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Real-time Fuzzy Fractional-Order Control of Electrically Driven Flexible-Joint Robots

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ABSTRACT: Fractional order control of electrically driven flexible-joint robots has been addressed in this paper. The controller design strategy is based on the actuators' electrical subsystem considering to voltage saturation nonlinearity. Hence, the knowledge of the actuator/robot dynamics model is not required as it is for many other control strategies. The overall closed-loop system is proven to be stable and the joint position tracking error is uniformly bounded based on the Lyapunov's stability concept. The satisfactory performance of the proposed control scheme is verified by experimental results.

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1. INTRODUCTION

Reviewing the robotic researches in the last decades indicates that control of flexible joint robots is one of the most challenging tasks in this field. On the other hand, their widespread application in various fields such as space manipulators and articulated hands [1] has made it a popular research area. Many valuable control strategies have been applied to flexible joint robots to enhance the system performance. A task-space controller based on the back-stepping approach has been presented in [2]. An observer-based controller for flexible joints robots has been developed, [3], in which the uncertainties on the motor-side are successfully eliminated using a disturbance observer. Also, many other approaches such as nonlinear adaptive control [4], passivity-based control [5], adaptive back-stepping control [6], global position-feedback tracking control [7], Singular perturbation approach [8-9], predictive control [10], adaptive fuzzy approaches [11-12], hierarchical sliding mode control [13], dynamic surface control [14], and higher-order differential feedback control [15] have been studied. It is worth noting that most of them have ignored the actuator dynamics in their design procedure. In other words, their control laws calculate the desired torque that should be applied to the manipulator joints.

Since most robotic systems use electrical motors as actuators, recently, some voltage-based controllers have been presented for electrically driven flexible joint robot manipulators (EDFJR). A decentralized robust back-stepping like control strategy for EDFJR considering the effects of actuator voltage input constraint has been proposed in [16]. Adaptive form of this work has also been presented in [17] that guarantees only BIBO stability of the systems' states. The considerable point is that, stability is analyzed separately in saturated and unsaturated operation areas. However, the stability of the closed-loop system may not be guaranteed through these separations, since transitions from saturation area to unsaturated area and vice versa are neglected. As an extension in this field, a robust Lyapunov-based controller for EDFJR using voltage control strategy has been proposed in [18]. The controller design procedure in [18] is based on the third order instead of the fifth order system dynamics, while all system states are remained bounded and the position errors of the links asymptotically converge to zero. An indirect adaptive fuzzy controller for EDFJR manipulators has been developed in [19]. The controller structure differs from the previous ones due to using one control loop whereas the commonly used control design employs two control loops. Nevertheless, the stability analysis presented in [19], does not address the saturated area properly. In [20], the previous results on the robust stability of EDFJR presented by [16] have been modified. It should be emphasized that considering electrical motors dynamics increases the system order and consequently, the number

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of required feedbacks will be increased. Moreover, actuator saturation is another challenging issue, which should be taken into consideration in the controller design, since it imposes additional nonlinearities to the closed-loop system [21-22]. To the best of our knowledge, there are very few works in the control literature, which deal with the actuator saturation in voltage-based control of flexible joint manipulators. Thus, the contributions of this paper are designing a suitable voltage-based controller for flexible joint manipulators to consider the actuator saturation problem.

Studying the literature on the field of adaptive and robust control in recent years, remains no doubt that uncertainty estimation and compensation play the key role in improving the controller performance [23-25]. At the heart of this area is the Stone-Weierstrass theorem [26]. Many advances and successes in neuro-fuzzy control of complicated uncertain nonlinear multivariable systems owe to this fundamental theorem and during the last few decades, numerous neuro-fuzzy control structures for various systems have been presented [27-29]. The reason for these widespread applications of neuro-fuzzy systems may be the fact that with the help of Stone-Weierstrass theorem, determination of the regressor matrices can be avoided. However, fractional order control of electrically driven flexible joint robots using voltage control strategy remains as an open problem.

In this paper, we are going to address an indirect adaptive fuzzy fractional-order control for EDFJR considering to actuator input constraint. The controller design is not dependent on the dynamics of the actuators and manipulators, thus is a model-free controller. The overall closed-loop system is proven to be stable and the joint position tracking errors are uniformly bounded based on the Lyapunov stability concepts. Most of previous approaches proposed for position control of flexible joint electrically driven robots (FJER) utilize back-stepping or back-stepping-liked control strategy which requires convergence of internal signals to their desired values called as fictitious control signals [20]. This strategy is complicated and time consuming, whereas each joint of the robot is described by a 5th-order cascade differential equation. Therefore, as studied in this paper, the best idea is focusing on the convergence of the system output and meanwhile guaranteeing boundedness of other states (internal signals). Consequently, the control law dimension and its implementation costs are reduced. This is the main problem which has been considered in the proposed approach.

