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Adaptive interaction robot control with estimation of contact force

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Abstract: This paper deals with a new adaptive force-position control of a robotic manipulator based on force estimation. First, an adaptive position controller is derived with contact force component as estimated parameters. Second, a supervisory external loop is added in order to regulate the contact force to the desired value. Extensive simulations with 2-DOF manipulator illustrate the followed approach.

1. INTRODUCTION

In the free motion, joint position or tip Cartesian position can be successfully controlled via model-based adaptive control strategies also in presence of uncertainties about the parameters of the arm (Slotine and Li, 1988; Ortega and Spong, 1989), uncertainties in the structure (Alonge, D'Ippolito and Raimondi, 2004) and in case of partial state feedback (Alonge, D'Ippolito and Raimondi, 2003). However, manipulation tasks often involve the interaction of the robotic arm with the environment. Due to the lack of knowledge about the real world, purely positional control strategies brings to very poor interaction control performances in term of tracking errors, actuator saturation and damaging risk for the manipulated object and the manipulator tool itself. Proper execution of constrained motion tasks can be achieved using control systems which attempt accommodation of unplanned external forces. Moreover, if direct measurements of the contact force are used in the control strategy, the extra information supplied by the force sensor may help compensate for the lack of knowledge about the real world. Since the contact force is significantly representative of the interaction with the environment, some direct force control techniques have been developed in the last year: hybrid position/force control (Raibert and Craig, 1981), operational space force and position control (Khatib, 1987) and parallel force/position control (Chiaverini and Sciavicco, 1993; Chiaverini, Siciliano and Villani, 1994; Siciliano and Villani, 1999). If the contact surface is compliant, inner position/outer force control strategy can also be considered, which means that a force control loop is closed around an inner position loop (De Shutter and Van Brussel, 1988). In the above control techniques force feedback must be obtained from suitable force/torque sensor. Unfortunately, force/torque sensors are very noisy and little reliable. On the contrary, given an accurate robot model, accurate environment force estimates can be determined without the need for force sensors, by using the model based observer originally derived for velocity estimates (Nicosia and Tomei, 1990), modified in (Hacksel and Salcudean, 1994) in order to obtain contact force estimation, supposed constant. A drawback of this approach is increasing computational complexity due to full dynamics non linear model based observer computation and knowledge of exact dynamics model of the arm.

The aim of this paper is to obtain a direct force and position control, computational efficient, avoiding use of force sensors and exact model of the arm. For this purpose, first, model-based adaptive control concepts are extended to the compensation of the interaction term by estimating force component as a new parameter to be estimated by the adaptive controller (Bruno, 2007). Second, an external force loop regulates contact force to the desired constant value acting on the reference position of the inner loop.

In Section 2 the mathematical model of the manipulator is considered with its main properties. Control law and its stability proof are given in Section 3. Finally, in Section 4 and 5 simulation results and some conclusion are given respectively.

2. MATHEMATICAL MODEL

The mathematical model of a robotic arm interacting with the environment is given by

$$\boldsymbol{B}(\boldsymbol{q})\ddot{\boldsymbol{q}}+\boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}}+\boldsymbol{F}\dot{\boldsymbol{q}}+\boldsymbol{g}(\boldsymbol{q})=\boldsymbol{u}-\boldsymbol{J}^T(\boldsymbol{q})\boldsymbol{h} \qquad (1)$$

where $\boldsymbol{u}\in\Re^n$ is the vector of the joint torques, $\boldsymbol{q}\in\Re^n$ is the vector of the generalized joint coordinates, $\boldsymbol{B}(\boldsymbol{q})$ is the inertia matrix, $\boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})$ collects functional terms relative to Coriolis and centripetal torques, vector $\boldsymbol{g}(\boldsymbol{q})$ represents effect of gravity, $\boldsymbol{F}\dot{\boldsymbol{q}}$ is the viscous friction term, $\boldsymbol{J}(\boldsymbol{q})$ is the *6* by *n* jacobian matrix and $\boldsymbol{h}\in\Re^6$ is the force and torque interaction term.

