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Research Paper

Stability of Robust Lyapunov Based Control of Flexible-Joint Robots Using Voltage Control Strategy Revisited

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Abstract
Many advanced robot applications such as assembly and manufacturing require mechanical interaction of the robot manipulator with the environment. Any back-stepping based control strategy proposed for position control of electrical flexible joint robots requires a convergence of internal signals to its desired value called a fictitious control signal. This problem is complicated and time-consuming, whereas a 5th-order nonlinear differential equation describes each joint of the robot. The best idea is to focus on the convergence of main signals while the other signals in the system remain bounded. With this in mind, this paper present a robust Lyapunov-based controller for the flexible joint electrically driven robot (FJER) considering input nonlinearities associated with actuator constraints. It also finds uncertainties associated with robot dynamics. The proposed approach is based on a third-order model instead of a fifth-order model of the robotic system. The stability is guaranteed in the presence of both structured and unstructured uncertainties. The actuator/link position errors asymptotically converge to zero while the other signals are bounded. Simulation results on a 2-DOF electrical robot manipulator effectively verify the efficiency of the proposed strategy.

Keywords
Nonlinear Robust Control, Stability Analysis, Actuator Saturation, Flexible-joint Robots

1. Introduction

Recent researches have indicated that the voltage-based control strategy could become a serious competitor to the torque-based control strategy for servo applications [1-2]. In practice, a torque-based control law cannot be given directly to the torque inputs of an electrical manipulator. It's then necessary to provide another control law for the actuators to supply the proposed torques in the manipulator joints [3]. Requirements such as a high degree of automation and fast speed operation are another reason for this. Robot performance degrades quickly as speed increases. High velocity causes dynamic problems. As a result, the role of actuators dynamics cannot be ignored in the control structure [4].

The significant point is that employing an electrical subsystem of the actuator dynamics causes several challenging problems. Including the actuator, dynamics increases the complexity of the system model. This problem becomes worse, especially in the case of flexible joint robot manipulators. Since a 5^{th} order nonlinear differential equation should be employed for describing any joint of FJER, which in turn increases the computational burden of control algorithms [4]. In addition, actuator models are subjected to various nonlinearities such as saturation, backlash, dead-zone, and hysteresis, making the control design problem extremely difficult [5].

To deal with these problems Izadbakhsh and Fateh [4] proposed a nonlinear robust tracking controller for FJER in the presence of uncertainties associated with both robot dynamics and actuator nonlinearities. The proposed approach is related to the crucial role of the motors' electrical subsystem, thus free from the mechanical subsystem of the actuator dynamics, considered here as unmodeled dynamics. It is, in fact, a back-stepping-like control scheme without regard to the actuators' mechanical subsystems. The significant point is that the proposed approach involves a complex stability analysis and supposes some assumptions, which are sententious. Such an assumption has been previously utilized in the paper [6]. In other words, stability was analyzed separately in saturated and unsaturated operation areas. However, the stability of the closed-loop system may not be guaranteed through these separate analyses (transition from saturation area to unsaturated zone and vice versa). Moreover, it was proposed a robust decentralized controller for electrically driven robots (EDRs) by adaptive fuzzy estimation technique and considering voltage input as the control signal [7]. However, a problem arises from using neural network/fuzzy systems. Khorashadizadeh and Fateh [8] addressed a control algorithm for electrically driven robot manipulators. The proposed approach employs a voltage control strategy, which is simpler and more efficient than the torque control strategy due to being free from manipulator dynamics. It does not require velocity feedback which is attractive from the control implementation point of view. In another research, Khorashadizadeh and Fateh [9] proposed a robust control scheme for electrically driven robots using a voltage control strategy considering the implementing many robotic tasks in the task space. The proposed controller is more straightforward, less computational, and requires less feedback. The researchers [10], used a developed VBD control to study the performance of the voltage and frequency control of the island micro gird. A Robust Anti-Windup control strategy has been proposed for n-Degree-of-Freedom (DOF) electrically driven robots in the presence of model uncertainties and external disturbances subject to actuator voltage input constraint [11]. Other authors presented a method for simultaneous clearing of energy and storage markets [12]. Automation significantly decreases the necessity for human sensory and mental requirements. Umer and Khan [13] comprised Bluetooth-based home automation using Arduino UNO, sensing the brightness through photo-resistor and actuating accordingly. An improvement in the robust stability analysis of EDR has been presented in paper [14]. The author presented a FAT-based direct adaptive control scheme for EDRs in the presence of nonlinearities associated with actuator input constraints. A robust fractional PI^{λ} controller for flexible joint electrically driven robots using voltage control strategy has been presented by Kheirkhahan [15]. The proposed approach guarantees the robustness of the control system to both structured and unstructured uncertainties associated with robot dynamics. In Comparison with integer-order controllers, the fractional type shows a better tracking performance. A robust task-space controller for EDR manipulators is developed based on the voltage level [16]. The proposed control law compensates for uncertainties such as parametric uncertainties, external disturbances, and imperfect transformation. It has been shown that ignoring the actuator dynamics leads to bad transient performance.

