International Journal of Advanced Science and Technology
Vol. 34, September, 2011

Passivity Based Adaptive Control of Robotic Manipulators Electrically Controlled

[1]Nawal Azoui, [2]Lamir Saidi
Department of Electrical Engineering, Batna University, Algeria
[1]*n.azoui@yahoo.fr*, [2]*lamir_saidi@yahoo.fr*

Abstract

This paper presents a general approach for designing position adaptive control of a robot manipulator electrically controlled using passivity technique. Since a direct passive control structure requires precise knowledge of the robot model, the main interest of this contribution is to provide a direct adaptation law in order to improve performances against both robot model parameters uncertainties and disturbances. Besides, the proposed configuration permits a very remarkable facility of implementation. Simulations results are presented to illustrate the main points of this paper.

Keywords*: Actuator, Adaptive Control, Output Tracking, Passivity, Robot Control*

1. Introduction

Recently robot's actuator dynamics has been explicitly included in control schemes. This dynamics becomes extremely important during fast robot motion and highly varying loads [1-4]. However, the inclusion of actuators in dynamic equations complicates both the controller structure design and its stability analysis, and in order to avoid the increasing in the order of the dynamic equations order, both the arm and the motor dynamics are considered as two cascaded loops [5].

In [6], an adaptive tracking control for rigid-link electrically–driven robot manipulators in the case of arbitrary uncertain mechanical and electrical modeling parameters is designed. The authors of [7] used the backstepping integrator technique in order to conceive an adaptive hybrid control law taking into account the actuator dynamics for the robot manipulator.

A passivity control strategy requiring an exact knowledge of rigid robot model is presented in [8]; though it presents very satisfactory performances in terms of tracking desired trajectories, however, in practice, this ideal condition is never quite satisfied due to both various disturbances acting on the robot manipulator, and model uncertainties, hence the need to adapt the control to model uncertainties is crucial.

The present contribution aims to complete the previously mentioned research work using adaptive control strategy to the robot manipulator with electric actuators, and consequently to improve the performances against unknown parameters of the robot manipulator. This approach presents a very remarkable facility in terms of implementation and shows some good performances as illustrated by simulation results.

2. Robot and Actuator Dynamics Equations

Consider an n-link manipulator powered by DC motor actuators and modeled by the following dynamic expression [8]:

$$\begin{cases} M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = K_r \, I \\ L\,\dot{I} + R\,I + K_m\,\dot{q} = v \end{cases} \tag{1}$$

where symbols q, $\dot{q}$ and $\ddot{q}$ denote n-dimensional vectors of joint position, angular velocity and angular acceleration. $M(q) \in R^{n\times n}$ is a symmetric, positive definite inertia and mass matrix. $C(q,\dot{q}) \in R^{n\times n}$ is a matrix of the Coriolis and centrifugal forces. $G(q) \in R^n$ is the vector of gravity terms.

$I \in R^n$ is the armature current, $v \in R^n$ is the armature voltage, and $L, R, K_m, K_r \in R^n$ are positive definite diagonal matrices, which represent respectively, the actuator inductance, the actuator resistance, the constant coefficient of the actuator and the constant coefficient characterizing the electromechanical conversion between current and torque.

3. State Space Representation

Let us consider a two-link robot manipulator electrically controlled, where q_1 and q_2 are the articular positions, $\dot{q}_1$ and $\dot{q}_2$ are speeds, I_1 and I_2 are currents, v_1 and v_2 are the armature voltages, g_1 and g_2 are the gravity terms. (m_1, m_2) and (l_1, l_2) denote respectively the masses and the lengths of the robot manipulator arms.