The most important property of the above model is that of linearly parameterization in term of a set of suitable vector parameter $\boldsymbol{\pi}$, from that, the first term of equation (1) can be written as

$$B(q)\ddot{q}+C(q,\dot{q})\dot{q}+F\dot{q}+g(q)=Y(q,\dot{q},\ddot{q})\pi \tag{2}$$

Consider the interaction force and torque vector to be constant or slowly varying. Rearranging the regressor matrix we obtain

$$Y_a(q,\dot{q},\ddot{q})\pi_a = u \tag{3}$$

in which

$$\overbrace{Y_a(q,\dot{q},\ddot{q})}^{n\times(p+r)} = \begin{bmatrix} \overbrace{Y(q,\dot{q},\ddot{q})}^{n\times p} & \overbrace{J^T(q)}^{n\times r} \end{bmatrix} \tag{4}$$

and $\pi_a = \begin{bmatrix} \pi \\ h \end{bmatrix}$.

Regarding the model of the contact plane, we suppose an elastic contact and a model for the contact force

$$h = K\left(x - x_0\right) \tag{5}$$

where x is the contact point position, x_0 is a point on the contact plane at rest and K is the stiffness matrix which can be decomposed as (Chiaverini, Siciliano and Villani, 1994)

$$K = k\,nn^T \tag{6}$$

with k the stiffness coefficient in the normal direction to the contact plane n.

3. CONTROL LAW

Given the bounded trajectory, in the joint space, $q_d(t)$, $\dot{q}_d(t)$, $\ddot{q}_d(t)$, the control law

$$u = \hat{B}(q)\ddot{q}_r + \hat{C}(q,\dot{q})\dot{q}_r + \hat{F}_v\dot{q}_r + \hat{g}(q) + J^T(q)\hat{h} + K_D\sigma =$$

$$= Y_a(q,\dot{q},\dot{q}_r,\ddot{q}_r)\hat{\pi}_a + K_D\sigma, \tag{7}$$

with the estimation law

$$\dot{\tilde{\pi}}_a = \dot{\hat{\pi}}_a = K_{\pi_a}^{-1} Y_a^T(q,\dot{q},\dot{q}_r,\ddot{q}_r)\sigma, \tag{8}$$

where $\tilde{\pi} = \hat{\pi} - \pi$, $\dot{q}_r = \dot{q}_d + \Lambda\tilde{q}$, $\ddot{q}_r = \ddot{q}_d + \Lambda\dot{\tilde{q}}$, $\sigma = \dot{\tilde{q}} + \Lambda\tilde{q}$, and $\tilde{q} = q_d - q$, guaranties asymptotic tracking of the given trajectory despite the interaction.

The proof can be made starting from the scalar function

$$V(t) = \frac{1}{2}\left[\sigma^T B(q)\sigma + \tilde{\pi}_a^T K_{\pi_a}\tilde{\pi}_a\right]. \tag{9}$$

Following a procedure very similar to that in (Slotine and Li, 1988) follows that using model (1) and control law (7) with estimation law (8), the total derivative respect to the time of the function (9) is

$$\dot{V}(t) = -\sigma^T\left(K_D + F\right)\sigma \tag{10}$$

which can be shown to be asymptotically vanishing by using Barbalat's Lemma, which in turn implies that σ, and therefore $\dot{\tilde{q}}$ and $\tilde{q}$ are vanishing.

About parameter convergence to their true values, we obtain, asymptotically, the relation

$$Y_a(q_d,\dot{q}_d,\ddot{q}_d)\tilde{\pi}_a = Y_a(q_d,\dot{q}_d,\ddot{q}_d)\left(\hat{\pi}_a - \pi_a\right) = \mathbf{0}, \tag{11}$$

which implies that the estimated parameters converge to their true values if the condition

$$\forall t>0,\quad \exists\,\Delta>0, \alpha>0: \int_t^{t+\Delta} Y_a Y_a^T\,dt \ge \alpha I \tag{12}$$

Obviously, if the interaction phase follows a free motion phase, in the free motion trajectory control we can assure more easily the condition (12) and, than, we can consider

$$\hat{\pi} = \pi \tag{13}$$

in the following interaction phase.

