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Research Article

Exponential Tracking Control Using Backstepping Approach for Voltage-Based Control of a Flexible Joint Electrically Driven Robot

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This paper addresses the design of exponential tracking control using backstepping approach for voltage-based control of a flexible joint electrically driven robot (EFJR), to cope with the difficulty introduced by the cascade structure in EFJR dynamic model, to deal with flexibility in joints, and to ensure fast tracking performance. Backstepping approach is used to ensure global asymptotic stability and its common algorithm is modified such that the link position and velocity errors converge to zero exponentially fast. In contrast with the other backstepping controller for electrically driven flexible joint robot manipulators control problem, the proposed controller is robust with respect to stiffness uncertainty and allows tracking fast motions. Simulation results are presented for both single link flexible joint electrically driven manipulator and 2-DOF flexible joint electrically driven robot manipulator. These simulations show very satisfactory tracking performances and the superiority of the proposed controller to those performed in the literature using simple backstepping methodology.

1. Introduction

As demonstrated in [1], actuator dynamics constitute an important component of the complete robot dynamics. If actuator dynamics is ignored, the designed controller may not yield good system overall performance. In recent years, controls for robot manipulators, including the actuator dynamics, have received considerable attention and several control schemes have been developed [2–10]. In the early works Tarn et al. [2] proposed a nonlinear feedback robot controller that incorporates the robot manipulator dynamics as well as the robot joint motor dynamics. This study shows that the proposed controller gives better performance than nonlinear feedback robot controller based on the manipulator dynamics only. Carroll et al. [3] introduce a robust corrective tracking controller for rigid link electrically driven (RLED) robot manipulators operating under motion constraints, to overcome consideration of actuators dynamics and task space control problem. The controllers proposed in [2, 3] required full knowledge of system dynamics. If there are uncertainties in the dynamics, these controllers proposed may give a poor performance and may even cause instability. To overcome the uncertainties in the dynamics, robust controllers have been proposed in [4–10].

Stepanenko and Su [4] presented a simple robust nonlinear control law that incorporates the manipulator dynamics as well as dynamics of actuators. In contrast to the known methods, the presented design procedure is based on less restrictive assumptions regarding the characteristic of uncertainties. Lotfazar et al. [5] presented a hybrid adaptiv controller for rigid link electrically driven robot manipulators.

Integrator backstepping and passivity based method in the presence of parameters uncertainty and disturbance is suggested as a technique providing a framework for recursive design of nonlinear systems by achieving system stability in each step [6, 7]. In [8] voltage-based control strategy is presented as a novel approach for controlling electrically driven robot manipulators. In that study, the feedback linearization is applied on the electrical equations of the DC motors to cancel the current terms which transfer all manipulator dynamics to the electrical circuit of motor, and then the control design becomes simple.

All aforementioned studies are related to a control of rigid link electrically driven robots manipulators without considering joint flexibility. There are very few contributions in the literature about electrical flexible joint robots (EFJR) in which both of motor dynamics and joint flexibility are taken into account. Good et al. [11] showed that ignoring joint flexibility in manipulator dynamics and controller design causes degradation in performance of robots.

A simple adaptive robust control structure is designed for an EFJR manipulator under both structured and unstructured uncertainty by Fateh [9], but simulations results show poor tracking performance in tracking trajectory because the tracking error converges to 0.1 after a long time (6 s). The backstepping method is applied to cope with cascade structure and to find the control law to accomplish stabilization and tracking of a desired trajectory in [1]. In this study, a simulation result shows that the proposed controller is not robust in presence of external disturbances and is not fast in tracking trajectory. In [10], a robust decentralized controller for flexible joint electrically driven robots under imperfect transformation of control space, from task space to joint space, is presented.

The performance of all control strategies mentioned before is degraded for tracking purposes at high velocities. This is because of the dynamical terms such as Coriolis and centrifugal and the coupling effects which are related to the velocities of joints. These control systems are also dependent on the selected trajectory and the disturbances during the tracking operation. One solution is to compensate the dynamic term but this strategy can increase tracking error as seen in [9].

To cope with the problem of tracking trajectory at high velocity and variable joint stiffness, in this paper we proposed exponential tracking control using backstepping approach and we consider motor voltages as control input. The main idea is to modify the common backstepping algorithm such that the link position and velocity errors converge to zero exponentially fast. Backstepping approach ensures the global stability and global asymptotic stability of the close loop system.

This paper is organized as follows. In Section 2, the dynamic model of EFJR is presented in addition to its fundamental properties. In Section 3, exponential tracking control using backstepping approach is presented. Section 4 is devoted to the simulation results of the proposed control law. We achieve our task by a conclusion in Section 5.

2. EFJR Dynamic's Model

Consider the link part of EFJR as a flexible joint robot manipulator with known system parameters:

$$\begin{aligned} D(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) + K(q - q_m) &= 0, \\ J\ddot{q}_m + B\dot{q}_m + K(q_m - q) &= \tau, \end{aligned} \tag{1}$$

where $q \in R^n$ and $q_m \in R^n$ represent, respectively, the vectors of link positions and motor angles, K is the diagonal matrix representing joint stiffness, $D(q)$ is the link inertia matrix, $C(q,\dot{q})$ represents the Coriolis and centrifugal terms, $G(q)$ represents the gravitational terms, $\tau \in R^n$ is the vector of motor torques, and J is the diagonal matrix representing actuator inertia.

The dynamic equation (1) has been introduced in Spong [12], where the joint stiffness terms are assumed to be dominant relative to other parameters in the system. These equations are usually complicated nonlinear equations but they have several fundamental properties which can be exploited to facilitate control system design. These properties are as follows [12].

(1) The link inertia matrix $D(q)$ is symmetric and positive definite and both $D(q)$ and $D^{-1}(q)$ are uniformly bounded.