The rest of this paper is as follows. In section 2, the model of an *n*-link flexible joint robot manipulator is described. In section 3, the indirect adaptive fuzzy fractional-order controller is presented. The stability analysis is also discussed in this section. In section 4, some experimental results are illustrated and finally, some conclusions are given in Section 5. Note that, throughout this paper, we present the vectors and matrices in bold form.

2. ROBOT DYNAMICS

The dynamics of an electrically driven flexible-joint robot can be described by

$$\mathbf{D}(\mathbf{q})\ddot{\mathbf{q}}+\mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}}+\mathbf{g}(\mathbf{q})=\mathbf{K}(\mathbf{r}\boldsymbol{\theta}_m-\mathbf{q}) \tag{1}$$

$$\mathbf{J}\ddot{\boldsymbol{\theta}}_m+\mathbf{B}\dot{\boldsymbol{\theta}}_m+\mathbf{rK}(\mathbf{r}\boldsymbol{\theta}_m-\mathbf{q})=\mathbf{K}_m\mathbf{I}_a \tag{2}$$

$$\mathbf{R}\mathbf{I}_a+\mathbf{L}\dot{\mathbf{I}}_a+\mathbf{K}_b\dot{\boldsymbol{\theta}}_m=\mathbf{v}(t) \tag{3}$$

where $\mathbf{q}$ is the *n*-vector of joint angles, $\mathbf{D}(\mathbf{q})$ is the $n\times n$ inertia matrix, $\mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}}$ is the *n*-vector of centrifugal and Coriolis forces, $\mathbf{g}(\mathbf{q})$ is the gravitational forces vector, $\dot{\boldsymbol{\theta}}_m$ is the *n*-vector of motor angles, $\mathbf{I}_a$ is the *n*-vector of motor armature current, and $\mathbf{v}(t)$ is the *n*-vector control input voltage to the actuators. $\mathbf{J}$, $\mathbf{B}$, $\mathbf{r}$, $\mathbf{K}_m$, $\mathbf{L}$, $\mathbf{R}$, $\mathbf{K}_b$, and $\mathbf{K}$, are $n\times n$ constant diagonal matrices of actuator inertias, damping, gear-box ratio, torque constant, electrical inductance, electrical resistance, back-emf effects, and joint stiffness, respectively.

3. INDIRECT ADAPTIVE FUZZY FRACTIONAL-ORDER CONTROL

Equations (1)-(3) represent a fifth-order highly nonlinear dynamic system that makes the control problem extremely difficult. To cope with this problem, an indirect adaptive fuzzy fractional-order controller is developed based on the actuators' electrical subsystem and using voltage control strategy. The controller design procedure start by adding and subtracting the Caputo fractional derivative of the joint position variable, ${}_{t_0}^{C}D_t^{\alpha}q(t)$, to the left hand side of Equation (3) in decentralized form as

$${}_{t_0}^{C}D_t^{\alpha}q(t)-{}_{t_0}^{C}D_t^{\alpha}q(t)+RI_a+L\dot{I}_a+K_b\dot{\theta}_m=\mathrm{v}(t) \tag{4}$$

Where

$${}_{t_0}^{C}D_t^{\alpha}q(t)=\frac{1}{\Gamma(n-\alpha)}\int_{t_0}^{t}\frac{q^{(n)}(\tau)}{(t-\tau)^{\alpha-n+1}}d\tau.\quad t>t_0 \tag{5}$$

represents the Caputo fractional derivative of order $\alpha\in\Re^+$, and $\Gamma(n)$ denotes the famous Gamma function with $n=\min\{k\in\mathbb{N}/k>\alpha\}$ [30]. Let us define $F(I_a,\dot{I}_a,\dot{\theta}_m,{}_{t_0}^{C}D_t^{\alpha}q(t))$, called residual uncertainty as

$$F(I_a,\dot{I}_a,\dot{\theta}_m,{}_{t_0}^{C}D_t^{\alpha}q(t))=RI_a+L\dot{I}_a+K_b\dot{\theta}_m-{}_{t_0}^{C}D_t^{\alpha}q(t) \tag{6}$$

