields

$$\dot{V} \leqslant -\frac{1}{2}E^TQE + \frac{1}{2}\rho^2\|d\|^2 + \delta e^{-\upsilon t} \tag{18}$$

1. For any bounded disturbance, that is, $d \in L_\infty[0,\infty)$, there exists a $D > 0$ such that $\|d\| \leqslant D$. By inequality (18), one concludes $\dot{V} \leqslant -\lambda_Q\|E\|^2 + \rho^2D^2 + \delta$, where λ_Q is the minimum eigenvalue of Q. Thus, $\dot{V}$ is bounded. Choosing $\lambda_Q > (\rho^2D^2 + \delta)/\xi^2$ for any small $\xi > 0$, there is a $\beta > 0$ so that $\dot{V} \leqslant -\beta\|E\|^2 < 0$ for all $\|E\| > \xi$. Hence, there exists a $T > 0$ such that $\|E\| \leqslant \xi$ for all $t \geqslant T$. That means the tracking error is UUB[35] and all the closed-loop signals are bounded.
2. For $d \in L_2[0,\infty) \cap L_\infty[0,\infty)$, integrating the inequality (18) over $[0, t]$ yields

$$\frac{1}{2}\int_0^T \|E(t)\|_Q^2 dt + V(E(T), \tilde{\varphi}(T)) \leqslant V(E(0), \tilde{\varphi}(0)) + \frac{\delta}{\upsilon}(1 - \delta e^{-\upsilon t}) + \frac{1}{2}\rho^2\int_0^T \|d(t)\|^2 dt,\ T \in [0,\infty) \tag{19}$$

By definition, $I_0 = 2(V(E(0), \tilde{\varphi}(0)) + (\delta/\upsilon))$ one obtains

$$\int_0^T \|E(t)\|_Q^2 dt \leqslant I_0 + \rho^2\int_0^T \|d(t)\|^2 dt \qquad T \in [0,\infty) \tag{20}$$

That shows that $\|E\|$ is bounded and square-integrated. Given error dynamic (equation (9)) and control law (equation (7)), since all closed-loop signals are bounded, $\dot{E}$ is also bounded. Hence, $E, \dot{E} \in L_\infty[0,\infty)$ and $E \in L_2[0,\infty)$ and Barbalat's lemma[35] guarantees that tracking error converges to zero, for uncertain switched system exposed to external disturbances. ■

Theorem 1 only guarantees that the tracking error is UUB for $d \in L_\infty[0,\infty)$. While, in real-world robotic applications, asymptotic tracking may be needed, even an external disturbance is not square-integrable. In Theorem 2, an adaptive output feedback controller is presented to ensure that the tracking error tends to zero. Define the augmented time varying vector $\Phi_\sigma(t) = [\phi_\sigma^T(t), d(t)]^T \in \mathbb{R}^{3n+m+1}$ and augmented regression vector $\Psi_a = [\Psi^T, 1]^T \in \mathbb{R}^{n\times(3n+m+1)}$. Since $d(t) \in L_\infty[0,\infty)$ and the parameters belong to a compact set, there is an unknown positive constant Υ such that

$$\|\Phi_k(t)\| \leqslant \Upsilon,\ \forall k \in \Lambda \tag{21}$$

Theorem 2. For the robot dynamic model (equation (4)), perturbed by some bounded disturbance d(t), the adaptive output feedback controller (equation (7)) with

$$\tau_r = -M_0\left(\hat{\Upsilon}^2\frac{\Psi_a^T\Psi_aB^TPE}{\|\Psi_aB^TPE\|\hat{\Upsilon} + \delta e^{-\upsilon t}}\right) \tag{22}$$

and update law

$$\dot{\hat{\Upsilon}} = \gamma\|\Psi_aB^TPE\| \tag{23}$$

where $\hat{\Upsilon}$ is the estimated value of Υ and $P = P^T > 0$ is the solution of Lyapunov equation

$$A^TP + PA \leqslant -H,\ H = H^T > 0 \tag{24}$$

ensures asymptotic link position tracking for switched system, under arbitrary switching.