The previous dynamic model (eq. 1) can be written in the matrix form as follows:

$$v_e = M_e(\zeta_1)\ddot{\zeta}_1 + C_e(\zeta_1,\dot{\zeta}_1)\dot{\zeta}_1 + D_e\zeta_1 + G_e(\zeta_1) \tag{2}$$

where

$$M_e = \begin{bmatrix} M_1 & M_2 & 0 & 0 \\ M_3 & M_4 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}; \quad C_e = \begin{bmatrix} C_1 & C_2 & 0 & 0 \\ C_3 & C_4 & 0 & 0 \\ K_{m1} & 0 & L_1 & 0 \\ 0 & K_{m2} & 0 & L_2 \end{bmatrix}$$

and

$$D_e = \begin{bmatrix} 0 & 0 & -K_{r1} & 0 \\ 0 & 0 & 0 & -K_{r2} \\ 0 & 0 & R_1 & 0 \\ 0 & 0 & 0 & R_2 \end{bmatrix}; \; G_e = \begin{bmatrix} g_1 \\ g_2 \\ 0 \\ 0 \end{bmatrix}; \; v_e = \begin{bmatrix} 0 \\ 0 \\ v_1 \\ v_2 \end{bmatrix}.$$

L_i, R_i, K_{mi} and K_{ri} $(i = 1,2)$ are positive definite parameters, which represent respectively, the actuator inductances, the actuator resistances, the actuator constant coefficients and the constant coefficients characterizing the electromechanical conversion between currents and torques.

The terms M_i $(i = 1:4)$, C_i $(i = 1:4)$, and g_i $(i = 1,2)$ are expressed as follows:

$M_1 = m_2 l_2^2 + 2\, m_2 l_1 l_2 \cos(q_2) + (m_1 + m_2) l_1^2$; $M_2 = m_2 l_2^2 + m_2 l_1 l_2 \cos(q_2)$;
$M_3 = m_2 l_2^2 + m_2 l_1 l_2 \cos(q_2)$; $M_4 = m_2 l_2^2$; $C_1 = -2 m_2 l_1 l_2 \sin(q_2)\, \dot{q}_2$; $C_2 = -m_2 l_1 l_2 \sin(q_2)\, \dot{q}_2$;
$C_3 = m_2 l_1 l_2 \sin(q_2)\, \dot{q}_1$; $C_4 = 0$; $g_1 = m_2 l_2 g \cos(q_1 + q_2) + (m_1 + m_2) l_1 g \cos(q_1)$;
$g_2 = m_2 l_2 g \cos(q_1 + q_2)$.

The retained state variables are:

$$\zeta_1 = [q_1, q_2, I_1, I_2]^T \text{ and } \zeta_2 = \dot{\zeta}_1 = [\dot{q}_1, \dot{q}_2, \dot{I}_1, \dot{I}_2]^T \tag{3}$$

From equations (2) and (3), the state space representation is determined by:

$$\begin{cases} \dot{\zeta}_1 = \zeta_2 \\ \\ \dot{\zeta}_2 = \ddot{\zeta}_1 = M_e^{-1}\left(-C_e \zeta_2 - D_e \zeta_1 - G_e + v_e\right) \end{cases} \tag{4}$$

where $\zeta_1 \in R^2$ represents the position and current state vector,
and $\zeta_2 \in R^2$ represents speed and the current derivatives state vector.

4. Passivity Adaptive Control of the Robots Manipulator

The passivity approach is based essentially on the Lagrangian form of the mechanical system; and the associated Lyapunov function has to be decreased to develop the control law.

For any vector $X \in R^n$, we assume that:

$$X^T \left(\dot{M}(\zeta_1, \dot{\zeta}_1) - 2C(\zeta_1, \dot{\zeta}_1) \right) X = 0 \tag{5}$$

Consider the following control law:

$$\tau = M_e(\zeta_1)\ddot{\zeta}_{1r} + C_e(\zeta_1, \dot{\zeta}_1)\dot{\zeta}_{1r} + D_e \zeta_1 + G_e(\zeta_1) + K_v S + K_p E \tag{6}$$

where
$$E(t) = \zeta_{1d} - \zeta_1 \;;\; \dot{E}(t) = \dot{\zeta}_{1d} - \dot{\zeta}_1$$
$$S(t) = \dot{\zeta}_{1r} - \dot{\zeta}_1 = \dot{E}(t) + \Lambda' E(t)$$
and
$$\dot{\zeta}_{1r} = \dot{\zeta}_{1d} + \Lambda' E(t)$$

K_v, K_p and ζ_{1d} are respectively, a constant 4×4 diagonal matrix, symmetric and positive, and desired value of ζ_1. Λ' is a positive definite matrix.