(2) If $C(q,\dot{q})$ is suitably chosen, the matrix $N(q,\dot{q}) = \dot{D}(q) - 2C(q,\dot{q})$ is skew symmetric and $C(q,\dot{q})$ is uniformly bounded.

(3) The gravitational term $G(q)$ is uniformly bounded.

(4) For rigid joint manipulator, the system parameters appear linearly in the equation as coefficients of known functions of q, $\dot{q}$, and $\ddot{q}$. By defining each coefficient as a separate parameter, we can represent the robot dynamics as

$$D(q)\ddot{q} + C(q,\dot{q}) + G(q) + K(q - q_m) = Y(q,\dot{q},\ddot{q})\theta, \tag{2}$$

where θ is an r-dimensional vector of parameters and $Y(q,\dot{q},\ddot{q})$ is an $n \times r$ matrix of known function called *regressor*.

In order to obtain the motor voltages as the inputs of system, consider the electrical equation of geared permanent magnet DC motors in the matrix form as

$$L\dot{I} + RI + K_b\dot{q}_m = u, \tag{3}$$

where $u \in R^n$ is a vector of motor voltages, $I \in R^n$ is a vector of motor currents, and $\dot{q}_m$ is a vector of motor velocities. R, L, and K_b represent a $n \times n$ diagonal matrices for the coefficients of armature resistance, armature inductance, and back-emf constant, respectively. The motor torque vector τ as the input for dynamic equation (1) is produced by the motor current vector as

$$HI = \tau, \tag{4}$$

where K_m is a diagonal matrix of the torque constants.

In order to derive the control law with backstepping approach we choose $x_1 = q_m$, $x_2 = \dot{q}_m$, and $x_3 = I$. The dynamic system of (1), (3), and (4) is described as

$$\begin{gathered} D(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) + Kq = Kx_1, \\ \dot{x}_1 = x_2, \\ \dot{x}_2 = J^{-1}Hx_3 - J^{-1}K(x_1 - q) - J^{-1}Bx_2, \\ \dot{x}_3 = L^{-1}u - L^{-1}Rx_3 - L^{-1}K_b x_1. \end{gathered} \tag{5}$$

In deriving the control law, the overall system is regarded as the cascade of three parts: the robot link dynamics, the motor dynamics, and the electrical part of the motor. The link dynamics is actuated by the motor angles q_m through the flexible joints, the motor dynamics is actuated by the motor torques τ, and the electrical part is actuated by the motor voltage u.

3. Controller Design

Backstepping is a recursive design methodology for constructing of both feedback control laws and associated Lyapunov functions in a systematic manner, whose significance for nonlinear control can be compared to root locus or Nyquist's method for linear systems. The key idea in backstepping is to let certain states act as "virtual controls" of others [2]. For the used backstepping methodology, the system must be in strict-feedback form. Since the nonlinear equation of dynamic model presented in (5) is strict-feedback, backstepping controller design is proper choice to accomplish our control purposes.

In order to cope with flexibility of the joints and the loss of velocity due to this flexibility, we compute the desire control law of the link dynamics such that the link position and velocity errors converge to zero exponentially fast.

Step 1. Assume that x_1 is the control input. Then, the first equation of the system (5) is just the system with rigid joint robot dynamics and a good control law x_1^{des} for x_1 would be

$$x_1^{\text{des}} = q + K^{-1}\left[D(q)\dot{v} + C(q,\dot{q})v + G(q) - K_d r\right], \tag{6}$$

where K_d is a diagonal matrix with positive elements, $v = q^{\text{des}} - \lambda_1\tilde{q}$, $\tilde{q} = q - q^{\text{des}}$, $r = \dot{q} - v = \dot{\tilde{q}} + \lambda_1\tilde{q}$, and λ_1 is a positive diagonal matrix.

Define $z_1 = x_1 - x_1^{\text{des}}$; substituting this new variable in the first equation of system (5) we obtain

$$D(q)\dot{r} + C(q,\dot{q})r + K_d r = Kz_1. \tag{7}$$

Now, let us choose a Lyapunov function candidate $V_1 = (1/2)r^T D(q)r$. In order to investigate the stability of system (6), we compute its derivative. Then, we have

$$\begin{aligned} \dot{V}_1 &= \frac{1}{2}r^T\dot{D}(q)r + r^T D(q)\dot{r} \\ &= \frac{1}{2}r^T\dot{D}(q)r + r^T\left[-K_d r - C(q,\dot{q})r + Kz_1\right] \\ &= -r^T K_d r + r^T K z_1 + \frac{1}{2}r^T\left[\dot{D}(q) - 2C(q,\dot{q})\right]r, \end{aligned} \tag{8}$$

where the matrix $[\dot{D}(q) - 2C(q,\dot{q})]$ is skew symmetric and implies that $r^T[\dot{D}(q) - 2C(q,\dot{q})]r = 0$. Then, we obtain

$$\dot{V}_1 = -r^T K_d r + r^T K z_1. \tag{9}$$

If $z_1 = 0$, then $\dot{V}_1 < 0$ and $r \to 0$ as $t \to \infty$. Moreover, since $r = \dot{\tilde{q}} + \lambda_1\tilde{q}$ and the transfer function $1/(s+\lambda_1)$ is stable and is a minimum phase, it follows that $\dot{\tilde{q}} \to 0$ and $\tilde{q} \to 0$ exponentially as $t \to \infty$.

Step 2. Now assume that x_2 is the control input of the second equation of system (5). In order to compute the control law for this equation, we first differentiate z_1.

Consider $\dot{z}_1 = \dot{x}_1 - \dot{x}_1^{\text{des}}$; defining $\rho_1 = \dot{x}_1^{\text{des}}$, then

$$\dot{z}_1 = x_2 - \rho_1, \tag{10}$$

where $\rho_1 = f(q, \dot{q}, \ddot{q}, q^{\text{des}}, \dot{q}^{\text{des}}, \ddot{q}^{\text{des}}, \dddot{q}^{\text{des}})$.

