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Voltage-Based Control of the Industrial PUMA 560 Robot Using Passivity-Based Theorem

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Abstract
Passivity is one of the most useful tools in stability analysis and controller design procedures. In this paper, first a voltage law is proposed such that the closed loop electrical dynamic of the actuator be passive. In the second step, a passivity-based control law is designed to guaranty the asymptotically stability of the system's states. Finally, the proposed control law is applied to the PUMA 560 robot to show the performance of the control method.

Keywords*: Passivity-based control, Voltage-based strategy, Robot Manipulators.*

1 Introduction

Passivity is a useful physically concept in systems and control theory. The stored internal energy in a passive system is bounded from above by the externally supplied energy. It is clear that this energy dissipation property has important implications for closed-loop stability [1-3]. Robotic control is one of the fields that passivity plays an important role for it. Recently, most of the researchers worked on passivity-based control of robots [4-6]. The vast consentration of these literatures are on the torque control of the robots. However, in practice, implementing the torque control command is a control problem since it cannot be applied to the inputs of actuators for driving the manipulator[7,8]. In most cases, the torque control law is very large and time consuming which involves a problem of limit sampling rate. Therefore, the tracking error increases as velocity increases.

The main contribution of this paper is designing a passivity based theorem controller with considering the motor electrical dynamic of the joints. The voltage strategy helps to design a simple and robust controller and the passivity theorem suggests a term which guaranties the asymptotic stability of the errors. Some definition and theorem are introduced to help the better understanding of the subject. Finally, the simulation results are presented for a two link PUMA 560 robot.

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2 Problem Definition

The mechanical dynamic of an n-link robot manipulators is defined as [7]

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = T, \qquad (1)$$

where $q,\dot{q} \in R^n$ *are the joint position vector, the vector of joint velocity, respectively.* $M(q) \in R^{n\times n}$, $C(q.\dot{q})\dot{q} \epsilon R^{n\times n}$ *and* $G(q) \in R^n$ *are the inertia matrix, Coriolis and Centrifugal torques and the vector of gravitational torques, respectively. The inserted torque on the joint to derive the manipulator is the load torque (T) of motor, that is considered in the dynamic equation formed as:*

$$T_m = J_m\ddot{\theta}_m + B_m\dot{\theta}_m + rT \qquad (2)$$

where T_m *is the motor torque, r is the gear reduction coefficient,* J_m *is the sum of actuator and gear inertia,* B_m *is the damping coefficient, and* θ_m *is the rotor position. It is important to note that the motor current is related to the motor torque as* $T_m = K_m I$ *where* K_m *is the motor torque constant. The electrical circuit of the permanent magnet dc motor can be written as follows [7]:*

$$V = R\,I + L\,\dot{I} + K_b\left(\dot{\theta}_m\right) \qquad (3)$$

where R, L and $K_b = K_m$ *are the resistance, inductance and back emf constant of the armature, respectively. V(t) is the armature voltage and I(t) is the armature current, and the motor position is related to the joint position with the reduction gear as:*

$$q = r\,\theta_m \;\; \longrightarrow \;\; \dot{\theta}_m = r^{-1}\dot{q}\,. \qquad (4)$$

In the control voltage strategy, the input of the system is the motor vaoltages, therefore, the current and the joint torque of the robot will be controlled. Finally, according to the equation (1) the joint position will be converge to the desired position.

3 Passivity-Based Control Law

Before defining the passivity-based control law, it is nessessary to introduce some preliminaries. For this reason, consider the following nonlinear affine system.

$$\begin{cases} \dot{x} = f(x) + g(x)u \\ \quad y = h(x) \end{cases} ,where\;\; x \in R^n,\;\; (u,y) \in R^m,\;\; f(0) = h(0) = 0 \qquad (5)$$

Definition 3.1 [1]. *System (5) is passive, between its input u and its output y, if there exist a positive semi-definite storage function S(x) such that:*

$S(0) = 0$ *and* $\dot{S} \leqslant y^T u.$

Definition 3.2 [1]. *System (5) is Zero-State Observable (ZSO), if there is no solution of* $\dot{x} = f(x)$ *which staisfies* $\{h(x) = 0\}$, *except the solution* $x(t) \equiv 0$.

Theorem 3.3 [1]. *If system (5) is passive with a positive definite storage function and also is ZSO, then the control input* $\mathrm{u} = -\mathrm{k}\Psi(\mathrm{y})$ *guaranties the asymptotic stability of x, where k is a positive constant,* $\Psi(0) = 0$ *and,* $\forall\, \mathrm{y} \neq 0,\ \mathrm{y}^{\mathrm{T}}\Psi(\mathrm{y}) > 0$.

