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Adaptive position/force control for robot manipulators in contact with a rigid surface with uncertain parameters

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ABSTRACT

Most position/force control schemes assume that the contact surface is exactly known. In the presence of constraint uncertainties these controllers cannot ensure convergence to zero of position and force errors. In this work, an adaptive scheme is proposed for robot manipulators that perform interaction tasks with rigid surfaces. Both robot and constraint surface parameters are considered to be uncertain. The proposed scheme locally estimates the surface by means of force measurements. Experimental results are presented to illustrate the good performance of the proposed approach.

1. Introduction

Many industrial tasks performed by robots such as assembly, milling, pulling and object handling are required to control not only the robot end-effector position but also the applied force to the environment. Sensors are useful to control or to monitor the magnitude of the interaction forces in order to avoid damage on the manipulator and/or the environment.

Most schemes proposed in the literature are divided into impedance and hybrid position/force control. The impedance approach first proposed by Hogan [7] establishes a trade off between the contact force, position and velocity of the end-effector. On the other hand, the hybrid position/force scheme proposed by Raibert and Craig [17] separates the control task in two subspaces. Thus, the approach allows us to specify a desired position independent of the desired force. When the contact surface is rigid the environment can be modeled as a set of algebraic equations [14]. Arimoto et al. [1] introduced the Principle of Orthogonalization as an extended notion of hybrid control letting the position subspace be orthogonal to the force one. Similar control schemes have been proposed in Parra-Vega et al. [16] and Martínez-Rosas et al. [13]. These controllers can achieve a good performance when the environment is known.

In practice, there are always uncertainties in the robot dynamic and kinematic model parameters, for which several adaptive control schemes have been proposed (*e.g.* [5,2]). Another class of uncertainties refers to the lack of knowledge of constraint surface parameters (*e.g.* slope, radius of curvature, position of the surface [6,19]). To cope with this problem Wang et al. [22] proposed a PD like controller that only needs the nominal constraint. However, the approach is restricted to the set-point problem.

Another feasible solution is to use an online procedure for identification of the constraint surface. Yoshikawa and Sudou [23] proposed an approach that locally estimates the constraint surface by means of force measurements. However, the controller requires the knowledge of the robot model and force derivatives; also the orientation of the end-effector is not considered. To avoid this problem Namvar and Farhad [15] proposed a control scheme that estimates the constraint Jacobian. The estimated Jacobian is used to project the velocity errors and the desired velocity onto the contact surface but it is not employed to modify the desired motion online. An adaptive control scheme that estimates the constraint and the Jacobian and modifies the desired trajectory online (only for flat surfaces) is presented in Doulgeri and Arimoto [10].

On the other hand, some algorithms based on visual servoing and force control have been proposed for online estimation of the constraint geometry (*e.g.* [8]). Leite et al. [12] proposed a kinematic control scheme based on adaptive visual servoing and direct force control. The camera parameters as well as the constraint surface were considered to be uncertain. A hybrid vision-force controller for robots with uncertain kinematics and unknown constraint was introduced in Cheah et al. [3].

In order to cope with rigid surfaces with unknown parameters, an adaptive position/force control is proposed in this paper that estimates both the constraint parameters and the gradient vector as well. The proposed algorithm takes into account robot and constraint parameters uncertainties. The advantages of this scheme are summarized as follows: (1) The controller only needs the end effector

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position and the measured force to locally estimate the constraint surface and to modify online the desired trajectory. (2) The algorithm is not restricted to flat surfaces. (3) The controller is easy to implement since it does not require any coordinate transformation as the result in de Queiroz et al. [4]. (4) The measured force is not used to cancel the reaction force as in Karayiannidis and Doulgeri [10]. Experimental results are presented to show the good performance of the control approach. The paper is organized as follows. The robot model in contact with a rigid surface and some model properties are given in Section 2. The proposed adaptive position/force control is developed in Section 3. Section 4 shows the experimental results. Finally, some conclusions are given in Section 5.