This paper presents some improvement on the stability results given by Izadbakhsh and Fateh [4], with the same impact on the closed-loop system stability. It proves that the link/motor position tracking errors are asymptotically converging to zero while the other signals remain bounded. In the present paper, $|\cdot|$ symbolizes the absolute value operator and $\|\cdot\|$ denotes the Euclidean and spectral norm operators in the case of vectors and matrices, respectively.

2. Dynamics of flexible joint electrically driven robot

This section presents the mathematical model of the robot manipulator and several properties that facilitate the subsequent development of the proposed nonlinear robust controller. An *n*-link, serially connected, revolute FJER can be described mathematically using the following dynamic model [17]:

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

$$J_m\ddot{\theta} + B_m\dot{\theta} + rK(r\theta - q) = k_m i \tag{2}$$

$$L\dot{I} + RI + k_b\dot{\theta} = u(t) \tag{3}$$

Where $q \in \Re^n$ and $\theta \in \Re^n$ denote the link position and the actuator position, respectively. The matrix $D(q) \in \Re^{n\times n}$ is the inertia matrix, $C(q,\dot{q}) \in \Re^{n\times n}$ is the Coriolis-centrifugal matrix, $g(q) \in \Re^n$ is the gravity vector, and $T_d \in \Re^n$ is the vector representing the bounded torque disturbance. The constant positive definite diagonal matrices $K \in \Re^{n\times n}$, $J_m \in \Re^{n\times n}$, $B_m \in \Re^{n\times n}$, $r \in \Re^{n\times n}$, $k_m \in \Re^{n\times n}$, $L \in \Re^{n\times n}$, $R \in \Re^{n\times n}$, and $k_b \in \Re^{n\times n}$, represent the flexibility constants, the inertia, the damping constants, the gear-box ratio, the torque constant, the electrical inductance, the resistance, and the back-emf effects, respectively. The control vector $u(t) \in \Re^n$ represents the applied voltage at each actuator. Form a practical implementation point of view, the actuator input is subjected to some constraints, called motor saturation limits. This usually occurs between the output of the controller and the PWM module [2]. According to this, it is assumed that the relation between the actual actuator's input $(u(t))$ and control signal produced by the controller $(v(t))$ is given by

$$u(t) = \text{sat}(v(t)) \tag{4}$$

Where $\text{sat}(v(t)) \in \Re^n$ is the saturation function. Now, substituting (4) in to (3) leads to

$$L\dot{I} + RI + k_b\dot{\theta} = \text{sat}(v(t)) \tag{5}$$

Remark 1: The control input given by (4) indicates that the motor voltage is limited, that is

$$|u_i(t)| \le v_{i_{\max}} \tag{6}$$

Where $u_i(t)$ stands for the *i*-th entry of vector $u(t)$, and $v_{i_{\max}}$ is a positive constant representing the maximum permitted voltage of the *i*-th motor. As a result, the variables I, $\dot{I}$ and $\dot{\theta}$ are bounded [6].

Remark 2: The following upper bounds associated with the actuator model are required for use in the subsequent analysis in determining the sufficient conditions on the control parameters.

$$\xi_R = \lambda_{\max}\{R\} \quad , \quad \xi_L = \lambda_{\max}\{L\} \quad , \quad \xi_{k_b} = \lambda_{\max}\{k_b\} \tag{7}$$

Where $\lambda_{\max}\{\cdot\}$ denote the maximum eigenvalue of a matrix. In addition, parameters, ξ_i , ξ_Δ , and $\xi_{\dot\theta}$ are utilized to show the maximum value of the current vector, the time derivative of the current, and motor angular velocity. Listed below are several properties associated with the robot equation of (1).

Property 1: The inertia matrix $D(q)$ is a symmetric, positive definite matrix, which satisfies the following bounding inequality [18]:

$$d_1\|x\|^2 \le x^T D(q)x \le d_2\|x\|^2 \tag{8}$$

For any $x \in \Re^n$, where d_1 and d_2 are known positive constants such that $d_1 \le d_2$.