Then the good control law x_2^{des} for x_2 would be

$$x_2^{\text{des}} = -r - \lambda_2 z_1 + \rho_1, \tag{11}$$

where λ_2 is diagonal matrix with positive elements.

Define $z_2 = x_2 - x_2^{\text{des}}$. From (10) and (11) we have that

$$\dot{z}_1 = -r - \lambda_2 z_1 + z_2. \tag{12}$$

Choosing a Lyapunov function candidate

$$V_1 = V_1 + \frac{1}{2}z_1^T K z_1 \tag{13}$$

and computing its derivative, we have

$$\begin{aligned} \dot{V}_2 &= \dot{V}_1 + z_1^T K \dot{z}_1 \\ &= -r^T K_d r - z_1^T K \lambda_2 z_1 + z_1^T K z_2. \end{aligned} \tag{14}$$

If $z_2 = 0$, then $\dot{V}_2 < 0$ and $r \to 0$, $z_1 \to 0$ as $t \to \infty$. Moreover since $z_1 = x_1 - x_1^{\text{des}}$, it follows that $x_1 \to x_1^{\text{des}}$ as $t \to \infty$.

Step 3. Also we assume that x_3 is control input for the third equation of system (5). Before computing the control input, we first differentiate z_2.

Consider $\dot{z}_2 = \dot{x}_2 - \dot{x}_2^{\text{des}}$; defining $\rho_2 = \dot{x}_2^{\text{des}}$, then

$$\dot{z}_2 = J^{-1}Hx_3 - J^{-1}K(x_1 - q) - J^{-1}Bx_2 - \rho_2, \tag{15}$$

where $\rho_2 = f(q, \dot{q}, \ddot{q}, \dddot{q}, q^{\text{des}}, \dot{q}^{\text{des}}, \ddot{q}^{\text{des}}, \dddot{q}^{\text{des}}, \overset{(4)}{q}{}^{\text{des}})$ and $\overset{(4)}{q}{}^{\text{des}}$ is the fourth differentiate of the desire link angle q^{des}. $\ddot{q}$ is computed by differentiating the following equation:

$$\ddot{q} = D(q)^{-1}\left[Kx_1 - C(q,\dot{q})\dot{q} - G(q) - Kq\right]. \tag{16}$$

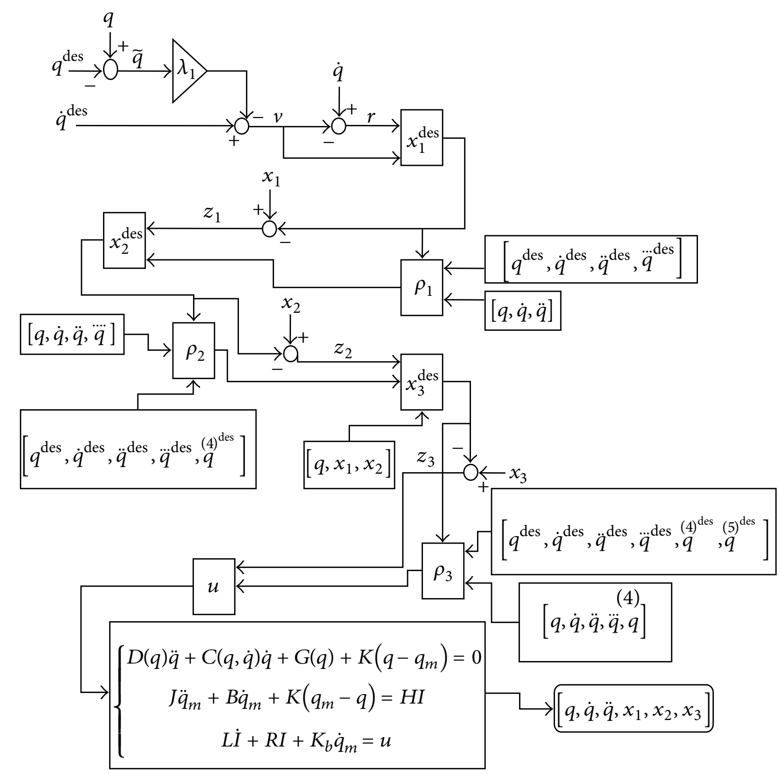

Figure 1: Block diagram of the exponential tracking control structure.

Table 1: Values of system parameters used in numerical simulation.

Parameters symbol	Link and motors 1 and 2 parameters values
m	1.5 kg
l	0.3 m
I	0.012 kg·m^2
K	500 Nm·rad^{-1}
J	0.025 kg·m^2
L	0.025 H
R	1.6 Ohm
K_b	0.5 Nm·A^{-1}
B	0.001 Nm·s·rad^{-1}
H	1 Nm·A^{-1}
ε	0.15 m

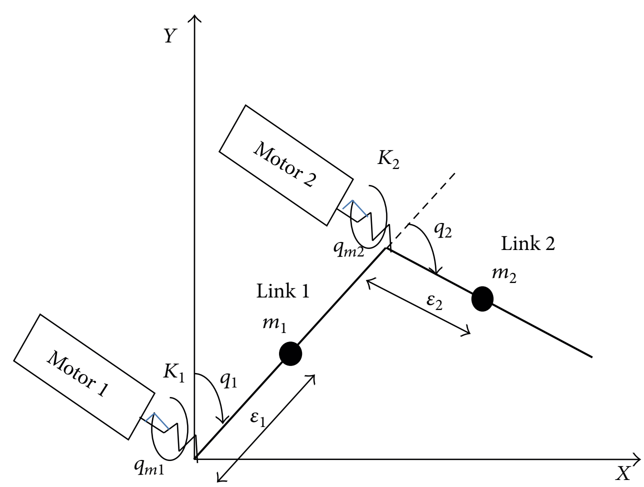

Figure 2: 2-DOF electrically driven flexible joint robot manipulator.