Condition (13) implies that in the interaction phase the control law (7) with

$$\hat{\pi}_a = \begin{bmatrix} \pi \\ \hat{h} \end{bmatrix}, \tag{14}$$

and the estimation law

$$\dot{\hat{h}} = K_h^{-1} J(q)\sigma \tag{15}$$

guaranties asymptotic tracking of the given trajectory despite the interaction. The proof can be made, in this case, starting from

$$V(t) = \frac{1}{2}\left[\sigma^T B(q)\sigma + \tilde{h}^T K_h \tilde{h}\right], \tag{16}$$

which has the same total derivative respect to the time (10).

The asymptotic condition

$$J^T(q)\tilde{h} = J^T(q)\left[\hat{h} - h\right] = \mathbf{0} \tag{17}$$

implies now that, if

$$\forall t>0,\quad \exists\,\Delta>0, \alpha>0: \int_t^{t+\Delta} J(q)J^T(q)\,dt \ge \alpha I, \tag{18}$$

the interaction term is asymptotically exactly estimated.

In order to regulate the interaction force to a constant value, the outer control loop

$$d\,x_{dn}(\mathrm{t}) = k\int\left(h_d - \hat{h}_n(\mathrm{t})\right)dt \tag{19}$$

in which $\hat{h}_n = \boldsymbol{n}^T \hat{\boldsymbol{h}}$, being $\boldsymbol{n}$ the unity vector normal to the contact plane, h_d is the desired contact force vector and $d\, x_{dn}(\mathrm{t})$ is the desired position additive term assuring that the trajectory lies on a plane parallel to the contact plane with the desired contact force.

4. SIMULATION RESULTS

Simulation results was made in Simulink environment considering the mathematical model of the 2-DOF manipulators in Fig.1, the control law (7) and the estimation law (15), whose parameters are given in Tables 1-3.

A linear Cartesian reference path was given as input of the control system with model of Fig.1 and the proposed control law. The results are given in Figures 2-5.

In particular Fig. 2 shows that the estimated contact force component along the direction normal to the contact plane closely track the true one and both converges to the desired one which is constant and equal to .8 N.

Fig. 3 shows that after a small transient the estimated contact force along the contact plane vanish according to its true value.

Fig. 4 shows that position tracking errors are maintained very small from the inner adaptive controller and vanish when contact force became constant, as theoretically proved in Section 2.

Fig. 5 shows the mechanism of the outer force loop which corrects the normal component of the reference position in order to accomplish to the desired contact force. The true normal position component closely track the desired one and converge to it which is the exact position corresponding to the desired contact force. The desired trajectory component along the contact plane is unmodified by the force control loop, as in the hybrid control (Raibert and Craig, 1981).

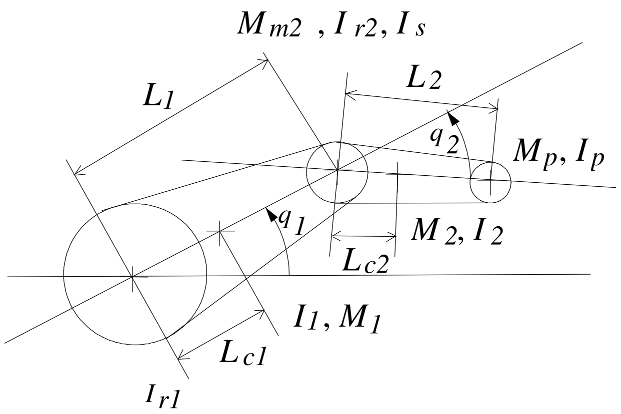

Fig. 1 Schematic of the 2-DOF manipulator

Table 1. Definition of the mechanical parameters

M_1, I_1	mass and inertia coefficient of the link 1
M_2, I_2	mass and inertia coefficient of the link 2
M_p, I_p	mass and inertia coefficient of the payload
I_{r1}	inertia coefficient of the motor 1
M_{m2}, I_s, I_{r2}	mass, inertia coefficient of the stator and inertia coefficient of the rotor of the motor 2
L_1	length of link 1
L_2	length of link 2
L_{c1}	distance of the center of gravity of the link 1 from the axis of the joint 1
L_{c2}	distance of the center of gravity of the link 2 the axis of the joint 2