Property 2: The centrifugal-Coriolis matrix $C(q,\dot q)$ in (1) can be defined such that it possesses the following skewed-symmetric matrix property with the time derivative of the inertia matrix [18].

$$x^T\left(\frac{1}{2}\dot D(q) - C(q,\dot q)\right)x = 0 \quad , \quad \forall x \in \Re^n \tag{9}$$

Property 3: The centrifugal-Coriolis matrix $C(q,\dot q)$, the gravity vector $g(q)$, and the bounded torque disturbance T_d in (1) can be upper bounded as follows [18]

$$\|C(q,\dot q)\| \le \zeta_c\|\dot q\| \quad , \quad \|g(q)\| \le \zeta_g \quad , \quad \|T_d\| \le \zeta_t \tag{10}$$

Where ζ_g , ζ_c , and ζ_t are known positive scalar constants.

Property 4: The robot equation of (1) is linear in the parameters in that the left-hand side of the equation can be expressed in a regression matrix form as follows [18]

$$D(q)\ddot q + C(q,\dot q)\dot q + g(q) = W(q,\dot q,\ddot q)P \tag{11}$$

Where $W(q,\dot q,\ddot q)$ a matrix of known is functions of the link variables, and P is the vector of constant parameters.

3. Controller design

The dynamic model of the manipulator in (1), (2), and (5) includes actuator nonlinearities, flexibility in the joint, as well as highly nonlinear coupling between the joint motions, which results in an increased control problem difficulty depending on the complexity of robot configuration. A two-step nonlinear robust tracking controller will be presented for FJER by employing voltage signal as the control input to tackle this problem.

3.1 Control Law for Robot Subsystem

Suppose that, equation (1) can be rewritten as

$$D_i(q)\ddot{q} + C_i(q,\dot{q})\dot{q} + g_i(q) + T_{di} + r^{-1}q = e_\theta + \theta_d \quad (12)$$

Where $D_i = r^{-1}K^{-1}D$, $C_i = r^{-1}K^{-1}C$, $g_i = r^{-1}K^{-1}g$, $T_{di} = r^{-1}K^{-1}T_d$, and e_θ denotes the difference between the actual actuator position and the desired actuator position called fictitious control signal, as

$$e_\theta = \theta - \theta_d \quad (13)$$

Let the filtered link position tracking error be given by

$$S_q = \Xi - \dot{q} \quad (14)$$

Where

$$E = q_d - q \quad , \quad \Xi = \dot{q}_d + \alpha E \quad (15)$$

With α being a positive definite diagonal matrix.

Assumption 1: The desired link position trajectory $q_d \in \Re^n$, and its time derivatives up to a necessary order are known and bounded time functions.
It is clear from (14) that the link position tracking error is asymptotically stable if S_q go to zero. With this in mind, the control problem is now to design the desired motor position θ_d as

$$\theta_d = \hat{D}_i\dot{\Xi} + \hat{C}_i\Xi + \hat{g}_i + \rho S_q + r^{-1}q + \tau_{rl} \quad (16)$$

That guaranties convergence of q to q_d, with $\hat{D}_i$, $\hat{C}_i$ and $\hat{g}_i$ denoting estimates of D_i, C_i and g_i, respectively. The parameter ρ is a positive definite diagonal matrix and τ_{rl} is designed for canceling both parametric and unstructured uncertainties associated with robot manipulators during the stability analysis in a later section. Now, substituting (16) into (12), rearranging with some manipulation this leads to

$$D_i\dot{S}_q + C_iS_q + \rho S_q = W(q,\dot{q},\Xi,\dot{\Xi})\tilde{P} + T_{di} - \tau_{rl} - e_\theta \quad (17)$$

Where $\tilde{P} = P - \hat{P}$ is the parametric estimation error, $\hat{P}$ denotes an estimation of P, and

$$W(q,\dot{q},\Xi,\dot{\Xi})\tilde{P} = (D_i - \hat{D}_i)\dot{\Xi} + (C_i - \hat{C}_i)\Xi + (g_i - \hat{g}_i) \quad (18)$$

3.2 Control Law for Motor Subsystem

Here, the control objective is to design a control input $v(t)$ for the actuators of the FJER to ensure that the actual actuator position θ tracks θ_d. Toward this end, the following ginner-loop control law is proposed

$$v(t) = \hat{R}I + \hat{k}_b(\dot{\theta}_d - K_pe_\theta) + u_{rm} \quad (19)$$

Where $(\hat{\cdot})$ is the estimate of $(\cdot)$, K_p is a positive definite gain matrix and u_{rm} is considered for canceling both parametric and unstructured uncertainties associated with dynamic motor equations.