Choosing a Lyapunov function candidate

$$V_3 = V_2 + \frac{1}{2} z_2^T K H^{-1} J z_2 \tag{17}$$

and computing its derivative, we have

$$\begin{aligned} \dot{V}_3 &= \dot{V}_2 + z_2^T K H^{-1} J \dot{z}_2 \\ &= -r^T K_d r - z_1^T K \lambda_2 z_1 + z_1^T K z_2 + z_1^T K z_2 \\ &\quad + z_2^T K \left[x_3 - H^{-1} K \left(x_1 - q \right) - H^{-1} B x_2 - H^{-1} J \rho_2 \right]. \end{aligned} \tag{18}$$

Define $z_3 = x_3 - x_3^{\text{des}} \rightarrow x_3 = z_3 + x_3^{\text{des}}$. Substituting this expression into (18), we obtain

$$\begin{aligned} \dot{V}_3 &= -r^T K_d r - z_1^T K \lambda_2 z_1 + z_1^T K z_2 + z_1^T K z_2 \\ &\quad + z_2^T K \left[z_3 + x_3^{\text{des}} - H^{-1} K \left(x_1 - q \right) \right. \\ &\quad \left. - H^{-1} B x_2 - H^{-1} J \rho_2 \right]. \end{aligned} \tag{19}$$

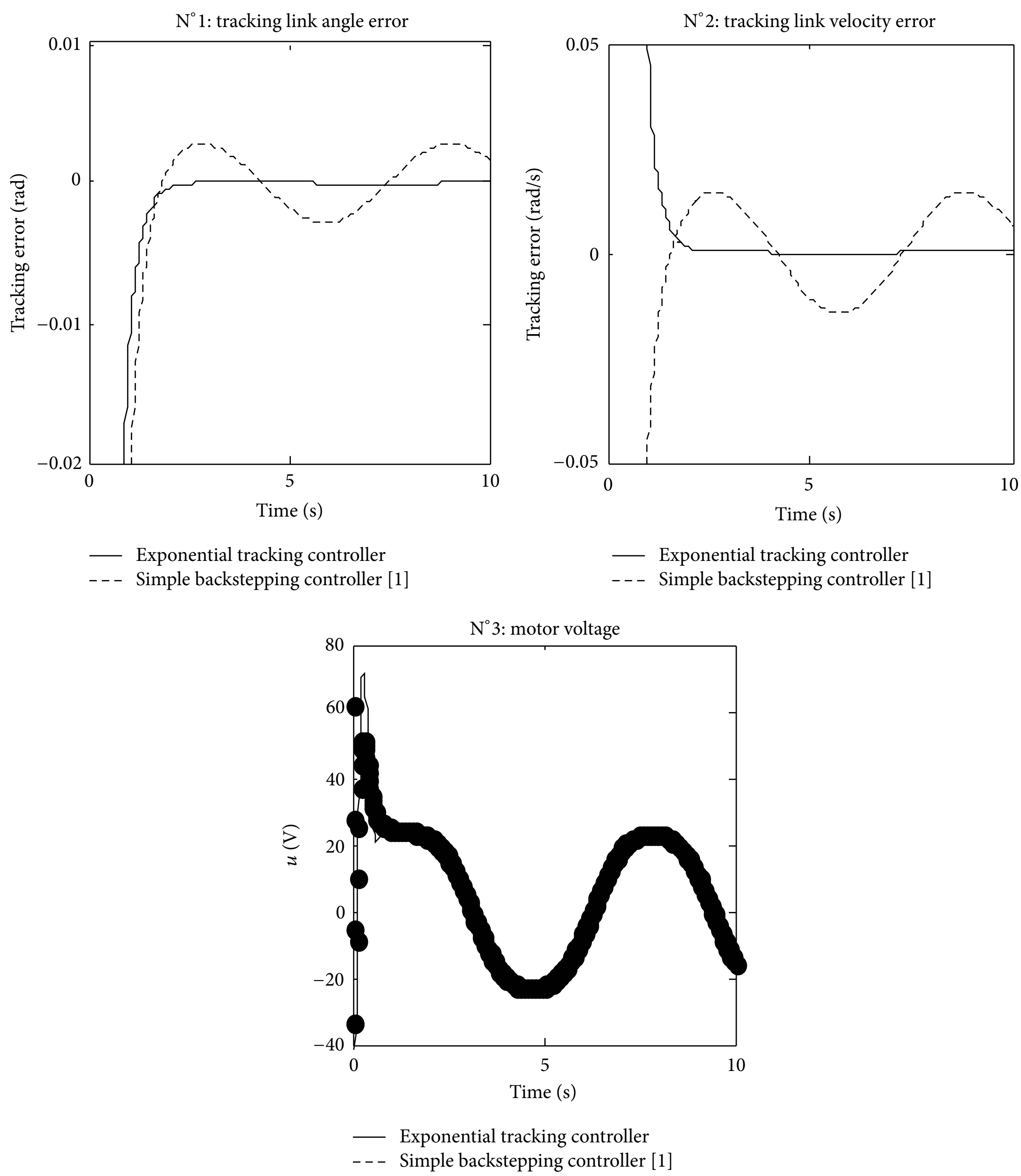

Figure 3: Comparative performance in tracking sine trajectory.

In order to satisfy Lyapunov stability condition, we choose

$$x_3^{\text{des}} = -z_1 - \lambda_3 z_2 + H^{-1}K\left(x_1 - q\right) + H^{-1}Bx_2 + H^{-1}J\rho_2. \tag{20}$$

Then,

$$\dot{V}_3 = -r^T K_d r - z_1^T K\lambda_2 z_1 - z_2^T K\lambda_3 z_2 + z_2^T K z_3. \tag{21}$$

Step 4. In this step, the motor voltage is computing in order to ensure global asymptotical stability of system. We first differentiate z_3.