2. Dynamic model and properties

Consider a n degree of freedom revolute manipulator in contact with a frictionless rigid environment described by m algebraic equations given by

$$\boldsymbol{\varphi}(\boldsymbol{q},\boldsymbol{\vartheta})=\boldsymbol{0}, \tag{1}$$

where $\boldsymbol{\vartheta}\in\Re^{l}$ is a constant parameter vector. The equations of motion of the manipulator are given by

$$\boldsymbol{H}(\boldsymbol{q})\ddot{\boldsymbol{q}}+\boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}}+\boldsymbol{D}\dot{\boldsymbol{q}}+\boldsymbol{g}(\boldsymbol{q})=\boldsymbol{\tau}+\boldsymbol{J}_{\varphi}^{\mathrm{T}}(\boldsymbol{q},\boldsymbol{\vartheta})\boldsymbol{\lambda}, \tag{2}$$

where $\boldsymbol{q}\in\Re^{n}$ is the vector of joint generalized coordinates, $\boldsymbol{H}(\boldsymbol{q})\in\Re^{n\times n}$ is a symmetric positive definite inertia matrix, $\boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}}\in\Re^{n}$ represents the vector of Coriolis and centrifugal forces, $\boldsymbol{g}(\boldsymbol{q})\in\Re^{n}$ is the vector of gravitational forces, $\boldsymbol{D}\in\Re^{n\times n}$ is a positive semi-definite matrix that contains viscous friction coefficients, $\boldsymbol{\tau}\in\Re^{n}$ is the vector of generalized torques, $\boldsymbol{\lambda}\in\Re^{m}$ is the vector of Lagrange multipliers (physically represents the exerted forces to the environment by the robot). The gradient matrix $\boldsymbol{J}_{\varphi}(\boldsymbol{q},\boldsymbol{\vartheta})=\nabla_{\mathrm{q}}\boldsymbol{\varphi}(\boldsymbol{q},\boldsymbol{\vartheta})$ maps a vector onto a normal plane to the surface depicted by (1).

2.1. Model properties

Property 1. *The inertia matrix $\boldsymbol{H}(\boldsymbol{q})$ satisfies*

$$\lambda_{\mathrm{h}}\|\boldsymbol{y}\|^{2}\le\boldsymbol{y}^{\mathrm{T}}\boldsymbol{H}(\boldsymbol{q})\boldsymbol{y}\le\lambda_{\mathrm{H}}\|\boldsymbol{y}\|^{2}\quad\forall\boldsymbol{q},\boldsymbol{y}\in\Re^{n} \tag{3}$$

with $\lambda_{\mathrm{h}}\triangleq\lambda_{\min}(\boldsymbol{H}(\boldsymbol{q}))$, $\lambda_{\mathrm{H}}\triangleq\lambda_{\max}(\boldsymbol{H}(\boldsymbol{q}))$ *and* $0<\lambda_{\mathrm{h}}<\lambda_{\mathrm{H}}<\infty$. □

Property 2. *With a proper definition of* $\boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})$, *the matrix* $\dot{\boldsymbol{H}}(\boldsymbol{q})-2\boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})$ *is skew symmetric.* □

Property 3. *With a proper definition of the robot model parameters it is*

$$\boldsymbol{H}(\boldsymbol{q})\ddot{\boldsymbol{q}}+\boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}}+\boldsymbol{D}\dot{\boldsymbol{q}}+\boldsymbol{g}(\boldsymbol{q})=\boldsymbol{\tau}+\boldsymbol{J}_{\varphi}^{\mathrm{T}}(\boldsymbol{q},\boldsymbol{\vartheta})\boldsymbol{\lambda}=\boldsymbol{Y}(\boldsymbol{q},\dot{\boldsymbol{q}},\ddot{\boldsymbol{q}})\boldsymbol{\theta}+\boldsymbol{J}_{\varphi}^{\mathrm{T}}(\boldsymbol{q},\boldsymbol{\vartheta})\boldsymbol{\lambda}, \tag{4}$$

where $\boldsymbol{Y}(\boldsymbol{q},\dot{\boldsymbol{q}},\ddot{\boldsymbol{q}})\in\Re^{n\times p}$ *is the regressor and* $\boldsymbol{\theta}\in\Re^{p}$ *is a constant parameter vector.* □

The derivative of constraint (1) is given by

$$\dot{\boldsymbol{\varphi}}(\boldsymbol{q},\boldsymbol{\vartheta})=\boldsymbol{J}_{\varphi}(\boldsymbol{q},\boldsymbol{\vartheta})\dot{\boldsymbol{q}}=\boldsymbol{0}. \tag{5}$$

The velocity vector $\dot{\boldsymbol{q}}$ belongs to the null space of the matrix $\boldsymbol{J}_{\varphi}(\boldsymbol{q},\boldsymbol{\vartheta})\in\Re^{m\times n}$, which means that the velocity is always tangent to the surface at the contact point.