Equation (4) can be rewritten as follows

$${}_{t_0}^{C}D_t^{\alpha}q(t)+F(I_a,\dot{I}_a,\dot{\theta}_m,{}_{t_0}^{C}D_t^{\alpha}q(t))=\mathrm{v}(t) \tag{7}$$

From practical point of view, the range of actuator input may limit by some upper and lower bound [20]. Suppose that the input limitation is described as

$$\mathrm{v}(t)=\mathrm{sat}(\mathrm{u}(t))=\begin{cases}\xi_u & ;\mathrm{u}(t)>\xi_u\\ \mathrm{u}(t) & ;-\xi_u\le\mathrm{u}(t)\le\xi_u\\ -\xi_u & ;\mathrm{u}(t)<-\xi_u\end{cases} \tag{8}$$

where $\mathrm{v}(t)$ represents the actual actuator input, $\mathrm{sat}(\mathrm{u}(t))\in\Re$ represents the saturation function, $\mathrm{u}(t)$ represents the controller output, and $\xi_u > 0$ denotes the maximum admissible voltage of the motor. When controller output falls outside linear range of the actuator operation, actuator saturation occurs. The non-implemented control signal by the device, denoted as $\mathrm{dzn}(\mathrm{u}(t),\xi_u)$, is then given by [31, 32]

$$\mathrm{dzn}(\mathrm{u}(t),\xi_u)=\mathrm{u}(t)-\mathrm{sat}(\mathrm{u}(t)) \tag{9}$$

Now, substituting (8) into (7), and using (9), it follows that

$$\begin{aligned}{}_{t_0}^{C}D_t^{\alpha} q(t) + F(I_a, \dot{I}_a, \dot{\theta}_m, {}_{t_0}^{C}D_t^{\alpha} q(t)) = \mathrm{u}(t) \\ -\,\mathrm{dzn}(\mathrm{u}(t),\xi_u)\end{aligned} \tag{10}$$

Remark 1: Equation (8) indicates that the motor voltage is bounded, i.e,

$$|\mathrm{v}(t)| \le \xi_u \tag{11}$$

As a result, the variables I_a, $\dot{I}_a$, and $\dot{\theta}_m$ are upper bounded as ξ_I, $\xi_{\dot{I}}$ and $\xi_{\dot{\theta}_m}$, respectively [31].

The considerable point is that the uncertain term $F(I_a, \dot{I}_a, \dot{\theta}_m, {}_{t_0}^{C}D_t^{\alpha} q(t))$ cannot be evaluated directly, since the actual values of the motor dynamic parameters are unknown. Under these circumstances, indirect adaptive fuzzy fractional-order control with a set of tunable parameters is employed to approximate lumped uncertainty. Overall control law is as follows:

$$\begin{aligned}\mathrm{u}(t) = {}_{t_0}^{C}D_t^{\alpha} q_d(t) + k_p(q_d(t) - q(t)) \\ +\hat{F}(I_a, \dot{I}_a, \dot{\theta}_m, {}_{t_0}^{C}D_t^{\alpha} q(t))\end{aligned} \tag{12}$$

where $q_d(t)$ is the desired trajectory, k_p is a positive control gain, and $\hat{F}(I_a, \dot{I}_a, \dot{\theta}_m, {}_{t_0}^{C}D_t^{\alpha} q(t))$ is a fuzzy system to estimate the function $F(I_a, \dot{I}_a, \dot{\theta}_m, {}_{t_0}^{C}D_t^{\alpha} q(t))$. Purposefully, $\hat{F}(I_a, \dot{\theta}_m, {}_{t_0}^{C}D_t^{\alpha} q(t))$ excludes $\dot{I}_a$ since the electrical time constant of the DC motor is ignorable in comparison with its mechanical time constant. In addition, $\dot{I}_a$ might be noisy. As a result, using $\dot{I}_a$ measurement in the controller is not recommended. Now, substituting (12) into (10) yields

$${}_{t_0}^{C}D_t^{\alpha} e(t) + k_p e(t) = F - \hat{F} + \mathrm{dzn}(\mathrm{u}(t),\xi_u) \tag{13}$$

Where

$$e(t) = q_d(t) - q(t) \tag{14}$$

represents joint position tracking error. Consider the inputs of fuzzy system x_1, x_2, and x_3 as

$$x_1 = I_a,\ \ x_2 = \dot{\theta}_m,\ \ x_3 = {}_{t_0}^{C}D_t^{\alpha} q(t) \tag{15}$$