Consider $\dot{z}_3 = \dot{x}_3 - \dot{x}_3^{\text{des}}$; defining $\rho_3 = \dot{x}_3^{\text{des}}$, then

$$\dot{z}_3 = L^{-1}u - L^{-1}Rx_3 - L^{-1}K_b x_2 - \rho_3, \tag{22}$$

where $\rho_3 = f(q, \dot{q}, \ddot{q}, \dddot{q}, \overset{(4)}{q}, q^{\text{des}}, \dot{q}^{\text{des}}, \ddot{q}^{\text{des}}, \dddot{q}^{\text{des}}, \overset{(4)}{q}{}^{\text{des}}, \overset{(5)}{q}{}^{\text{des}})$ and $\overset{(4)}{q}$ is the fourth differentiate of the link angle q. $\overset{(4)}{q}$ is computed by differentiating twist (16).

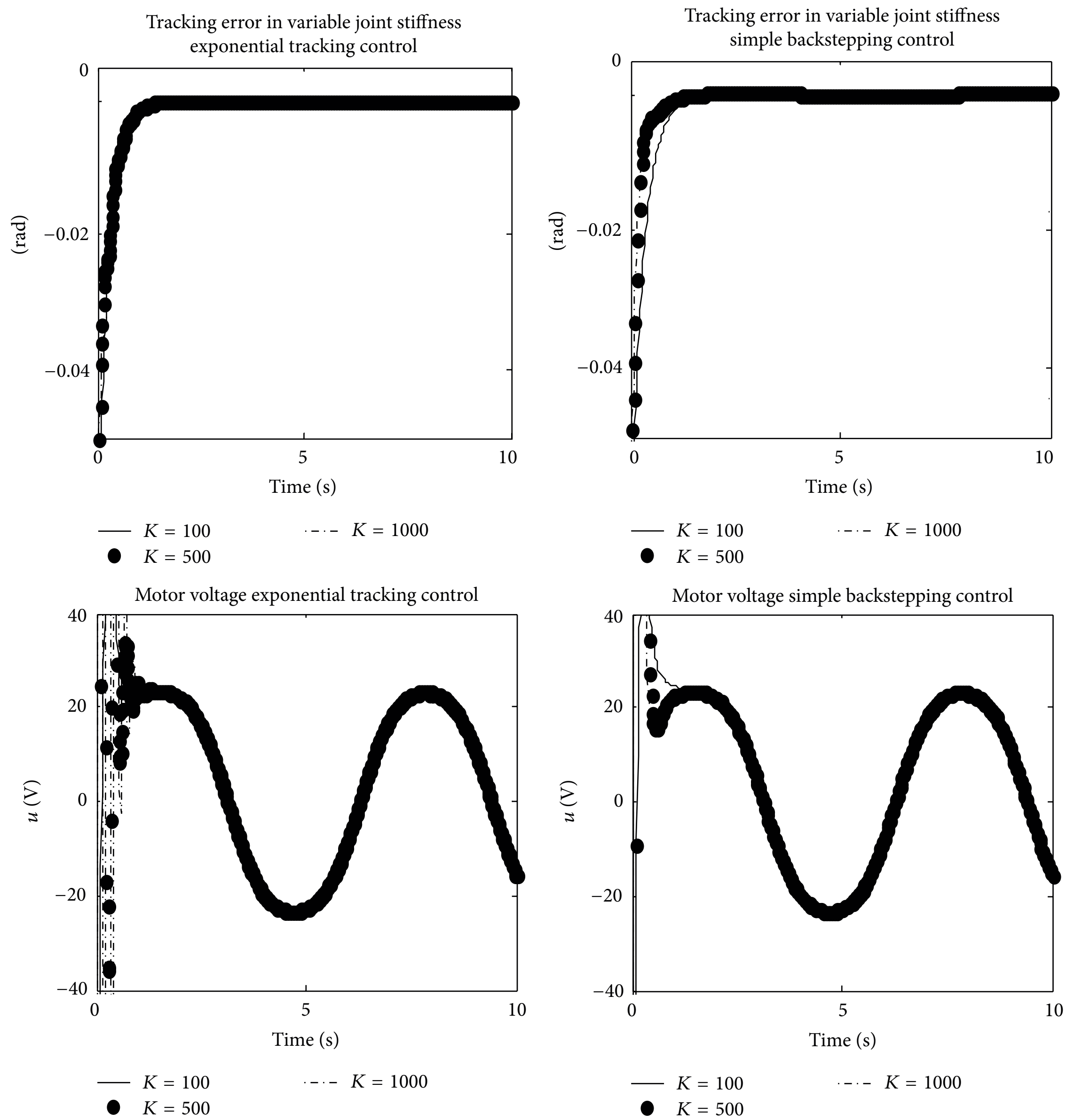

Figure 4: Comparative tracking performance in variable joint stiffness.

Let us define the Lyapunov function candidate as $V_4 = V_3 + (1/2)z_3^T KLz_3$, and computing its derivative, we have

$$\begin{aligned}\dot{V}_4 &= \dot{V}_3 + z_3^T KL\dot{z}_3 \\ &= -r^T K_d r - z_1^T K\lambda_2 z_1 - z_2^T K\lambda_3 z_2 + z_2^T K z_3 \\ &\quad + z_3^T K\left[U - Rx_3 - K_b x_2 - L\rho_3\right].\end{aligned} \tag{23}$$

In order to stabilize the fourth equation of system (5), the control law is chosen as

$$u = -z_2 - \lambda_4 z_3 + Rx_3 + K_b x_2 + L\rho_3, \tag{24}$$

where λ_3 is diagonal matrix with positive elements.