Property 4. *The vector $\dot{\boldsymbol{q}}$ can be written as*

$$\dot{\boldsymbol{q}}=\boldsymbol{Q}(\boldsymbol{q},\boldsymbol{\vartheta})\dot{\boldsymbol{q}}+\boldsymbol{P}(\boldsymbol{q},\boldsymbol{\vartheta})\dot{\boldsymbol{q}}=\boldsymbol{Q}(\boldsymbol{q},\boldsymbol{\vartheta})\dot{\boldsymbol{q}}, \tag{6}$$

where $\boldsymbol{P}(\boldsymbol{q},\boldsymbol{\vartheta})\triangleq\boldsymbol{J}_{\varphi}^{+}(\boldsymbol{q},\boldsymbol{\vartheta})\boldsymbol{J}_{\varphi}(\boldsymbol{q},\boldsymbol{\vartheta})\in\Re^{n\times n}$, $\boldsymbol{J}_{\varphi}^{+}(\boldsymbol{q},\boldsymbol{\vartheta})\triangleq\boldsymbol{J}_{\varphi}^{\mathrm{T}}(\boldsymbol{q},\boldsymbol{\vartheta})\left(\boldsymbol{J}_{\varphi}(\boldsymbol{q},\boldsymbol{\vartheta})\boldsymbol{J}_{\varphi}^{\mathrm{T}}(\boldsymbol{q},\boldsymbol{\vartheta})\right)^{-1}\in\Re^{n\times m}$ *is the Moore–Penrose pseudoinverse and* $\boldsymbol{Q}(\boldsymbol{q},\boldsymbol{\vartheta})\triangleq\boldsymbol{I}-\boldsymbol{P}(\boldsymbol{q},\boldsymbol{\vartheta})\in\Re^{n\times n}$. *The projection matrices satisfy* $\boldsymbol{QP}=\boldsymbol{O}$, $\boldsymbol{QQ}=\boldsymbol{Q}=\boldsymbol{Q}^{\mathrm{T}}$ *and* $\boldsymbol{PP}=\boldsymbol{P}=\boldsymbol{P}^{\mathrm{T}}$. *Since both matrices are orthogonal we also have* $\boldsymbol{QJ}_{\varphi}=\boldsymbol{O}$ *and* $\boldsymbol{J}_{\varphi}^{\mathrm{T}}\boldsymbol{Q}=\boldsymbol{O}$. □

2.2. Parametrization

For simplicity's sake, we rewrite the constraint surface in task space coordinates as

$$\boldsymbol{\varphi}(\boldsymbol{x},\boldsymbol{\vartheta})=\boldsymbol{0}. \tag{7}$$

In the task space coordinates the applied force is given by

$$\boldsymbol{f}=\boldsymbol{J}_{\varphi x}^{\mathrm{T}}(\boldsymbol{x},\boldsymbol{\vartheta})\lambda, \tag{8}$$

where $\boldsymbol{J}_{\varphi\mathrm{x}}(\boldsymbol{x},\boldsymbol{\vartheta})=\nabla_{\mathrm{x}}\boldsymbol{\varphi}(\boldsymbol{x},\boldsymbol{\vartheta})\in\Re^{m\times n}$. Applying the chain rule it is possible to get

$$\boldsymbol{J}_{\varphi}(\boldsymbol{q},\boldsymbol{\vartheta})=\frac{\partial\boldsymbol{\varphi}(\boldsymbol{x},\boldsymbol{\vartheta})}{\partial\boldsymbol{x}}\cdot\frac{\partial\boldsymbol{x}}{\partial\boldsymbol{q}}=\boldsymbol{J}_{\varphi x}(\boldsymbol{x},\boldsymbol{\vartheta})\boldsymbol{J}(\boldsymbol{q}), \tag{9}$$

where $\boldsymbol{J}(\boldsymbol{q})$ is the analytical Jacobian.