Proof. Choose the CLF

$$V(E, \tilde{\Upsilon}) = E^TPE + \frac{1}{2\gamma}\tilde{\Upsilon}^2 \tag{25}$$

where $\tilde{\Upsilon} = \Upsilon - \hat{\Upsilon}$. Differentiating V for any $k \in \Lambda$, yields

$$\dot{V} \leqslant -E^THE + (\phi_k^T\Psi + \tau_r^TM_0^{-1} + d^T)B^TPE + \frac{1}{\gamma}\tilde{\Upsilon}\dot{\tilde{\Upsilon}} \tag{26}$$

substituting robust control law equation (22) into equation (26), for any $k \in N$, implies that

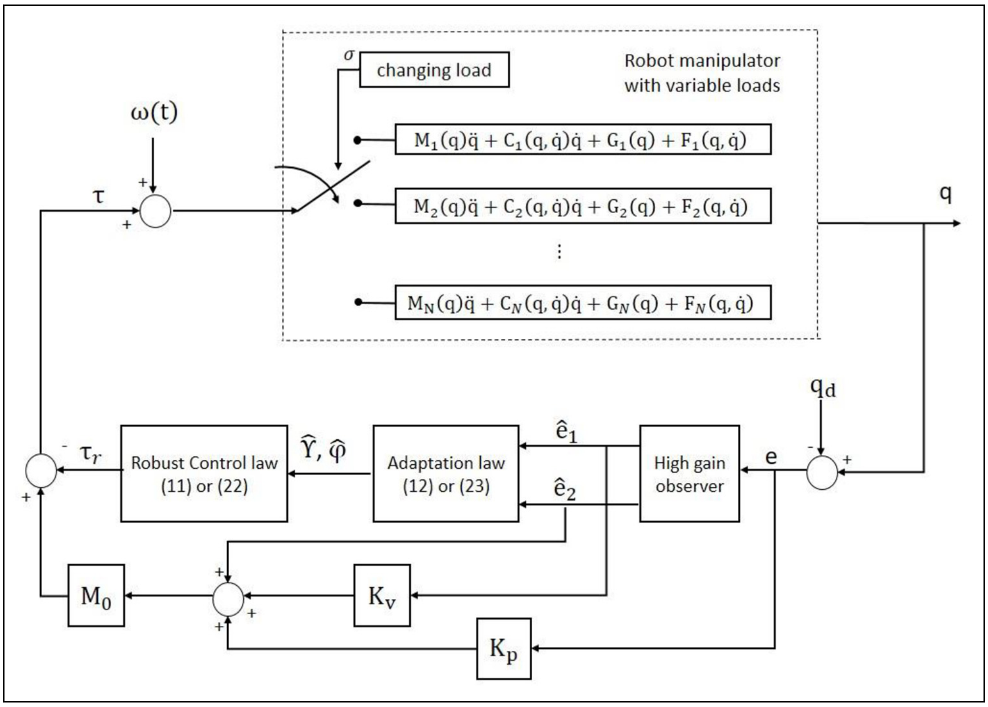

Figure 1. Block diagram of the proposed adaptive robust control algorithm in Theorems 1 and 2.

$$\dot{V} \leqslant -E^THE + \Phi_k^T\Psi_a B^T PE - \hat{Y}^2 \frac{E^TPb\Psi_a^T\Psi_a B^TPE}{\|\Psi_a B^T PE\|\hat{\varphi} + \delta e^{-\upsilon t}}\Bigg) - \frac{1}{\gamma}\tilde{Y}\dot{\hat{Y}} \tag{27}$$

Using update law (equation (23)) implies that

$$\dot{V} \leqslant -E^THE + \delta e^{-\upsilon t} \tag{28}$$

By integrating inequality (28) over $[0, t]$ one obtains

$$\int_0^T \|E(t)\|_H^2 dt + V\left(E(T), \tilde{Y}(T)\right) \leqslant V\left(E(0), \tilde{Y}(0)\right) + \frac{\delta}{\upsilon}\left(1 - \delta e^{-\upsilon t}\right),\ T \in [0, \infty) \tag{29}$$

which indicates $E \in L_2[0, \infty)$. In addition, using inequality (28), it can be concluded that $\dot{V} \leqslant -\lambda_H\|E\|^2 + \delta$, where λ_H is the minimum eigenvalue of H. By following the proof of Theorem 1, Barbalat's lemma guarantees that the tracking error converges to zero despite the disturbances, under arbitrary switching. ■

The overall structure of the proposed scheme for controlling the switched robotic system is depicted in Figure 1.