Then it follows that

$$\dot{V}_4 = -r^T K_d r - z_1^T K\lambda_2 z_1 - z_2^T K\lambda_3 z_2 - z_3^T K\lambda_4 z_3 \le 0. \tag{25}$$

According to the Lyapunov stability analysis, the developed control law (24) guarantees that the equilibrium points $r_1 = 0$, $z_1 = 0$, $z_2 = 0$, and $z_3 = 0$ are exponentially asymptotically stable. Moreover, the control law (6) ensures that $\dot{\tilde{q}} \rightarrow 0$ and $\tilde{q} \rightarrow 0$ exponentially as $t \rightarrow \infty$. Exponential function property ensures that the tracking errors $\dot{\tilde{q}}$ and $\tilde{q}$ converge quickly to zero. This quickness can deal with the looseness of velocity due to the flexibility of joint and its variable stiffness; therefore, control law (24) allows tracking trajectory in high velocity.

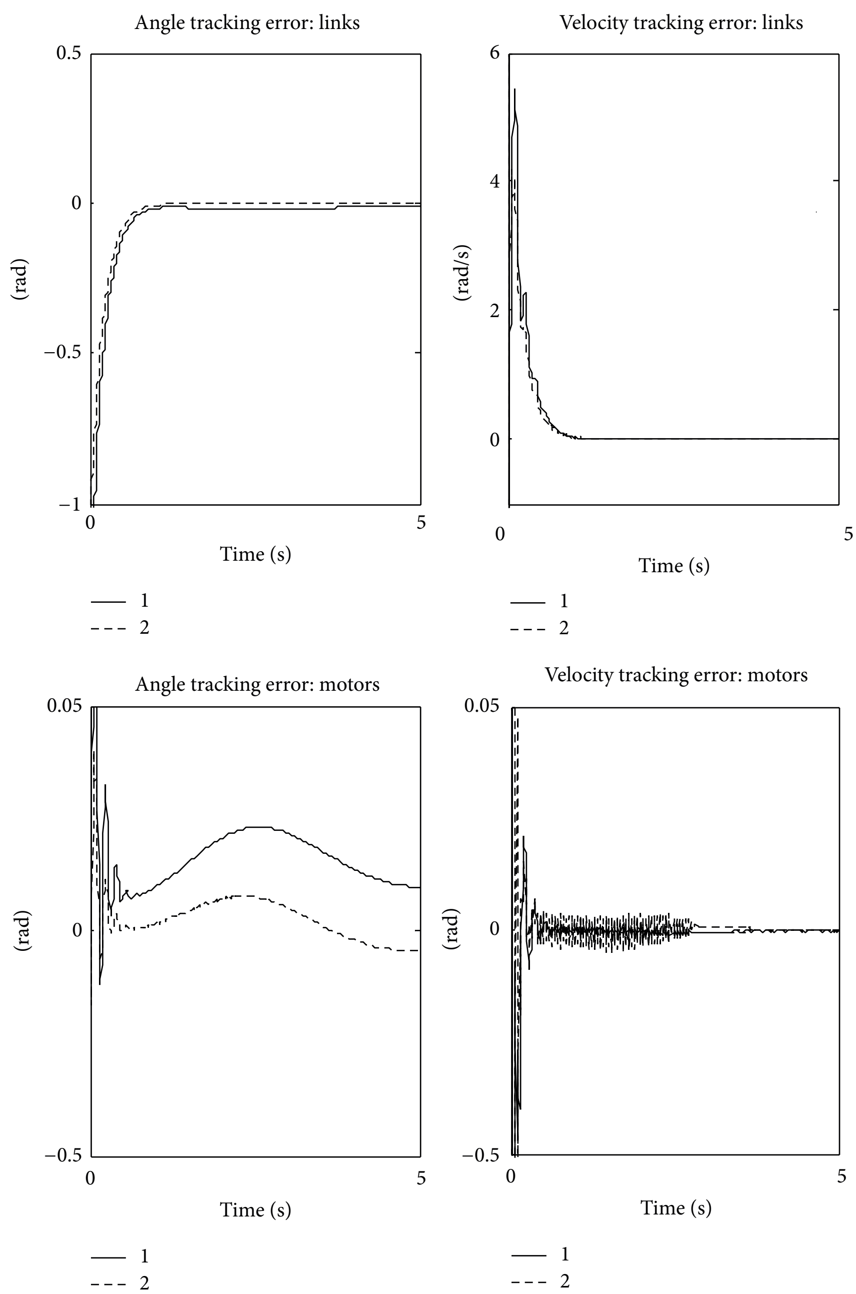

Figure 5: Tracking links angles and velocity error.

Combining (12), (15) and (20), and (22) and (24), the dynamical equation below is derived:

$$\begin{pmatrix} \dot{z}_1 \\ \dot{z}_2 \\ \dot{z}_3 \end{pmatrix} = \begin{pmatrix} -\lambda_2 & \mathrm{Id}_{2*2} & 0_{2*2} \\ -J^{-1}H & -J^{-1}H\lambda_3 & J^{-1}H \\ 0_{2*2} & -L^{-1} & -L^{-1}\lambda_4 \end{pmatrix} \begin{pmatrix} z_1 \\ z_2 \\ z_3 \end{pmatrix} + \begin{pmatrix} -r \\ 0_{1*2} \\ 0_{1*2} \end{pmatrix}, \tag{26}$$

where 0_{2*2} is a 2×2 zeros matrix and Id_{2*2} is a 2×2 identity matrix; then exponential tracking control structure method is given by Figure 1.

4. The Cases Studies and Simulation Results

Two cases were studied in this section. In the first case, we will apply the proposed controller design in control of single flexible link electrically driven robot, in order to compare the exponential tracking controller performance to the simple backstepping controller performed in [1]. We will use the same model and the same parameter as those used in [1].