Definition 1: The hard saturation function, $sat(v_i(t), v_{i_{\max}})$, can be divided into a linear function $v_i(t)$ and a dead-zone function, $dzn(v_i(t), v_{i_{\max}})$, as shown in Ref [5]. Thus, the control input applied to the system through the actuator is expressed as follows:

$$sat(v(t)) = v(t) - dzn(v(t), v_{\max}) \tag{20}$$

Where

$$sat(v(t)) = \begin{bmatrix} sat(v_1(t)) \\ \vdots \\ sat(v_n(t)) \end{bmatrix} \quad , \quad dzn(v(t), v_{\max}) = \begin{bmatrix} dzn(v_1(t), v_{1_{\max}}) \\ \vdots \\ dzn(v_n(t), v_{n_{\max}}) \end{bmatrix} \tag{21}$$

Where $dzn(\cdot)$ is the dead-zone function, $v_i(t)$ is the control action generated by the controller, and $v_{\max}$ is the maximum voltage limit saturation level.

Substituting the control law (19) into (5)and using (20) results in

$$\hat{k}_b \dot{e}_\theta + \hat{k}_b K_p e_\theta = \eta + u_{rm} \tag{22}$$

Where

$$\eta = (\hat{R} - R)I + (\hat{k}_b - k_b)\dot{\theta} - L\dot{I} - dzn(v(t), v_{\max}) \tag{23}$$

4. Stability analysis

This section presents the main stability result in the form of a theorem. The two following lemmas are required during the proof of the theorem.

Lemma 1. $\|dzn(\cdot)\|$ is satisfied with the following condition:

$$\|dzn(v(t), v_{\max})\| \le \gamma(\xi_R \xi_i + \|\hat{k}_b(\dot{\theta}_d - K_p e_\theta)\| + \delta_{rm}) \tag{24}$$

Where γ is a constant, which always has a value smaller than 1.

Proof: Proof is the same as [5], considering remark 1, and the assumption of $\|u_{rm}\| \le \delta_{rm}$.

Lemma 2. $\|\hat{k}_b(\dot{\theta}_d - K_p e_\theta)\|$ is satisfied with the following condition:

$$\|\hat{k}_b(\dot{\theta}_d - K_p e_\theta)\| \le \frac{\mu + \gamma \xi_R \xi_i + (1+\gamma)\delta_{rm}}{(1-\gamma)} \le \xi_D \tag{25}$$

Proof: Considering (22), (23), and using Lemma 1, it can be concluded that

$$\|\hat{k}_b(\dot{\theta}_d - K_p e_\theta)\| \le \|dzn(v(t), v_{\max})\| + \|k_b \dot{\theta} + (R - \hat{R})I + L\dot{I}\| + \delta_{rm} \tag{26}$$

Assume that there exists a positive scalar constant denoted by μ that

$$\left\| k_b \dot{\theta} + (R - \hat{R}) I + L \dot{I} \right\| \le \xi_{k_b} \xi_{\dot{\theta}} + \xi_R \xi_i + \xi_L \xi_{\xi_\Delta} = \mu \tag{27}$$

Upon substituting of the dead-zone from (24), simplifying common terms, and some mathematical manipulation, the inequality in (25) can then be obtained. This completes the proof.

The closed-loop stability result and the conditions, which guarantee asymptotic motor/link position tracking error convergence, can then be described using the following theorem.

Theorem: Using the desired actuator position (16) and the actuator voltage input (19), asymptotically tracking for motor/link position tracking error will be obtained, provided that the min-max control inputs τ_{rl} of (16) and u_{rm} of (19) are designed to satisfying the following condition.

$$\left\| W(q, \dot{q}, \Xi, \dot{\Xi}) \tilde{P} + T_{di}(t) \right\| \le \delta_{rl} \quad , \quad \|\eta\| \le \delta_{rm} \tag{28}$$

Proof: To prove that $e_\theta, S_q \to 0$ as $t \to \infty$, the following positive definite function was chosen

$$V(S_q, e_\theta) = \frac{1}{2} S_q^T D_i(q) S_q + \frac{1}{2} e_\theta^T \hat{k}_b e_\theta \tag{29}$$