Suppose that three membership functions are defined for each fuzzy input. Consequently, there are 27 fuzzy rules. Consider the linguistic fuzzy rules as

$$\begin{aligned}&\mathit{Rule}\ l:\ \mathit{if}\ x_1\ \mathit{is}\ A_l \text{ and } x_2\ \mathit{is}\ B_l \text{ and} \\ &\quad x_3\ \mathit{is}\ C_l \text{ Then } \hat{F} \text{ is } D_l\end{aligned} \tag{16}$$

in which *Rule l* denotes the *lth* fuzzy rule for *l*=1,…,27. In the *lth* rule, the fuzzy variables x_1, x_2, x_3 and $\hat{F}$, will be evaluated by the fuzzy membership functions A_l, B_l, C_l, and D_l. Three membership functions P, Z, and N are given to the inputs x_1, x_2, and x_3 in the operating range of the system. The mathematic equations of membership functions for the input x_1 are

$$\begin{aligned}&\mu_Z(x_1) = \exp\left(-\frac{x_1^2}{2\sigma^2}\right),\ \sigma = 0.3 \\ &\mu_P(x_1) = \begin{cases} 0 & x < 0 \\ 1 - \mu_Z(x_1) & x \ge 0 \end{cases}, \\ &\mu_N(x_1) = \begin{cases} 0 & x > 0 \\ 1 - \mu_Z(x_1) & x \le 0 \end{cases}\end{aligned} \tag{17}$$

These functions are plotted in Fig. 1. Similarly, the membership functions for the inputs x_2, and x_3 have been defined. Also, the membership functions for the output $\hat{F}$ are in the form of

$$\mu_{D_l}(\hat{F}) = \exp\left(-\frac{(\hat{F} - \hat{y}_l)^2}{2\sigma^2}\right) \tag{18}$$

in which $\hat{y}_l$ is the center of D_l. According to [19], $\hat{F}$ can be represented as

$$\hat{F} = \sum_{l=1}^{27} \hat{y}_l \psi_l(x_1, x_2, x_3) = \hat{\mathbf{y}}^T \boldsymbol{\psi}(x_1, x_2, x_3) \tag{19}$$

where $\hat{\mathbf{y}} = [\hat{y}_1\ \ \dots\ \ \hat{y}_{27}]^T$ and $\boldsymbol{\psi} = [\psi_1\ \ \dots\ \ \psi_{27}]^T$ in which ψ_l is a positive value expressed as

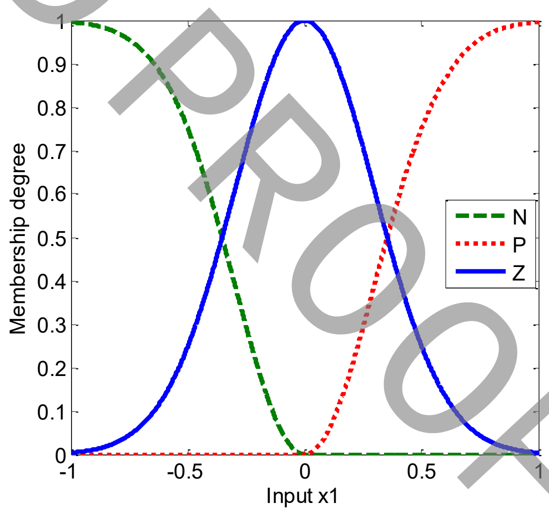

Fig. 1. Membership functions for the inputs x_1

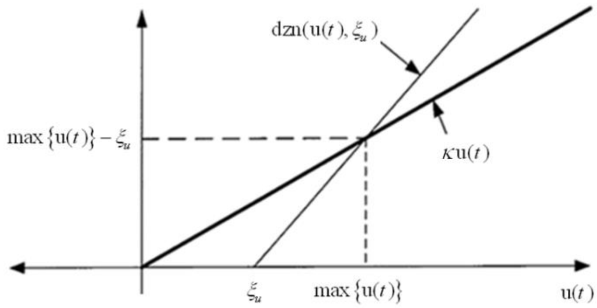

Fig. 2. Linear bound of dead-zone function

$$\psi_l(x_1,x_2,x_3) = \frac{\mu_{A_l}(x_1)\mu_{B_l}(x_2)\mu_{C_l}(x_3)}{\sum_{l=1}^{27}\mu_{A_l}(x_1)\mu_{B_l}(x_2)\mu_{C_l}(x_3)} \tag{20}$$

It is obvious that $\mu_{A_l},\mu_{B_l},\mu_{C_l}\in(0,1]$. As a result we have: $|\psi_l(x_1,x_2,x_3)|\le 1$ for l=1,…,27. Therefore, vector $\boldsymbol{\psi}=[\psi_1 \ \ \dots \ \ \psi_{27}]^T$ is bounded.