In order to show that the proposed controller can be applied in manipulators that contain more degrees of freedom, we consider, in the second case, the problem of control of two-degree-of-freedom flexible joint robot manipulators

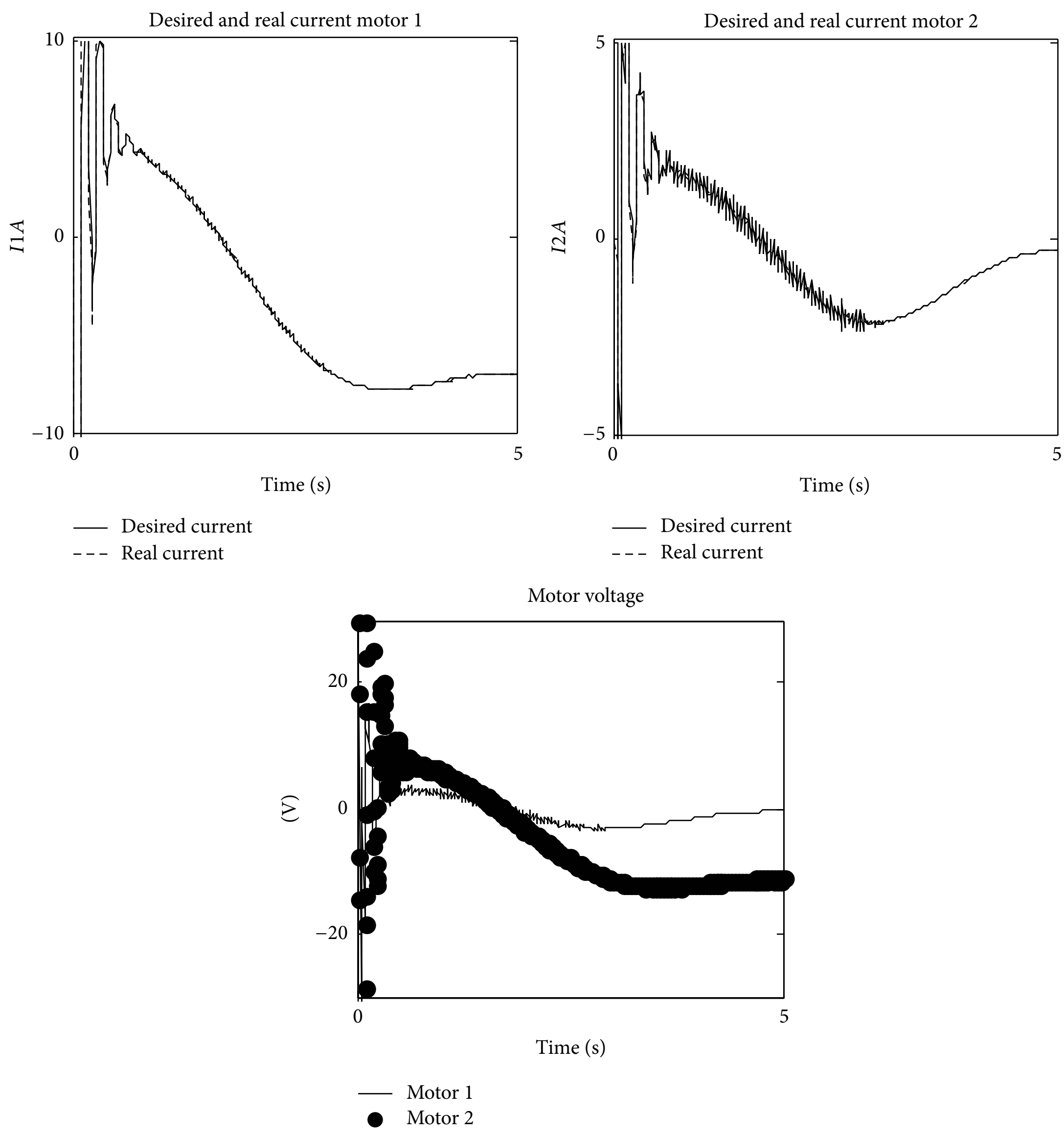

Figure 6: Motor's current and voltage.

driven by brushed DC motor (Figure 2), with parameters given in Table 1.

The dynamic model of this manipulator can be described in the form of (26):

$$D(q) = \begin{bmatrix} j_1 + j_2 + 2j_3\cos(q_2) & j_2 + j_3\cos(q_2) \\ j_2 + j_3\cos(q_2) & j_2 \end{bmatrix},$$

$$C(q,\dot{q})\,\dot{q} = \begin{bmatrix} -j_3\left(2\dot{q}_1\dot{q}_2 + \dot{q}_2^2\right)\sin(q_2) \\ j_3\dot{q}_1^2\sin(q_2) \end{bmatrix},$$

$$G(q) = \begin{bmatrix} -g_1\sin(q_1) - g_2\sin(q_2 + q_1) \\ -g_2\sin(q_2 + q_1) \end{bmatrix},$$

$$j_1 = m_1\varepsilon_1^2 + m_2 l_1^2 + I_1; \qquad j_1 = m_2\varepsilon_2^2 + I_2;$$

$$j_1 = m_2 l_1 \varepsilon_2;$$

$$g_1 = (m_1\varepsilon_1 + m_2 l_1)\,g; \qquad g_2 = m_2\varepsilon_2 g, \tag{27}$$

where ε_1 and ε_2 are, respectively, the link center of mass of links 1 and 2.

4.1. Comparative Study. In this case, we compare the performances in tracking trajectory of the proposed controller with the simple backstepping controller performed in [1], in the control of single flexible link manipulator driven by brushed DC motor modeled in [1].

The exponential tracking controller gains are set as $K_d = 6$; $\lambda_1 = 15$; $\lambda_2 = \lambda_3 = 5$; $\lambda_4 = 2$.