Combining (6) with (2), the closed loop error is expressed by the following equation:

$$M_e(\zeta_1)\dot{S} + C_e(\zeta_1, \dot{\zeta}_1) S = -K_v S - K_p E \tag{7}$$

Equation (7) defines a passive system with input $u = -K_v\, S$ and output $y = S$.

The state vector is $X = \begin{bmatrix} E & S \end{bmatrix}^T$. Let's, consider the following positive and definite energy function:

$$V(X,t) = \frac{1}{2} S^T M_e(\zeta_1) S + \frac{1}{2} E^T K_p E \tag{8}$$

Differentiating $V(t)$ with respect to time and using the property (5), we get:

$$\dot{V}(t) = -S^T K_V S - E^T \left(A^T K_P\right) E \tag{9}$$

Since: $$-S^T K_V S \geq \dot{V}(t)$$

Then: $$y^T u \geq \dot{V}(t)$$

Hence:

$$\int_{t_0}^{t} y^T(\sigma) u(\sigma) d\sigma \geq V(X(t),t) - V(X(t_0),t_0) \tag{10}$$

Equation (9) shows that the closed loop system with this control law is stable according to Lyapunov's criterion; however, the performances are linked to accuracy of the model. Mass and inertia parameters of the robot model can not be known precisely when the robot is moving. Thus, it is necessary to find a reliable method to estimate efficiently these parameters. To enhance this control law against the parametric uncertainties of the robot model, we introduce an improvement using a direct adaptation law. It modifies the estimated dynamics in order to cancel the position and speed errors. The used estimation procedure is that detailed in [5]:

4.1 Adaptation law

The parameters estimation using the direct method is based on the desired current calculation strategy. Thus, the desired expression of the current I_d takes the following form [8]:

$$\mathrm{I}_d = K_r^{-1}(\hat{Y}p - K_d \varepsilon) \tag{11}$$

with $\hat{Y}p = \hat{M}(\mathrm{q})\dot{\zeta}_2^* + \hat{C}(\mathrm{q},\dot{q})\zeta_2^* + \hat{G}(q)$ and $\zeta_2^* = \dot{\mathrm{q}}_\mathrm{d} - \Lambda(q - \mathrm{q}_d)$

were $p = \begin{bmatrix} p_1 & p_2 \end{bmatrix}^T$ is a vector of unknown parameters, the symbol (^) stands for estimated matrix, Λ, K_d are positive definite diagonal matrices, and q_d, $\dot{q}_d$ are respectively the desired values of the joint position q and the speed $\dot{q}$.

So, the adaptation law can be expressed as [5]

$$\dot{\hat{p}} = -\Gamma \hat{Y}^T \varepsilon \tag{12}$$

with $\varepsilon = \dot{q} - \zeta_2^*$ and $\Gamma = diag\begin{bmatrix} \Gamma_1 & \Gamma_2 \end{bmatrix}$ are positive and definite matrices.

where

$$Y^T = \begin{bmatrix} \begin{array}{l} \left(l_2^2 + 2l_1 l_2 \cos(q_2) + l_1^2\right)\dot{\zeta}_{21}^* + \left(l_2^2 + l_1 l_2 \cos(q_2)\right)\dot{\zeta}_{22}^* \\ + \left(-2l_1 l_2 \sin q_2 \dot{q}_2\right)\zeta_{21}^* + \left(-l_1 l_2 \sin q_2 \dot{q}_2\right)\zeta_{22}^* \\ + \left(l_2 g \cos(q_1 + q_2) + l_1 g \cos q_1\right) \end{array} & l_1^2 \dot{\zeta}_{21}^* + l_1 g \cos q_1 \\ \begin{array}{l} \left(l_2^2 + l_1 l_2 \cos q_2\right)\dot{\zeta}_{21}^* + \left(l_1 l_2 \sin q_2 \dot{q}_1\right)\zeta_{21}^* \\ + l_2^2 \dot{\zeta}_{22}^* + l_2 g \cos(q_1 + q_2) \end{array} & 0 \end{bmatrix}$$