Differentiating $V(S_q, e_\theta)$ for time yields

$$\dot{V}(S_q, e_\theta) = \frac{1}{2} S_q^T \dot{D}_i(q) S_q + S_q^T D_i(q) \dot{S}_q + e_\theta^T \hat{k}_b \dot{e}_\theta \tag{30}$$

Substituting (17) and (22) into (30) leads to

$$\begin{aligned} \dot{V}(S_q, e_\theta) = {} & \frac{1}{2} S_q^T \dot{D}_i(q) S_q + e_\theta^T (-\hat{k}_b K_p e_\theta + \eta + u_{rm}) \\ & + S_q^T (-C_i S_q - \rho S_q + W(q, \dot{q}, \Xi, \dot{\Xi}) \tilde{P} + T_{di} - \tau_{rl} - e_\theta) \end{aligned} \tag{31}$$

Which can be simplified by applying the skew symmetry property given in (9) to yield

$$\begin{aligned} \dot{V}(S_q, e_\theta) = {} & -\begin{bmatrix} S_q^T & e_\theta^T \end{bmatrix} Q \begin{bmatrix} S_q \\ e_\theta \end{bmatrix} + e_\theta^T (\eta + u_{rm}) \\ & + S_q^T \left(W(q, \dot{q}, \Xi, \dot{\Xi}) \tilde{P} + T_{di} - \tau_{rl} \right) \end{aligned} \tag{31}$$

Where

$$Q = \begin{bmatrix} \rho & 0.5 I_n \\ 0.5 I_n & \hat{k}_b K_p \end{bmatrix}$$

Remark3: The last matrix is negative definite if

$$\hat{k}_b K_p > 0.25 \rho^{-1} \tag{33}$$

Which is met by choosing appropriate diagonal matrices of controller gains ρ and. K_p .

Next, an upper bound for $\dot{V}(S_q, e_\theta)$ is obtained by using the triangle-inequality, and the bounding constants presented in remark 2as

$$\begin{aligned}\dot{V}(S_q, e_\theta) \le & -\lambda_{\min}(Q)\left\|\begin{bmatrix} S_q \\ e_\theta \end{bmatrix}\right\|^2 + \|e_\theta\|\|\eta\| + e_\theta^T u_{rm} \\ & + \|S_q\|\left\|W(q,\dot{q},\Xi,\dot{\Xi})\tilde{P} + T_{di}\right\| - S_q^T \tau_{rl}\end{aligned} \tag{34}$$

Equation (34) is guaranteed to be negative definite if the robust control inputs are selected as

$$\tau_{rl} = \delta_{rl}(\mathrm{t})\frac{S_q}{\|S_q\|} \quad \text{for} \quad \|S_q\| \ne 0 \tag{35}$$

$$u_{rm} = -\delta_{rm}\frac{e_\theta}{\|e_\theta\|} \quad \text{for} \quad \|e_\theta\| \ne 0 \tag{36}$$

Where $\delta_{rl}(\mathrm{t})$ and δ_{rm} are positive scalar constants, namely, a bounding function to show the upper bound of uncertainties (28), which completes the proof.

Since $\dot{V}(S_q, e_\theta)$ is negative definite, then asymptotically converges of $\begin{bmatrix} S_q^T & e_\theta^T \end{bmatrix}$ to zero can be concluded. Equation (13) is Hurwitz, therefore, boundedness of q and $\dot{q}$ can be obtained with the Assumption1. Moreover, boundedness of θ can be proved, whereas θ_d is bounded. These results together remark 1 gives boundedness of the all system's states. As a result, the robotic system has Bounded Input-Bounded Output (BIBO) stability.

5. Simulation results

The simulation task is carried out based on 2-DOF flexible joints electrically driven robotic arms. The parameters of the robotic system can be described as follows

$$\begin{aligned}
&D(q) = \begin{bmatrix} d_{11} & d_{12} \\ d_{21} & d_{22} \end{bmatrix} \\
&d_{11} = m_2(l_1^2 + l_{c2}^2 + 2l_1 l_{c2} cos(q_2)) + m_1 l_{c1}^2 + I_1 + I_2 \\
&d_{21} = d_{12} = m_2 l_{c2}^2 + m_2 l_1 l_{c2} cos(q_2) + I_2 \\
&d_{22} = m_2 l_{c2}^2 + I_2 \\
&C(q,\dot{q})\dot{q} = \begin{bmatrix} -2m_2 l_1 l_{c2} sin(q_2)(\dot{q}_1\dot{q}_2 + 0.5\dot{q}_2^2) \\ m_2 l_1 l_{c2} sin(q_2)\dot{q}_1^2 \end{bmatrix} \\
&g(q) = \begin{bmatrix} (m_1 l_{c1} + m_2 l_1) g cos(q_1) + m_2 l_{c2} g cos(q_1 + q_2) \\ m_2 l_{c2} g cos(q_1 + q_2) \end{bmatrix}
\end{aligned} \tag{37}$$