Remark 2. Unlike with some previous investigations,[25] which robust tracking control problem is restricted to $d \in L_2[0, \infty)$, in this article, the asymptotic tracking controller is proposed for robot dynamic model (equation (4)) perturbed by any bounded disturbance d(t), under arbitrary switching. Furthermore, the friction vector is considered and the assumption of a known constant bound for $\|C(q, \dot{q})\|$ and $\|G(q)\|$ is relaxed here.

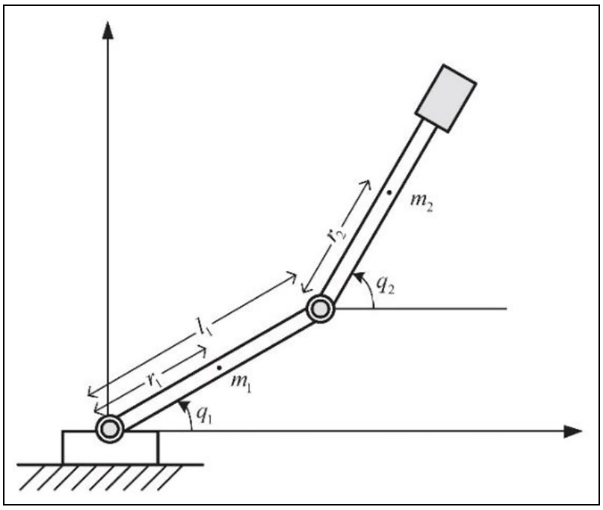

Figure 2. Structure of robot manipulator.

Simulation study

In order to demonstrate the effectiveness of the main results, proposed output tracking controllers are applied to a 2-DOF planar manipulator with changing loads. The dynamics of the robot manipulator, shown in Figure 2, are given by[24]

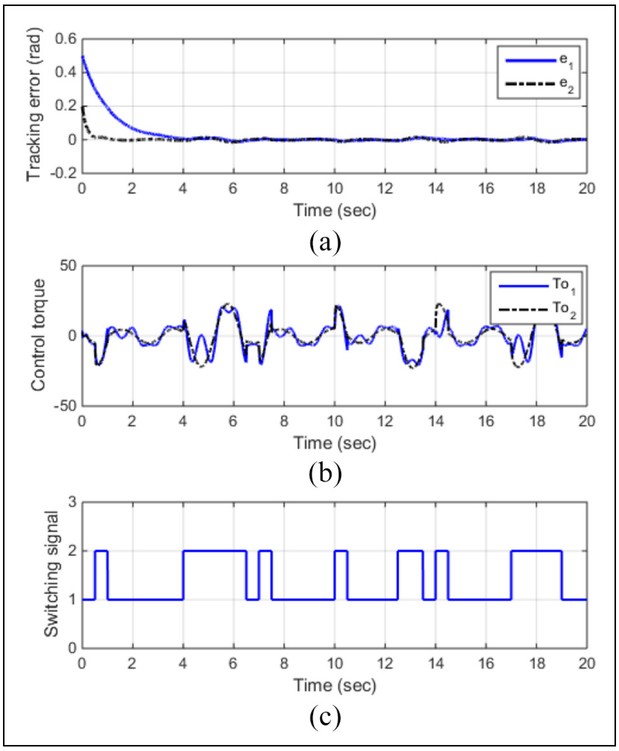

Figure 3. Time history of simulation results of case 1: (a) tracking error, (b) control effort, and (c) switching signal.