We consider the desired trajectory of the link angular position as follows: $q^{\mathrm{des}} = \sin(t)$rad. The state initial conditions are selected as $[0.6; 0.5; 0.5; 0.2; 0]$.

The simulation results are presented in Figure 3.

Figure 3 shows that the performance of the proposed controller is superior in tracking trajectory to the one performed in [1] (N°1 and N°2), with the same motor voltage (N°3).

To compare robust performances with respect to joint stiffness uncertainties, we simulate the system control for joint stiffness variables 100, 500, and 1000 using the same controllers.

Figure 4 shows that, with the same motor voltage, the proposed controller gives better robust performance with respect to uncertain stiffness than the controller computed in [1], because the tracking error for the proposed controller is the same in presence of joint stiffness as shown in Figure 4.

4.2. Evaluating Performances of Controller in Manipulator with More Degrees of Freedom. In order to show that the proposed control strategy is applicable to manipulator with more degrees of freedom and more flexible joint, the simulation results are presented for two-degree-of-freedom flexible joint manipulator presented previously. For this purpose, the exponential tracking controller gains are set as $K_d = \mathrm{diag}(5, 5)$; $\lambda_1 = \mathrm{diag}(5, 5)$; $\lambda_2 = \mathrm{diag}(5, 2)$; $\lambda_3 = \mathrm{diag}(8, 5)$; $\lambda_4 = \mathrm{diag}(1.2, 1.2)$.

The controller (24) is used to track the desire trajectory:

$$q_1^{\mathrm{des}} = q_2^{\mathrm{des}} = 0.5 - \cos\left(\frac{\pi}{5}t\right) \mathrm{rad}. \tag{28}$$

The state initial conditions are the same as those used in Section 4.1.

The simulation results are given by Figures 4 and 5.

Figure 5 shows the performance of the proposed controller on tracking trajectory. As seen in Figure 5, in less than 1 sec, our control goal is satisfied.

Figure 6 showed that the goal is satisfied with a small voltage and current, because after 1 sec, the motor voltages remain between −20 volts and 20 volts.

A comparison of the tracking performance of joint stiffness is shown in Figure 7. The control system has been simulated for joint stiffness 400, 500, and 1000 using the same controller's gains.

The tracking control showed similar behaviors in different values of joint stiffness. This result showed the robustness of our proposed controller with respect to joint stiffness uncertainties.

As shown in Figure 8, the motor voltages respond fast with high value in the beginning. But after a small time (less than 1 sec), the values remain under ∓20 volts.

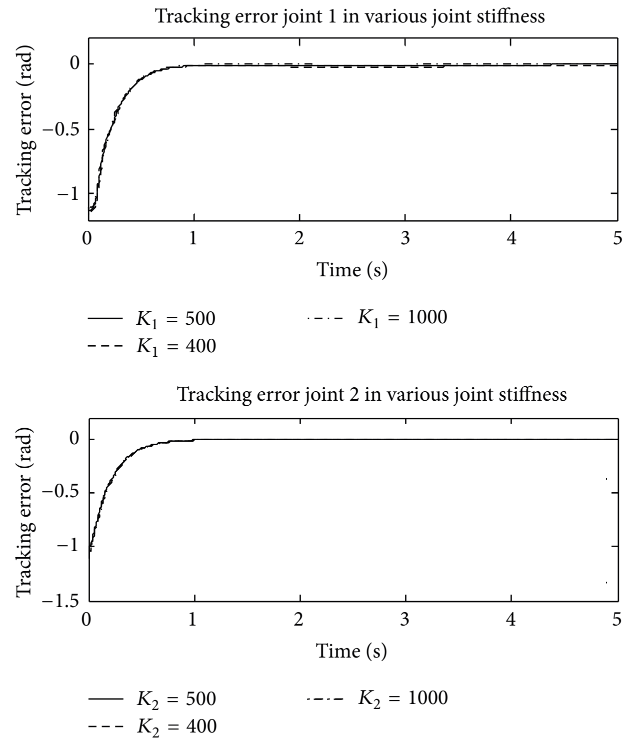

FIGURE 7: Tracking error in various values of joint stiffness.

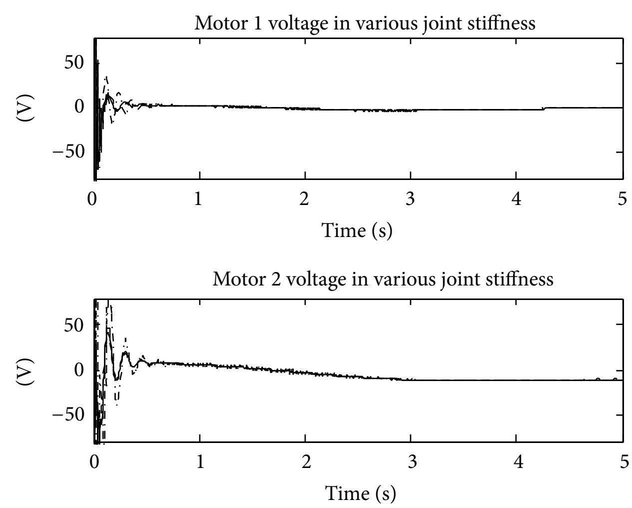

FIGURE 8: Motor voltage in various values of joint stiffness.

5. Conclusion

Exponential tracking control using backstepping approach was proposed in this paper to cope with the difficulty introduced by the cascade structure in EFJR's dynamic model, to deal with flexibility in joints, and to ensure fast tracking performance. The controller design was performed by modifying common backstepping algorithm such that the link position and velocity errors converge to zero exponentially fast. The suggested controller required feedback information of position and velocity on the links and motors and armature current of each motor. The simulation results indicated that the proposed controller is superior to the simple backstepping controller performed in the literature for the control problem of EFJR and that it is robust with respect to joint stiffness uncertainties.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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