Where m_1 and m_2 are the mass of links 1 and 2, respectively; q_1 and q_2 are the angles of joints 1 and 2, l_1 and l_2 are the lengths of links 1 and 2, I_i is the link's moment of inertia given in the center of mass, l_{ci} is the distance between the center of mass of link and the ith joint, and g is the gravity acceleration. The manipulator dynamic parameters are defined as $m_1 = 15kg$ and $m_2 = 6kg$, $I_1 = 5\ kg\text{-}m^2$ and $I_2 = 2\ kg\text{-}m^2$; $l_1 = l_2 = 1m$ and $l_{c1} = l_{c2} = 0.5m$; Also, the actuator parameters are chosen as

$R = diag(1.6, 1.6)\Omega$

$L = diag(10^{-3}, 10^{-3})(\mathrm{H})$,

$r = diag(0.02, 0.02)$,

$k_m = k_b = diag(0.26, 0.26)(\mathrm{Nm/A})$,

$J_m = diag(2\times10^{-4}, 2\times10^{-4})(kg\text{-}m^2)$,

$B_m = diag\,(10^{-3}, 10^{-3})(\mathrm{Nm\text{-}sec/rad})$,

and $K = diag(500, 500)(\mathrm{N\text{-}m/rad})$.

The reference trajectory is a circular trajectory specified by 0.15m radius centered at (0.35m, 0.35m) in the task space. The initial positions of the links are chosen far from desired values. The controller parameters are also selected as $\alpha = 100$, $\rho = 10$, and $K_p = 10$.

Under this setting, Figure 1 shows the tracking response of the robot endpoint in the task space. According to this figure, the proposed controller structure can reject the influence of various uncertainties and limit the tracking error to ignorable values. Figure 2 shows tracking error in the task space, which is bounded and in the range of 0.04m. A large amount of initial tracking error is because of the difference between the initial conditions of the link’s position and desired one. Moreover, the technical limits such as motor voltages and actuator currents are illustrated in Figure 3 and Figure 4, respectively. Simulation results clearly show the effectiveness of the proposed control scheme to stabilize the system under high flexibility in the joints robustly.