According to the universal approximation property of fuzzy systems, F can be represented by

$$F = \mathbf{y}^T\boldsymbol{\psi}(x_1,x_2,x_3)+\varepsilon \tag{21}$$

where $\mathbf{y}=[y_1 \ \ \dots \ \ y_{27}]^T$ is an optimal weighting vector, and ε denotes the bounded approximation error. Now, applying Equations (19) and (21) to equation (13) obtains the closed loop system as

$${}_{t_0}^{C}D_t^{\alpha}e(t)+k_pe(t)=\tilde{\mathbf{y}}^T\boldsymbol{\psi}(x_1,x_2,x_3)+\varepsilon+\mathrm{dzn}(\mathrm{u}(t),\xi_u) \tag{22}$$

where expression $\tilde{\mathbf{y}}=\mathbf{y}-\hat{\mathbf{y}}$ represents the difference between actual and estimated value of weighting vectors.

3. 1. Stability analysis

To proceed with subsequent stability analysis, the following lemma is required. First, the following three assumptions are enforced.

Assumption 1: The desired trajectory and its fractional-order derivatives are continuous and uniformly bounded.

Assumption 2: The motor parameters R, L, and K_b are assumed to be bounded from above and below. That is

$$\underline{r_a}\le R\le\overline{r}_a \quad , \quad \underline{l_a}\le L\le\overline{l}_a \quad , \quad \underline{k_b}\le K_b\le\overline{k}_b$$

where $(\underline{\bullet})$ and $(\overline{\bullet})$ are positive constants.

Assumption 3: The reconstruction error ε is bounded, i.e. $|\varepsilon|<c_\varepsilon$ with known c_ε.

Now, we are ready to present the following Lemma.

Lemma 1. $|\mathrm{dzn}(\mathrm{u}(t),\xi_u)|$ satisfies the following bounding inequality:

$$|\mathrm{dzn}(\mathrm{u}(t),\xi_u)|\le\frac{\kappa\varsigma}{(1-\kappa)} \tag{23}$$

where $\kappa=1-\frac{\xi_u}{\max\{\mathrm{u}(t)\}}$ is a constant smaller than 1.

Proof: Suppose that $\mathrm{u}(t)$ is within the bounds of $[-\max\{\mathrm{u}(t)\},\max\{\mathrm{u}(t)\}]$. Then,

$$|\mathrm{dzn}(\mathrm{u}(t),\xi_u)|\le\kappa|\mathrm{u}(t)| \tag{24}$$

is satisfied by Fig. 2. This result, together (6), (12) and (22) gives

$$\begin{aligned}|\mathrm{dzn}(\mathrm{u}(t),\xi_u)| &\le \kappa\left|{}_{t_0}^{C}D_t^{\alpha}q_d(t)+k_p(q_d-q)+\hat{F}\right|\\ &\le\kappa\left|RI_a+L\dot{I}_a+K_b\dot{\theta}_m\right|\\ &\quad+\kappa|\mathrm{dzn}(\mathrm{u}(t),\xi_u)|\end{aligned} \tag{25}$$

Assume that $|RI_a+L\dot{I}_a+K_b\dot{\theta}_m|\le\varsigma$, where $\varsigma=\overline{r}_a\xi_I+\overline{l}_a\xi_{\dot{I}}+\overline{k}_b\xi_{\dot{\theta}_m}>0$ is a known scalar defined by the use of Remark 1, and assumption 2. Thus:

$$|\mathrm{dzn}(\mathrm{u}(t),\xi_u)|\le\frac{\kappa\varsigma}{(1-\kappa)}$$

This completes the proof

To prove the closed loop stability and to find appropriate update law, let us consider the following positive definite function

$$V(e,\tilde{\mathbf{y}})=\frac{1}{2}e^2+\frac{1}{2}\tilde{\mathbf{y}}^T\mathbf{Q}\tilde{\mathbf{y}} \tag{26}$$

where $\mathbf{Q}\in\Re^{27\times27}$ is a positive definite matrix. Taking the Caputo fractional derivative to expression (26) and applying Lemma 4 from [33], it follows that

$${}_{t_0}^{C}D_t^{\alpha}V(e,\tilde{\mathbf{y}})\le e(t)\,{}_{t_0}^{C}D_t^{\alpha}e(t)+\tilde{\mathbf{y}}^T\mathbf{Q}\,{}_{t_0}^{C}D_t^{\alpha}\tilde{\mathbf{y}} \tag{27}$$