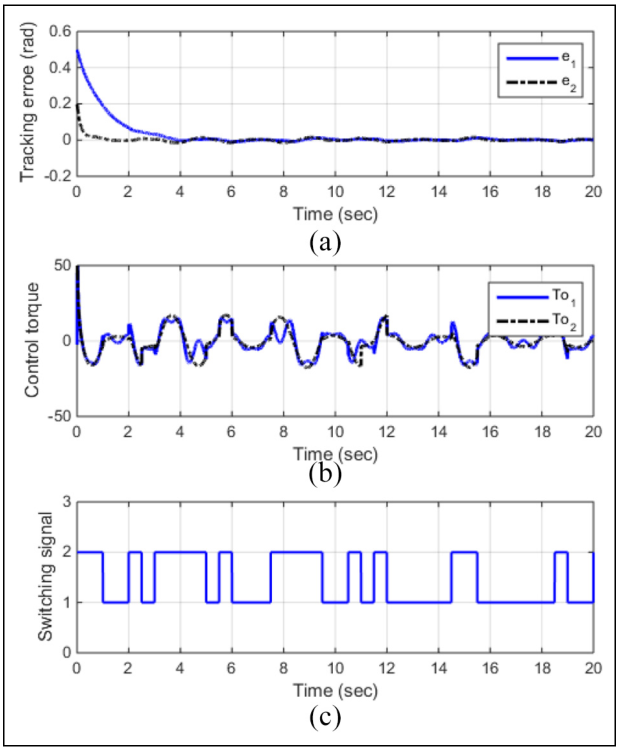

Figure 4. Time history of simulation results in case 2: (a) tracking error, (b) control effort, and (c) switching signal.

$$M_\sigma(q) = \begin{bmatrix} J_1 & m_2 r_2 l_1 \cos(q_2 - q_1) \\ m_2 r_2 l_1 \sin(q_2 - q_1) & J_2 \end{bmatrix} \tag{30}$$

$$C_\sigma(q) = m_2 r_2 l_1 \sin(q_2 - q_1) \begin{bmatrix} 0 & -\dot{q}_2 \\ \dot{q}_1 & 0 \end{bmatrix} \tag{31}$$

$$J_1 = \frac{4}{3} m_1 r_1^2 + m_2 l_1^2, \; J_2 = \frac{4}{3} m_2 r_2^2 \tag{32}$$

$$Y(q, \dot{q}, \ddot{q}) = \begin{bmatrix} \ddot{q}_1 & 0 & \cos(q_2 - q_1)\ddot{q}_2 - \dot{q}_2^2 \sin(q_2 - q_1) \\ 0 & \ddot{q}_2 & \cos(q_2 - q_1)\ddot{q}_1 - \dot{q}_1^2 \sin(q_2 - q_1) \end{bmatrix} \tag{33}$$

$$\theta_\sigma = [J_1 \quad J_2 \quad m_2 r_2 l_1] \tag{34}$$

$$F_\sigma(q, \dot{q}) = \begin{bmatrix} \mathrm{sgn}(\dot{q}_1) & -\mathrm{sgn}(\dot{q}_1)|\dot{q}_1|^{\frac{1}{2}} & \dot{q}_1 & 0 & 0 \\ 0 & 0 & 0 & \mathrm{sgn}(\dot{q}_2) & -\mathrm{sgn}(\dot{q}_2)|\dot{q}_2|^{\frac{1}{2}} \end{bmatrix} \tag{35}$$

As the load changes, the robot's parameters change from one value to another. Denoting $\sigma = 2$ for load carrying and $\sigma = 1$ for no load case, the actual values of the parameters for the two subsystems are specified in Table 1. The desired trajectory is considered as $q_d = [0.5\sin t \quad \sin 3t]^T$. The gain matrices and the positive-definite matrix M_0, respectively, are taken as $k_p = \mathrm{diag}(12, 12)$, $k_v = \mathrm{diag}(12, 2)$, and $M_0 = I_{2\times 2}$. The Riccati-like inequality (13) gives

$$P = \begin{bmatrix} 1.1264 & 0 & 0.1509 & 0 \\ 0 & 1.1264 & 0 & 0.1509 \\ 0.1509 & 0 & 0.1041 & 0 \\ 0 & 0.1509 & 0 & 0.1041 \end{bmatrix}$$

by choosing $\gamma = 0.7$, $\delta = 0.5$, $\upsilon = 0.1$, $\rho = 0.7$ and $r = 0.5$, the robust output feedback tracking controllers developed in Theorems 1 and 2 are easily established. Cases 1 and 2 are considered here to evaluate the effectiveness of controller, presented in Theorems 1 and 2, respectively:

Case 1. Bounded and square-integrable disturbance $d(t) = 2e^{-0.5t}\sin 5t$. The simulation results are presented with $q(0) = [0.5, 0.2]$, $\hat{\varphi}(0) = 0.7$ and a random switching signal with an average switching time of 0.5 s. Figure 3 demonstrates the results of tracking performance using the control law proposed in Theorem 1. As depicted in Figure 3, the effects of uncertainties and external disturbance are eliminated and tracking error asymptotically converges to zero, under arbitrary switching.