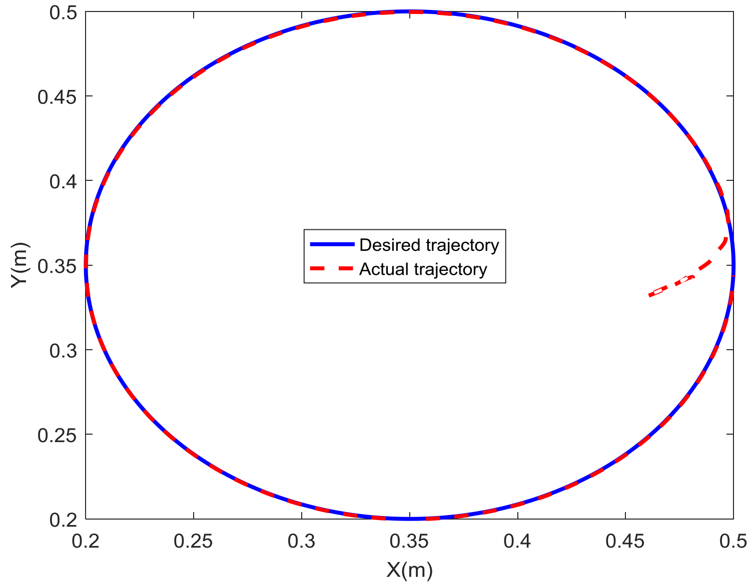

Figure1. Tracking performance in the task-space

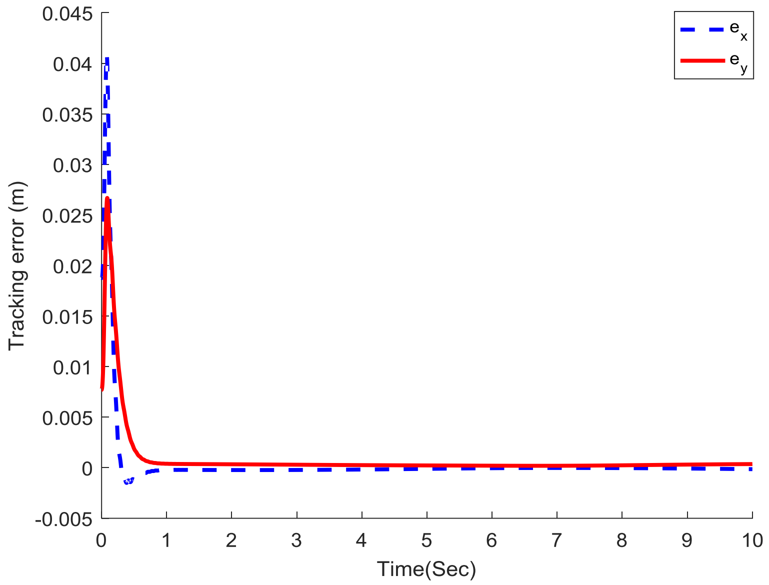

Figure 2. Tracking error in the task-space

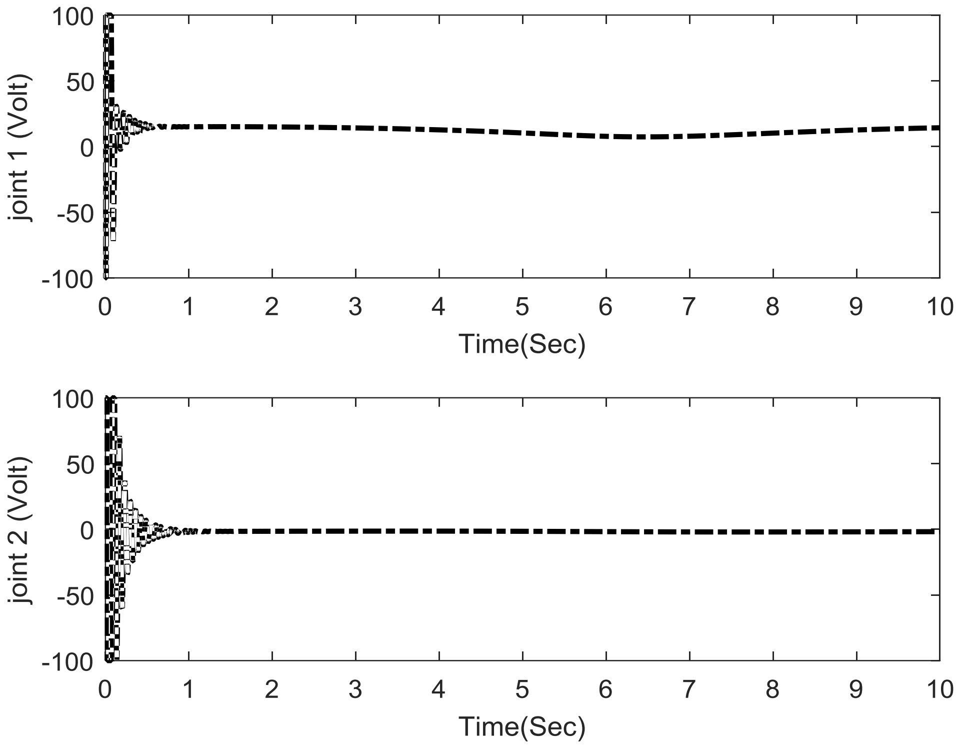

Figure 3. Control signals

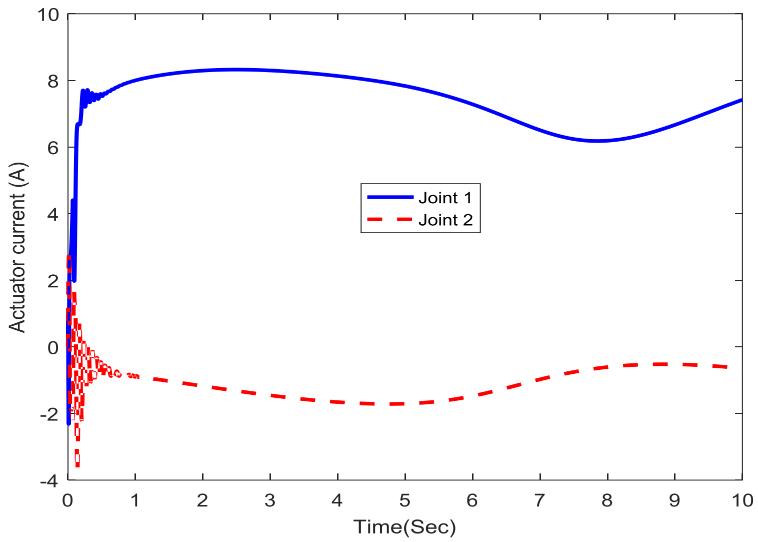

Figure 4. Actuator currents

6. Conclusion

This paper improves the stability results of the robust Lyapunov-based controller proposed by authors [4] considering actuator voltage input constraint. It is shown that the motor/link position tracking error converges to zero asymptotically, while the other signals of the system remain bounded. The proposed controller design is not dependent on the mechanical subsystem of the actuator's dynamic. Thus it is free from problems associated with torque control strategy in the design and implementation. Simulation results on a 2-DOF Flexible joint electrically driven robot show satisfactory tracking performance of the controlled system. The motors' voltage is permitted under the maximum values.

7. References

[1] Izadbakhsh, A. and Rafiei, S.M.R. 2009. Endpoint perfect tracking control of robots-A robust non inversion-based approach. International Journal of Control, Automation, and Systems. 7: 888-898.

[2] Yahyavi, M., Behnia, S. and Zamani, A. 2020. Suppressing Chaotic Oscillations of a Spherical Cavitation Bubble by Slave-Master Feedback. Advanced Journal of Science and Engineering. 1(2): 40–47.

[3] M. M. Fateh. 2008. International Journal of Control, Automation, and Systems. 6(5): 702-712.

[4] Izadbakhsh, A. and Fateh, M.M. 2014. Robust Lyapunov-based control of flexible-joint robots using voltage control strategy. Arabian Journal for Science and Engineering. 39: 3111-3121.

[5] Izadbakhsh, A. 2016. Robust control design for rigid-link flexible-joint electrically driven robot subjected to constraint: theory and experimental verification. Nonlinear Dynamics. 85: 751-765.

[6]Fateh, M. M. 2012. Robust control of flexible-joint robots using voltage control strategy. Nonlinear Dynamics. 67: 1525-1537.