Using expression (22) in (27), we have

$$\begin{aligned}{}_{t_0}^{C}D_t^{\alpha}V(e,\tilde{\mathbf{y}}) &\le -k_pe^2(t)+|e(t)|\left(|\varepsilon|+|\mathrm{dzn}(\mathrm{u}(t),\xi_u)|\right)\\ &\quad+\tilde{\mathbf{y}}^T(\boldsymbol{\psi}(x_1,x_2,x_3)e(t)-\mathbf{Q}\,{}_{t_0}^{C}D_t^{\alpha}\hat{\mathbf{y}})\end{aligned} \tag{28}$$

The update law is picked to be

$${}_{t_0}^{C}D_t^{\alpha}\hat{\mathbf{y}}=\mathbf{Q}^{-1}\boldsymbol{\psi}(x_1,x_2,x_3)e(t) \tag{29}$$

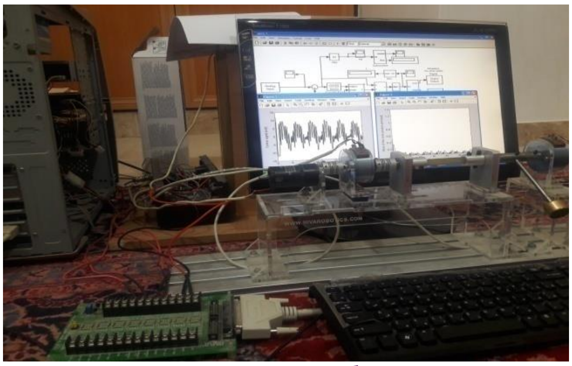

Fig. 3. Experimental setup

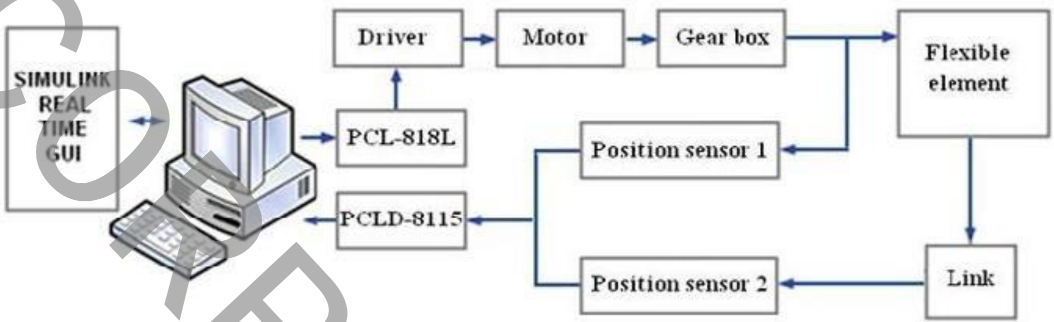

Fig. 4. Block diagram of the system

Therefore, (28) can be further written as

$$ {}_{t_0}^{C}D_t^{\alpha}V(e,\tilde{\mathbf{y}}) \le -k_p e^2(t) + |e(t)|\left(c_\varepsilon + \frac{\kappa\varsigma}{(1-\kappa)}\right) \quad (30)$$

where we have used Lemma 1 and assumption 3. As a result, ${}_{t_0}^{C}D_t^{\alpha}V(e,\tilde{\mathbf{y}})$ is negative semi-definite if

$$ |e| > \frac{1}{k_p}\left(c_\varepsilon + \frac{\kappa\varsigma}{(1-\kappa)}\right) \quad (31)$$