$$p = \begin{bmatrix} m_2 \\ m_1 \end{bmatrix}$$

5. Results and Discussion

The above proposed control strategy for a two–link robot manipulator electrically controlled has been verified through computer simulation using Matlab/Simulink. The parameters of the considered robot manipulator are those indicated in the appendix.

Figures 1 and 2 show the desired and the actual trajectories for the two joints. Both trajectories are practically identical. The settling time of the trajectory reference is less than 1s for the first joint, while the settling time of the trajectory reference for the second joint is almost insignificant. These results illustrate the ability and potency of the proposed adaptive passivity technique. The trajectory tracking is fairly good, with maximum errors of about ± 0.4 % for the first joint and less than ± 0.2 % for the second joint as shown in figures 3-(a, b) and 4-(a, b).

In figures 5 and 6, the estimated masses of the two links are compared with the exact ones. Small transient states occur before t=1s which are acceptable because of the inappropriate initialization values of the masses (94.5kg and 19.5kg).

The voltage inputs are shown in figures 7 and 8, which are within reasonable range. It is worth pointing that these voltages change in terms of magnitude and frequency in order to satisfy the tracking objective of the specified trajectories.

Also, it can be seen that the proposed technique is robust against parameters uncertainties and disturbances. Therefore, in the case of having an incomplete knowledge of the system, we propose to use this method to improve the system performances and to decrease the possible instability of the system. This is a subject of our continuing research.

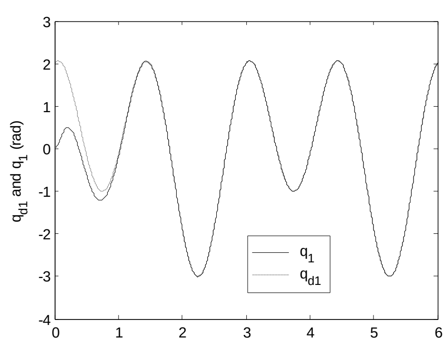

Figure 1. Desired trajectory tracking of the first joint

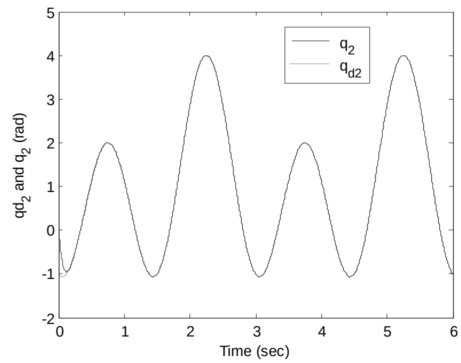

Figure 2. Desired trajectory tracking of the second joint

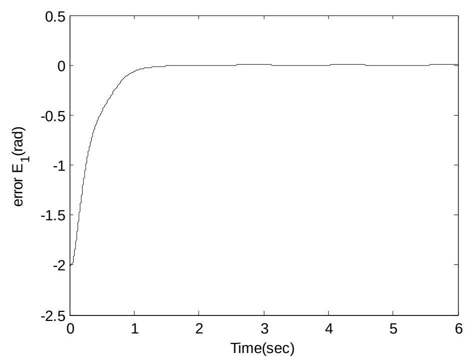

Figure 3.a. Desired trajectory tracking error of the first joint

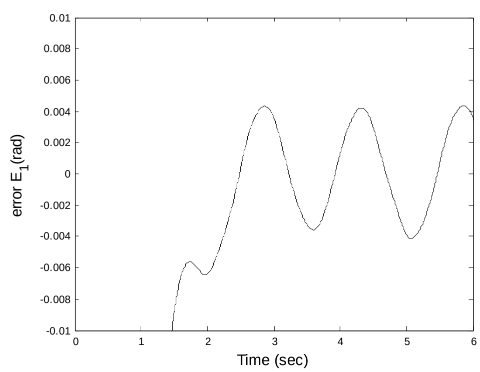

Figure 3.b. Zoom on the amplitude of the desired trajectory tracking error of the first joint