[7] Fateh, M.M. and Khorashadizadeh, S. 2012. Robust control of electrically driven robots by adaptive fuzzy estimation of uncertainty. Nonlinear Dynamics. 69: 1465–1477.

[8] Khorashadizadeh, S. and Fateh, M.M. 2017. Uncertainty estimation in robust tracking control of robot manipulators using the Fourier series expansion. Robotica. 35(2): 310-336.

[9] Khorashadizadeh, S. and Fateh, M.M. 2015. Robust task-space control of robot manipulators using Legendre polynomials for uncertainty estimation. Nonlinear Dynamics. 79: 1151-1161.

[10] Amouzad Mahdiraji, E. and Shariatmadar, S. M. 2020. Improving Flexibility and Control the Voltage and Frequency of the Island Micro-Grid Using Storage Devices. Advanced Journal of Science and Engineering. 1(1): 27–31.

[11] Izadbakhsh, A., Akbarzadeh Kalat, A., Fateh, M.M. and Rafiei, S.M.R. 2011. A robust anti-windup control design for electrically driven robots-Theory and Experiment, International Journal of Control, Automation, and Systems. 9: 1005-1012.

[12] Amouzad Mahdiraji, E. and SedghiAmiri, M. 2021. Market Clearing due to the Reliability of Electricity Generation Units. Advanced Journal of Science and Engineering. 2(1): 42–50.

[13] Umer, M., and Khan, M. M. 2020. Smart Home Automation Using ATMEGA328. Advanced Journal of Science and Engineering. 1(3): 86–90.

[14] Kheirkhahan, P. 2018. An Alternative Stability Proof for Direct Adaptive Function Approximation Techniques Based Control of Robot Manipulators, Journal of Modern Processes in Manufacturing and Production. 7(2): 41-46.

[15] Kheirkhahan, P. 2018. Robust Fractional-order Control of Flexible-Joint Electrically Driven Robots. Journal of Modern Processes in Manufacturing and Production. 7(1): 5-19.

[16] Kheirkhahan, P. 2017. Robust Control of Electrically Driven Robots in the Task Space. Journal of Modern Processes in Manufacturing and Production. 6(4): 5-22.

[17] Spong, M. W. 1987. Modeling and control of elastic joint robots. ASME The Journal of Dynamic Systems, Measurement and Control. 109: 310–319.

[18] Qu, Z. and Dawson, D. M. 1996. Robust tracking control of robot manipulators. New York: IEEE Press.