Assumption 1. It holds the following:

(a) The contact force $\boldsymbol{f}$ in task space is measurable.
(b) The dimension of the constraint surface is one $(m=1)$ and the geometry of the surface is known, while the parameter vector $\boldsymbol{\vartheta}$ is unknown or uncertain. Thus, the Lagrange multiplier λ in (8) represents the force magnitude and the gradient vector represents the direction of the applied force. Since it is considered a frictionless surface, from (8) one gets

$$\boldsymbol{J}_{\varphi x}^{\mathrm{T}}(\boldsymbol{x},\boldsymbol{\vartheta})=\frac{\boldsymbol{f}}{\|\boldsymbol{f}\|}\quad\text{whenever }\|\boldsymbol{f}\|\ne\boldsymbol{0}. \tag{10}$$

This implies that the gradient vector can be computed by means of force measurements.
(c) At $t=0$ the robot is in contact with the surface. □

Assumption 2. The gradient vector $\boldsymbol{J}_{\varphi x}^{\mathrm{T}}(\boldsymbol{x},\boldsymbol{\vartheta})$ is linear with respect to the parameter vector $\boldsymbol{\vartheta}$, *i.e*,

$$\boldsymbol{J}_{\varphi x}^{\mathrm{T}}(\boldsymbol{x},\boldsymbol{\vartheta})=\boldsymbol{W}_{\mathrm{x}}^{\mathrm{T}}(\boldsymbol{x})\boldsymbol{\vartheta}, \tag{11}$$

where $\boldsymbol{W}_{\mathrm{x}}(\boldsymbol{x})\in\Re^{m\times n}$ is a constraint regressor matrix. □

In view of (9) and (11) it is possible to get

$$\boldsymbol{J}_{\varphi}^{\mathrm{T}}(\boldsymbol{q},\boldsymbol{\vartheta})=\boldsymbol{J}^{\mathrm{T}}(\boldsymbol{q})\boldsymbol{W}_{\mathrm{x}}^{\mathrm{T}}(\boldsymbol{x})\boldsymbol{\vartheta}. \tag{12}$$

The estimated gradient vector is given by

$$\hat{\boldsymbol{J}}_{\varphi x}^{\mathrm{T}}(\boldsymbol{x},\hat{\boldsymbol{\vartheta}})=\boldsymbol{W}_{\mathrm{x}}^{\mathrm{T}}(\boldsymbol{x})\hat{\boldsymbol{\vartheta}}. \tag{13}$$

where $\hat{\boldsymbol{\vartheta}}$ is an estimate of $\boldsymbol{\vartheta}$. We define the error between the estimate gradient vector and the real one as (see Fig. 1(a))

$$\boldsymbol{e}_{\mathrm{f}}=\hat{\boldsymbol{J}}_{\varphi x}^{\mathrm{T}}-\boldsymbol{J}_{\varphi x}^{\mathrm{T}}=\boldsymbol{W}_{\mathrm{x}}^{\mathrm{T}}(\boldsymbol{x})\Delta\boldsymbol{\vartheta}, \tag{14}$$

where $\Delta\boldsymbol{\vartheta}\triangleq\hat{\boldsymbol{\vartheta}}-\boldsymbol{\vartheta}$ is the parameter estimation error vector. In order to specify a desired trajectory it is necessary to know the geometry of the surface. To deal with this problem it is possible to locally estimate the constraint surface by means of force measurements. By taking into account Fig. 1(b) a linear approximation of the constraint surface can be given by

$$\hat{\varphi}(\boldsymbol{x},\boldsymbol{\vartheta})=\hat{\boldsymbol{J}}_{\varphi x}\left(\boldsymbol{x}(t)-\boldsymbol{x}(t-\Delta t)\right)\approx 0 \tag{15}$$

where $\boldsymbol{x}(t)-\boldsymbol{x}(t-\Delta t)$ represents an infinitesimal displacement of the end-effector on the constraint surface in the time interval $[t,t-\Delta t]$. From a practical point of view, one can take $\boldsymbol{x}_{\mathrm{a}}=\boldsymbol{x}(t-\Delta t)$, where $\boldsymbol{x}_{\mathrm{a}}$ is the storage value at the instant $t-\Delta t$ and it can be approximated by

$$\dot{\boldsymbol{x}}_{\mathrm{a}}=-\eta\boldsymbol{x}_{\mathrm{a}}+\eta\boldsymbol{x}. \tag{16}$$