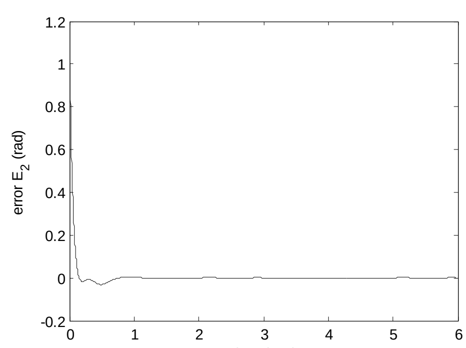

Figure 4.a. Desired trajectory tracking error of the second joint

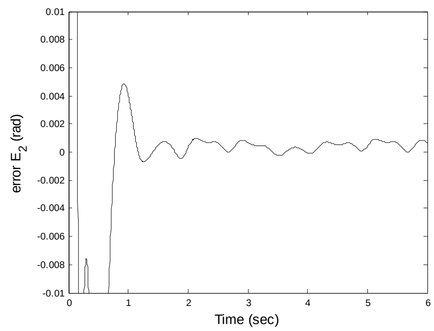

Figure 4.b. Zoom on the amplitude of the desired trajectory tracking error of the second joint

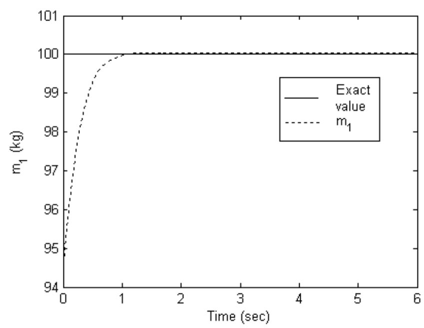

Figure 5. Estimated mass of the first joint

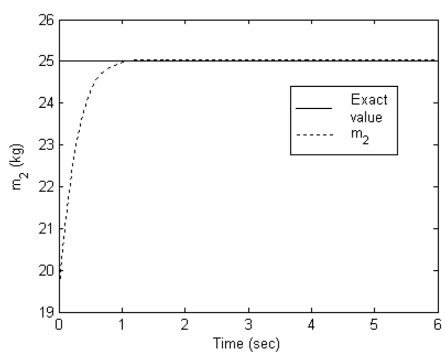

Figure 6. Estimated mass of the second joint

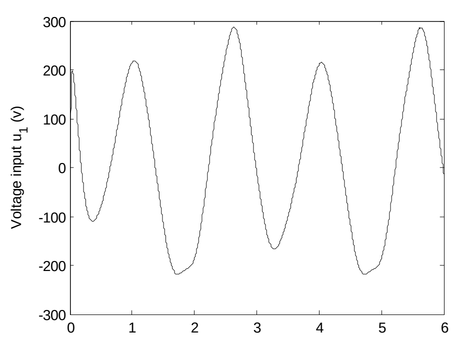

Figure 7. Voltage input of the first joint

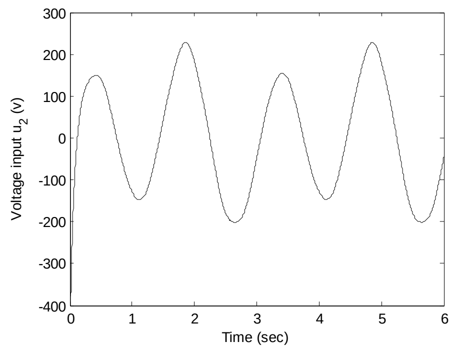

Figure 8. Voltage input of the second joint

7. Conclusion

In this paper an adaptive passivity control applied to the two-link robot manipulator electrically controlled is proposed. The developed algorithm guarantees the asymptotic stability of the global system, and illustrates its efficiency in eliminating the disturbances. The results show a good level of tracking accuracy. Moreover, the key advantage of this method lies in its simplicity on one hand and its robustness against parameters uncertainties, joint friction, and disturbances on the other hand.