Case 2. Bounded disturbance $d(t) = 1 + \sin 5t$. In this case, choosing $\hat{Y}(0) = 0.7$ and the initial values and switching signal similar to case 1, the adaptive control law suggested in Theorem 2 is applied to achieve asymptotic error convergence. Figure 4 shows the asymptotic convergence of tracking error to zero, despite the non-square-integrable disturbance d(t). As

Table 1. Parameter values of subsystems.

	m_1	r_1	l_1	m_2	r_2	α
$\sigma = 1$	1	1	2	1	1	$[1\ 0.2\ 0.1\ 0.8\ 0.1\ 0.06]^T$
$\sigma = 2$	1	1	2	2	1.5	$[2\ 0.3\ 0.15\ 1.9\ 0.27\ 0.1]^T$

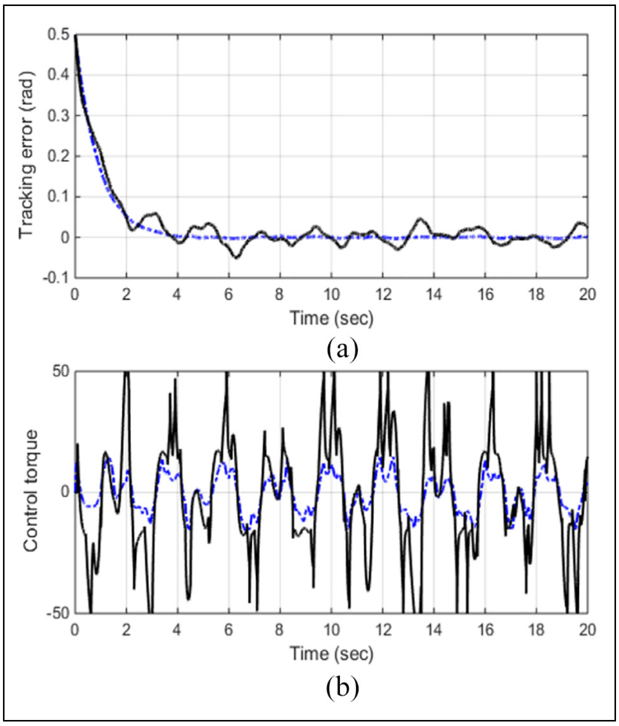

Figure 5. Time responses by applying the proposed controller in theorem 2 (–) dash dotted line and control algorithm in the work by Wang et al.[25] (—) to link position 1: (a) tracking error and (b) control effort.

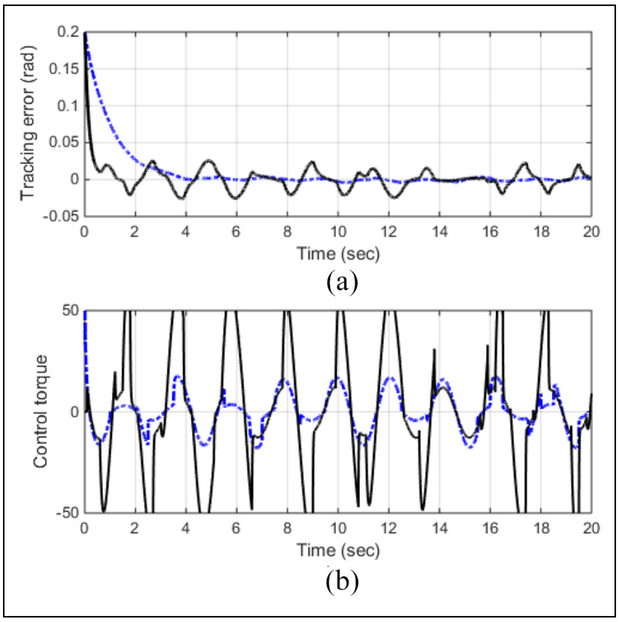

Figure 6. Time responses by applying the proposed controller in Theorem 2 (–) and control algorithms in the work by Wang et al.[25] (—) to link position 2: (a) tracking error and (b) control effort.