According to these definitions and theorem, a new voltage-based controller is proposed as:

$$V = RI + L\dot{I} + K_b r^{-1}\dot{q}_d + u_p \tag{6}$$

where $\dot{q}_d$ *is the desired joint position and* u_p *is the virtual input that is considered for passivation. By substituting (6) into (3) and with defining* $e = q - q_d$ *:*

$$u_p = K_b r^{-1}\dot{e}. \tag{7}$$

Suppose that the $S(e) = 0.5K_b r^{-1}e^T e$ *be the positive definite storage function for system (7). Then according to the Definition 3.1, it can be shown that the closed loop system (7) is passive between input* u_p *and defined output y=e.*

$$\dot{S} = K_b r^{-1}e^T\dot{e} = e^T u_p \leqslant y^T u_p \tag{8}$$

Also, according to the Definition 3.2, it is clear that system (7) is ZSO with the defined output y=e. Consiquently, according to the Theorem 3.3, the errors of the system will be asymptotically stable and converges to zero as $t \longrightarrow \infty$*, if the virtual control input is selected as bellow:*

$$u_p = -ke, \quad \forall\, \Psi(e) = e. \tag{9}$$

4 Simulation Results

In this section the proposed controller (6) is applied to the two link industrial robot PUMA 560 to show the efficiency of this method. Also, it is assumed that the voltages of the dc motors are limited. This assumption is considered in simulations. The parameter values of the dc motors are considered as follows [7]:

$\mathrm{J_m}\left(\frac{\mathrm{N.ms^2}}{\mathrm{rad}}\right) = 0.0002$, $\mathrm{B_m}\left(\frac{\mathrm{N.ms}}{\mathrm{rad}}\right) = 0.001$, $\mathrm{K_b}\left(\frac{\mathrm{V.s}}{\mathrm{rad}}\right) = 0.26$, $V_{max}(v) = 24$, $R(\Omega) = 1.6$, $L(H) = 0.001$, $r = 0.01$.

The desired joint position, controller gain and initial conditions are defined as:

$q_d = 1 - \cos\big((\pi/10) * t\big)$, $\quad k = diag\,(100\,)$, $\ q(0) = [2.5 \quad -2.5]^T$.

The shape of the trajectory plays a significant role for tracking control of the manipulator. The trajectory required to be smooth since the first and second derivatives of the joint positions are appeared in the electrical current. The simulation results are shown in figure 1. This figure depicts the good efficiency of the proposed controller since the tracking error converges to zero.

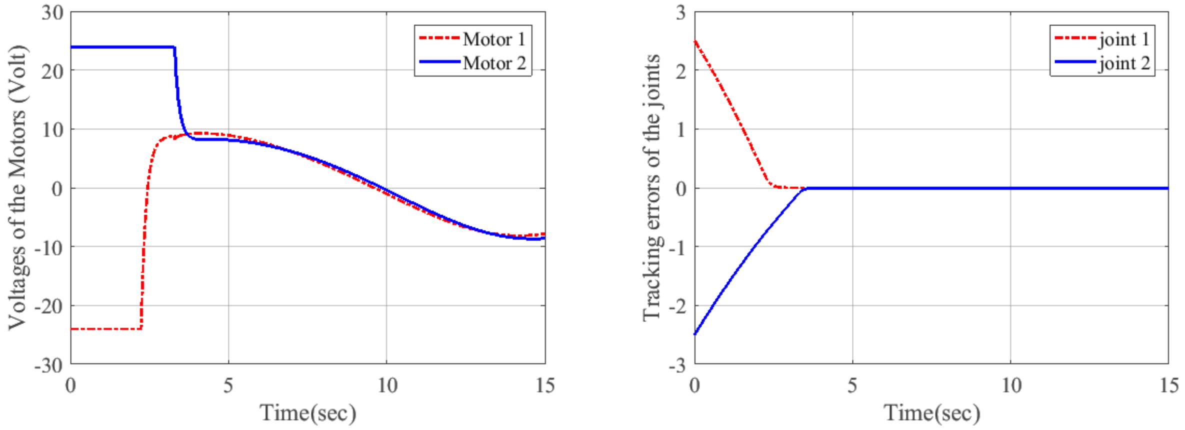

Figure 1. Voltages of the motors and tracking errors of the joints.

5 Conclusion

In this paper, a new voltage-base control law is proposed based on passivity theorem. Tracking error trajectories of the joint position shows the efficiency of this method. The simulations are applied to the industrial PUMA 560 robot.

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