Appendix: Parameters of the Robot

$$m_1(0) = 94.5\,\text{kg};\, m_2(0) = 19.5\,\text{kg};\, l_1 = 0.45\,\text{m};\, l_2 = 0.2\,\text{m};\; \Lambda_1 = 600; \Lambda_2 = 150; \Lambda' = 10I;$$

$$K_{d1} = 100; K_{d2} = 500; K_v = 1I;\, K_p = 10; \Gamma = 10I; q_1(0) = 0;\, q_2(0) = 0;$$

$$q_{d1} = 2\cos\left(\frac{4\pi t}{3}\right) + \sin\left(\frac{4\pi t}{3}\right)\ \text{rad}; 0 \le t \le 3;\ q_{d2} = 1 - 2\cos\left(\frac{4\pi t}{3}\right) - \sin\left(\frac{4\pi t}{3}\right)\ \text{rad}; 0 \le t \le 3.$$

References

[1] A. Lotfazar, M. Eghtesad and M. Mohseni, “Integrator Backstepping Control of a 5Dof Robot Manipulator Incorporating Actuator Dynamics,” Proc of IEEE. Conf on Control Applications, pp. 1007-1012, London, 2003.

[2] N. Azoui, L. Saidi, M. Mokhtari and S. Benacer, “Combinaison de la Commande Backstepping et la Passivité pour un Robot Manipulateur à Couple Electrique,” 2nd International Conference On Electronics Systems, Batna, Algeria, pp. 191-195, CISE’09, 25-26, 2009.

[3] N. Azoui, "Commande non linéaire d'un bras manipulateur", Magister thesis, Department of electrical Engineering, University of Batna, 2010.

[4] D. Nganga-Kouya, M. Saad, L. Lamarche and C. Khairallah, “Backstepping Adaptive Position Control for Robotic Manipulators,” Proc. of the American Control Conference, vol.1, pp. 636-640, 2001.

[5] D.M. Dawson, Z. Qu and J.J. Carroll, “Tracking Control of Rigid link Electrically Driven Robot Manipulator,” Int.J.of Control, Vol.56, pp. 991-1006, 1992.

[6] R. Guenther and L. Hsu “Variable structure adaptive cascade control of rigid- link electrically–driven robot manipulators,“ Proc of IEEE, int.conf. on decision and control, San Antonio, TX, USA, New York, Vol.03, pp. 2137-2142, 1993.

[7] C.Y. Su and Y. Stepanenko “Backstepping-Based hybrid adaptive control of robot manipulators incorporating actuator dynamics,” int.J. of adaptive control and signal processing, vol.11, pp. 141-153, 1997.

[8] F. Khelifi and F. Bouakrif, "Amélioration de la Commande Passive des Robots Manipulateurs en tenant compte des Perturbations," Proc. of the International Conference on Intelligent Robots and Systems, pp 123-128, September, 2008.

Authors

Nawal Azoui was born in Batna, Algeria in 1982. She received her Engineering Master degree and her magister in Robotics from the University of Batna, Algeria. Currently, she is a PhD student. Her research interests concern robotics, renewable energy and system optimization.

Lamir Saidi was born in Batna, Algeria in 1968. He received his Engineering Master degree from University of Constantine, Algeria, in 1991 and the Ph.D. degree from Savoie University, France, in 1996. Currently, he is Associate Professor at the Electrical Engineering department, University of Batna, Algeria. His interests include Digital Motion Control, Fuzzy control, Robust control Mechatronics, and Digital Signal Processing. He is member of CISE and RST.