expected in this case, the convergence of tracking error to zero is obtained with a bounded control torque. In order to show the effectiveness of the proposed method, compared with that of the method in the work by Wang et al.,[25] the results for link positions 1 and 2 are depicted in Figures 5 and 6, respectively. By applying the control torque, presented in Theorem 2, the control torque range has been significantly reduced and the tracking performance has improved.

Conclusion

In this article, considering a switched dynamic model for the robot manipulator with changing loads, a robust adaptive output feedback tracking control law is designed for robot manipulator in the presence of uncertainties and disturbances to attain H_∞ tracking performance. When external disturbance is L_2 and bounded, proposed controller ensures that tracking error converges to zero. Then, assuming that disturbance is not an L_2 signal, a novel adaptive output feedback tracking controller is developed for asymptotic convergence of tracking error to zero, under arbitrary switching. Compared with some existing results, the main contributions of this article are (1) the link velocity measurement is not required, (2) the nonlinear friction vector is taken into account, (3) the external disturbances and unknown parameters are not needed to be periodic nor to have known bounds, and (4) the control torque range is considerably reduced for link position tracking, using the proposed output feedback control schemes.

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References

1. Xiao D, Ghosh BK, Xi N, et al. Sensor-based hybrid position/force control of a robot manipulator in an uncalibrated environment. *IEEE T Contr Syst T* 2000; 8(4): 635–645.
2. Yang ZJ, Fukushima Y and Qin P. Decentralized adaptive robust control of robot manipulators using disturbance observers. *IEEE T Contr Syst T* 2011; 20(5): 1357–1365.
3. Nguyen KD and Dankowicz H. Adaptive control of underactuated robots with unmodeled dynamics. *Robot Auton Syst* 2015; 64: 84–99.
4. Koofigar HR. Adaptive tracking with external force disturbance rejection for uncertain robotic systems. *Int J Control Autom* 2014; 12(1): 169–176.
5. Kelly R. Global positioning of robot manipulators via PD control plus a class of nonlinear integral actions. *IEEE T Automat Contr* 1998; 43(7): 934–938.
6. Parra-Vega V, Arimoto S, Liu YH, et al. Dynamic sliding PID control for tracking of robot manipulators: theory and experiments. *IEEE Transactions on Robotics and Automation* 2003; 19(6): 967–976.
7. Nikdel N, Badamchizadeh MA, Azimirad V, et al. Adaptive backstepping control for an n-degree of freedom robotic manipulator based on combined state augmentation. *Robotics and Computer-integrated Manufacturing* 2017; 44: 129–143.
8. Sun W, Wu Y and Wang L. Trajectory tracking of constrained robotic systems via a hybrid control strategy. *Neurocomputing* 2019; 330: 188–195.
9. Ouyang PR, Acob J and Pano V. PD with sliding mode control for trajectory tracking of robotic system. *Robotics and Computer-integrated Manufacturing* 2014; 30(2): 189–200.
10. Baek J, Jin M and Han S. A new adaptive sliding-mode control scheme for application to robot manipulators. *IEEE T Ind Electron* 2016; 63(6): 3628–3637.
11. Jing C, Xu H and Niu X. Adaptive sliding mode disturbance rejection control with prescribed performance for robotic manipulators. *ISA T* 2019; 91: 41–51.
12. Nikdel N, Badamchizadeh M, Azimirad V, et al. Fractional-order adaptive backstepping control of robotic manipulators in the presence of model uncertainties and external disturbances. *IEEE T Ind Electron* 2016; 63(10): 6249–6256.
13. Dumlu A and Erenturk K. Trajectory tracking control for a 3-DOF parallel manipulator using fractional-order PIˆλ Dˆμ control. *IEEE T Ind Electron* 2013; 61(7): 3417–3426.