Since $V(e,\tilde{\mathbf{y}})$ is positive-definite and decrescent, it can be concluded from Theorem 3 of [33] that, the origin of the system (22) and (29) is uniformly stable. As a result, the joint position tracking error is bounded. Because e is bounded, boundedness of q can be obtained whereas q_d is bounded. In addition to this, ${}_{t_0}^{C}D_t^{\alpha}V(e,\tilde{\mathbf{y}}) \le 0$ implies that $\tilde{\mathbf{y}}$ is also uniformly bounded. Equation (22) is a linear fractional-order differential equation with bounded input. Thus, Equation (22) is stable based on Routh-Hurwitz criteria [34]. As a result, ${}_{t_0}^{C}D_t^{\alpha}e(t)$ is bounded. This result together with the boundedness of ${}_{t}^{C}D_t^{\alpha}q_d(t)$ implies that ${}_{t_0}^{C}D_t^{\alpha}q(t) = {}_{t_0}^{C}D_t^{\alpha}q_d(t) - {}_{t_0}^{C}D_t^{\alpha}e(t)$ is also bounded. From (2) we have

$$ J\ddot{\theta}_m + B\dot{\theta}_m + r^2K\theta_m = rKq + K_m I_a \quad (32)$$

which is a second-order linear differential equation with the bounded input. So, according to Routh-Hurwitz stability criteria, the variables $\theta_m, \dot{\theta}_m$, and $\ddot{\theta}_m$ are bounded. Extending these results to all the joints concludes stability of robotic system.

4. EXPERIMENTAL RESULTS

The laboratory set-up which has been considered for experimental study is shown in Fig 3. It is a single-link flexible joint manipulator. The joint consists of two aluminum plates joined by polyurethane material to possess high flexibility. The actuator is a geared permanent magnet DC motor, operating within ±12 volt input, directly driving one plate. A steel tube is connected to the second plate. Two potentiometers provide feedback of the motor and joint positions, while velocity information is obtained by filtering the position feedback data [35]. In order to realization of fractional-order term, we used the same notation as those defined in [36]. In order to control of the system by means of a PC, a PCL-818 I/O card and a PCLD-8115D data acquisition card of the Advantech Company are used for hardware interfacing under 10 msec sampling interval. The sampling period for I/O channels has been set to $T_s = 0.001\,\text{sec}$. Based on the identification process implemented on this system, its bandwidth is $W = 13Hz$. Thus, it is obvious that the condition of Nyquist–Shannon sampling theorem ($T_s \le \frac{1}{2W} = 0.03846$) is satisfied. The “Real-Time Workshop” facilities of the MATLA/SIMULINK are used for user interface. A block diagram of the system is shown in Fig. 4.

To explore the controller ability, performance of the proposed control method is compared with robust voltage-based control strategy given by [16]. The desired trajectory is chosen as

$$ q_d(t) = 1.26 - 0.63\sin\left(\frac{2\pi}{5}t\right) \quad (33)$$

The following settings are used for each controller.

1) For the proposed approach, the design parameters are selected as $k_p = 150$, $\alpha = 0.5$, and $\mathbf{Q} = 0.5I_{(27)}$, where $I_{(\cdot)}$ denotes the identity matrix.

2) For robust control strategy given by [16], $k_p = 100$, $k_i = 1500$, $k_d = 0.001$, $\beta = 1$, $\varepsilon = 10^{-6}$, and $\hat{k}_b = 0.26$.

Under these settings, experimental results were presented in Figs 5-8. Fig. 5 shows the output tracking performance. As can be seen, the proposed controller obtains suitable performance in tracking of reference trajectory. Joint position tracking errors are shown in Fig. 6. Fig. 7 shows the applied voltage to the actuator. Finally, Fig. 8 shows time evolution of the approximation of $\hat{F}$.

As a more quantitative comparison, the tracking performances are also measured in terms of three different performance indexes [35]: the RMS (root mean score) value of the joint position error on a trip of time T defined as

$$RMS[e(t)] = \sqrt{\frac{1}{T}\int_0^T |e(\upsilon)|^2 \, d\upsilon} \tag{34}$$

the maximum absolute value of the tracking error defined as $\max\{|e(t)|\}$, and integral of the square value (ISV) of the control input that shows the energy consumption.

$$ISV = \int_0^T u^2(\tau)d\tau \tag{35}$$

The time interval $5 \le t \le 30$ has been selected to compute these indexes. The results for each performance index are given in Table 1. The results of the first index are nearly the same for two controllers. The best performance for $\max\{|e(t)|\}$ is obtained using the fuzzy fractional order control scheme. To confirm it,

notice that the smallest value for the $\max\{|e(t)|\}$ is obtained by the fuzzy fractional order control scheme. The percentage of improvement is %33.5 with respect to robust control [16]. The best performance for the third index was obtained with the proposed fractional order controller because it has presented the smallest value for ISV; %79.31 improvement with respect to robust control [16].