Table 2. Values of the mechanical parameters

Dynamical		Kinematical
M_1 = 9.78 Kgf	I_1 = .334 Kgf·m/s2	L_1 = .359 m
M_2 = 4.45 Kgf	I_2 = .063 Kgf·m/s2	L_2 = .24 m
M_{m2} = 14 Kgf	I_{r1} = .267 Kgf·m/s2	L_{c1} = .136 m

Table 3. Controller's parameters

$\mathbf{K}_D = diag[10,10]$	$\mathbf{K}_{\pi_a} = diag[5,5]*10^{-4}$	$\boldsymbol{\Lambda} = diag[10,10]$

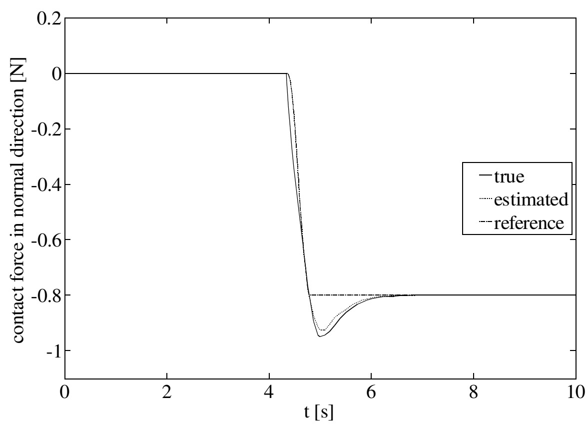

Fig. 2 Contact force component history in a direction normal to the contact plane

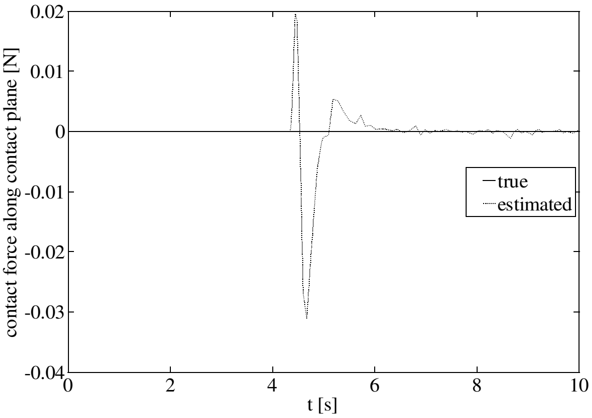

Fig. 3 Contact force component history along the contact plane

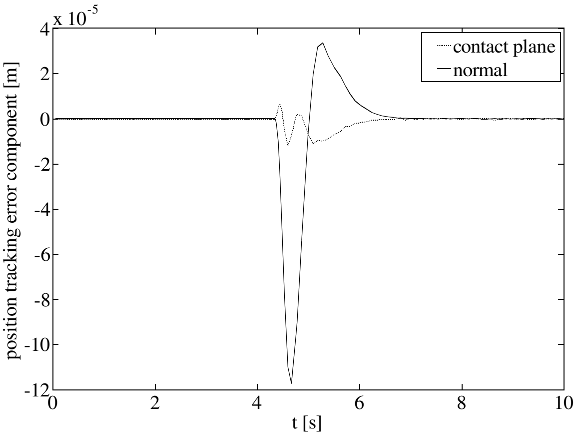

Fig. 4 Position tracking error component

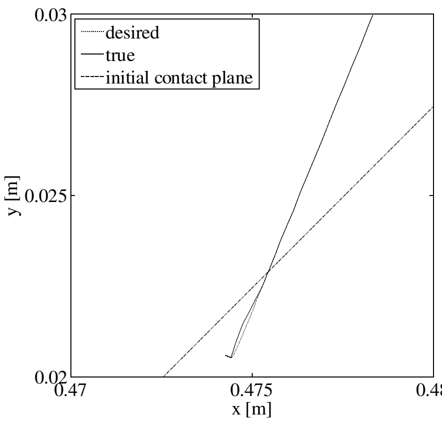

Fig. 5 End-effector's trajectory

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