14. Cho HC, Fadali MS, Lee KS, et al. Adaptive position and trajectory control of autonomous mobile robot systems with random friction. *IET Control Theory A* 2010; 4(12): 2733–2742.
15. Mallon N, van de Wouw N, Putra D, et al. Friction compensation in a controlled one-link robot using a reduced-order observer. *IEEE T Contr Syst T* 2006; 14(2): 374–383.
16. Márton L and Lantos B. Control of robotic systems with unknown friction and payload. *IEEE T Contr Syst T* 2010; 19(6): 1534–1539.
17. Mohammadi A, Tavakoli M, Marquez HJ, et al. Nonlinear disturbance observer design for robotic manipulators. *Control Eng Pract* 2013; 21(3): 253–267.
18. Chan L, Naghdy F and Stirling D. Extended active observer for force estimation and disturbance rejection of robotic manipulators. *Robot Auton Syst* 2013; 61(12): 1277–1287.
19. Purwar S, Kar IN and Jha AN. Adaptive output feedback tracking control of robot manipulators using position measurements only. *Expert Syst Appl* 2008; 34(4): 2789–2798.
20. Hung NVQ, Tuan HD, Narikiyo T, et al. Adaptive control for nonlinearly parameterized uncertainties in robot manipulators. *IEEE T Contr Syst T* 2008; 16(3): 458–468.
21. Huh SH and Bien Z. Robust sliding mode control of a robot manipulator based on variable structure-model reference adaptive control approach. *IET Control Theory A* 2007; 1(5): 1355–1363.
22. Dumlu A. Design of a fractional-order adaptive integral sliding mode controller for the trajectory tracking control of robot manipulators. *Proc IMechE Part I: J Systems and Control Engineering* 2018; 232(9): 1212–1229.
23. Noghreian E and Koofigar HR. Adaptive output feedback tracking control for a class of uncertain switched nonlinear systems under arbitrary switching. *Int J Syst Sci* 2018; 49(3): 486–495.
24. Wang X and Zhao J. Switched adaptive tracking control of robot manipulators with friction and changing loads. *Int J Syst Sci* 2015; 46(6): 955–965.
25. Wang X, Niu RS, Chen C, et al. H_∞ switched adaptive control for a class of robot manipulators. *T I Meas Control* 2014; 36(3): 347–353.
26. Rezazadeh AS, Koofigar HR and Hosseinnia S. Adaptive fault detection and isolation for a class of robot manipulators with time-varying perturbation. *J Mech Sci Technol* 2015; 29(11): 4901–4911.
27. Lim SY, Dawson DM and Anderson K. Re-examining the Nicosia-Tomei robot observer-controller from a backstepping perspective. *IEEE T Contr Syst T* 1996; 4(3): 304–310.
28. De Queiroz MS, Hu J, Dawson DM, et al. Adaptive position/force control of robot manipulators without velocity measurements: theory and experimentation. *IEEE T Syst Man Cy B* 1997; 27(5): 796–809.
29. Liu Z and Li C. Fuzzy neural network quadratic stabilization output feedback control for biped robots via H_∞ approach. *IEEE T Syst Man Cy B* 2003; 33(1): 67–84.
30. Kim E. Output feedback tracking control of robot manipulators with model uncertainty via adaptive fuzzy logic. *IEEE T Fuzzy Syst* 2004; 12(3): 368–378.
31. Zhang F, Dawson DM, de Queiroz MS, et al. Global adaptive output feedback tracking control of robot manipulators. *IEEE T Automat Contr* 2000; 45(6): 1203–1208.
32. Lewis FL, Dawson DM and Abdallah CT. *Control of robot manipulators*. Upper Saddle River, NJ: Prentice Hall PTR, 1993.
33. Canudas de Wit C, Noel P, Aubin A, et al. Adaptive friction compensation in robot manipulators: low velocities. *INT J Robot Res* 1991; 10(3): 189–199.
34. Khalil HK. Adaptive output feedback control of nonlinear systems represented by input-output models. *IEEE T Automat Contr* 1996; 41(2): 177–188.
35. Krstic M, Kanellakopoulos I and Kokotovic PV. *Nonlinear and adaptive control design*. New York: Wiley, 1995.