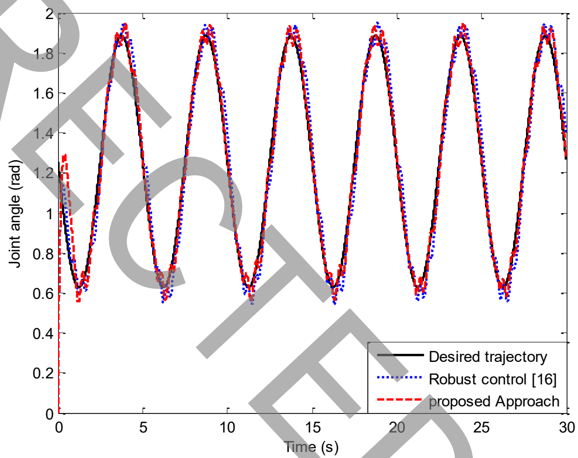

Fig. 5. output tracking performance

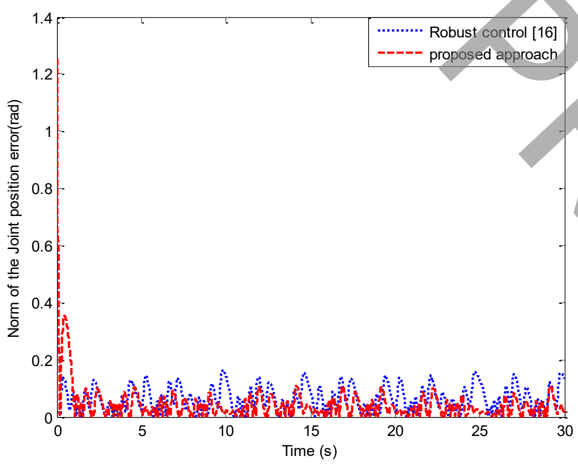

Fig. 6. Norm of the Joint position tracking error

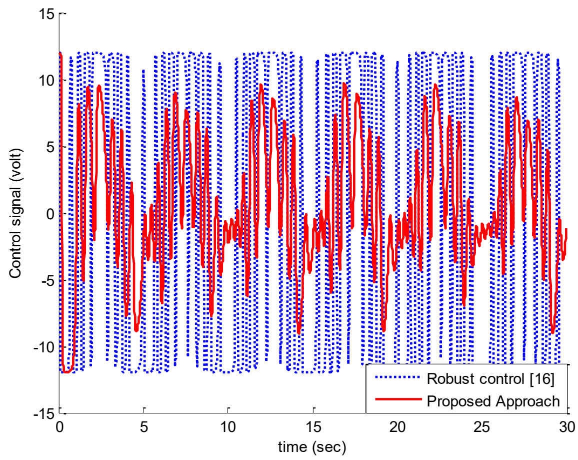

Fig. 7. Control signal

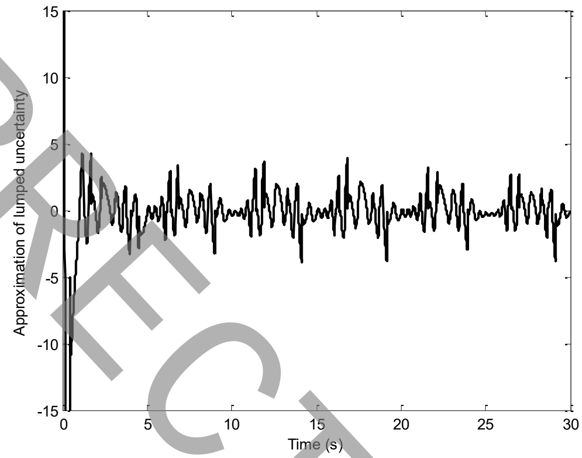

Fig. 8. approximation of $\hat{F}$

Table 1. Performance of three controllers

index	$RMS\{e(t)\}$	$\max\{\lvert e(t)\rvert\}$	ISV
unit	(rad)	(rad)	$(\text{volt})^2$
Robust control [16]	0.07943	0.1639	3773
Proposed approach	0.06839	0.109	780.5

5. CONCLUSIONS

In this paper, we have proposed an indirect adaptive fuzzy fractional-order control scheme for electrically driven flexible joint robots. The controller design is not dependent on the dynamics of the actuators and manipulators, thus is a model-free controller. The nonlinearities originated from actuator saturation have also been taken into consideration. Experimental results on a single-link flexible joint electrically driven robot are introduced to illustrate the performance and effectiveness of our approach.

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