AC 2009-130: ADAPTIVE ROBOT MANIPULATORS IN GLOBAL TECHNOLOGY

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Adaptive Robot Manipulators in Global Technology

Abstract

Model-based feedback control algorithms for robot manipulators require the on-line evaluation of robot dynamics and are particularly sensitive to modeling inaccuracies. This paper presents an adaptive technique for practical implementation of model-based robot control strategies and introduces a novel adaptive algorithm which makes the design insensitive to modeling errors. The design incorporates an on-line identification technique to eliminate parameter errors and individual joint controllers to compensate for modeling inaccuracies. An illustrated example is given to demonstrate the development of the proposed algorithm through a simple two-dimensional manipulator. New applications for robot manipulators are continually being discovered with global impacts due to integration of computer controlled robots.

I. Introduction

The continuously increasing demands for enhanced productivity and improved precision have imposed special requirements on the control of industrial robots and caused a shift of emphasis towards the dynamic behavior of manipulators. This shift has led to the development of model-based control algorithms which incorporate the dynamic model of the manipulator in the control law in order to decouple the robot joints. The underlying principle is to: (1) design a nonlinear feedback algorithm that will effectively linearize the dynamic behavior of the robot joints; and (2) synthesize linear controllers to specify the closed-loop response.

The critical assumption in model-based control is that the robot dynamics are modeled accurately based upon precise knowledge of the kinematic and dynamic parameters of the manipulator. Unfortunately, this assumption is not always practical. Inevitable modeling and parameter errors may degrade controller performance and even lead to instability. Modeling errors are introduced by unmodeled dynamics or simplified models that are designed to reduce the real-time computational requirements of the controller. Parameter errors arise from practical limitations in the specification of numerical values for the kinematic and dynamic robot parameters or from payload variations.

The objective of this paper is to introduce an adaptive design to improve the performance of robot manipulators. The proposed design augments the model-based robot controller with an adaptive identifier of robot dynamics to reduce parameter errors. The identifier estimates the dynamic parameters of the manipulator from measurements of the inputs and outputs (joint positions, velocities, and accelerations) and calibrates adaptively the model in the controller.

II. Problem Statement

The matrix-vector formulation of the closed-form dynamic model for a robot with N joint axes[1] is:

$$\mathbf{D}(q, \varphi)\,\ddot{q} + \mathbf{h}\,(q, \dot{q}, \varphi) = \mathbf{F}(t) \qquad (1)$$

In (1), q(t), $\dot{q}$(t), and $\ddot{q}$(t) are the joint position, velocity and acceleration vectors; φ is the vector of dynamics parameters; **D**(q, φ) is the inertial matrix; **h** $(q, \dot{q}, \varphi)$ is the coupling vector that incorporates the centrifugal, Coriolis, gravitational, and frictional force/torque vectors; and **F**(t) is the vector of actuating (motor) joint forces/torques.

The structured closed-form dynamic robot model in (1) provides physical insight into the nonlinear system and is thus very appealing from the control engineering point-of-view. The state of the robot is defined, at any time instant, by the N joint positions $q(t) = [q_1, q_2, \ldots, q_N]^T$ and the *N* joint velocities $\dot{q}(t) = [\dot{q}_1, \dot{q}_2, \ldots, \dot{q}_N]^T$. These 2N independent physical state-variables can be measured directly with currently available transducers.

In general, the parameter vector φ is unknown, although the convex subspace in which it lies may be well-defined. The parameter vector depends on the inertial and mass properties of the links as well as on the payload. We assume that an initial estimate of the parameter vector can be computed from engineering drawings or other design information about the robot links[1].
In the next section, we demonstrate that the problem of estimating φ is one of solving a set of linear equations. Consequently, the assumption that an initial estimate φ is available is not critical to the convergence of our algorithm. However, a reasonable initial estimate does increase the rate of convergence, thus decreasing the learning period of our algorithm.
The control objective is to drive the robot along a desired trajectory $q_d(t)$. The objective can be accomplished by generating the following model-based actuating signal:

$$t) = \mathbf{D}(q, \hat{\phi})\mathbf{u}(t) + \mathbf{h}(q, \dot{q}, \hat{\phi}) \quad (2)$$

where the commanded-acceleration is defined as:

$$\mathbf{u}(t) = r(t) - k_v \dot{q} - k_p q \quad (3)$$

Model-based robot control algorithms differ in their specification of the reference signal r(t). In (2), the caret signifies the estimated parameter vector implemented in the controller.
If the robot dynamics are modeled perfectly; that is, if $\hat{\phi} = \varphi$, then the controller in (2) and (3) guarantees that $q_d(t)=q(t)$. This is due to the positive-definiteness of inertial matrix, **D**(q, $\hat{\phi}$), for all **q**. The performance of the model-based robot controller degrades as the error in the estimates of the dynamics parameters increases. In practice, with a priori uncertain about the parameter vector, adaptive control provides a natural solution to this problem.

We seek to increase the performance of the model-based robot control algorithm by augmenting it with an adaptation mechanism. The purpose of this mechanism is to calibrate the actuating signal in (2) on the basis of on-line accumulating information about the behavior of controlled system. A block-diagram implementation of the proposed concept is presented in Figure 1. The adaptive mechanism is discussed in the following section.

III. Adaptive Algorithm

A characteristic feature of the manipulator dynamic (1) is that the inertial matrix **D**(q, $\hat{\phi}$) and coupling vector, **h** $(q, \dot{q}, \hat{\phi})$ are linear in the elements of the parameter vector φ. This feature is essential for the adaptation algorithm because it allows us to rewrite the manipulator dynamics as:

$$\mathbf{F}(t) = \mathbf{\Psi}(q, \dot{q}, \ddot{q})\varphi \quad (4)$$

where **Ψ**(t) is a nonlinear, time-varying matrix that depends upon the joint positions, velocities and accelerations.

Our model-based adaptive controller consists of two important steps: (i) estimating the dynamics parameters by solving equation (4); and (ii) using the obtained parameters in the computed-torque control law.

The Dynamics Parameters are estimated using a least-squares algorithm for a multi-output system. In general, the least-squares algorithm minimizes the cost function[2]

$$J_N(\varphi) = \tfrac{1}{2}(\varphi-\varphi_0)^T\mathbf{P}_0^{-1}(\varphi-\varphi_0) + 1/2\sum_{t=1}^{N}[\mathbf{F}(t) - \boldsymbol{\psi}(t-1)^T\varphi]^T\mathbf{R}^{-1}[\mathbf{F}(t)-\boldsymbol{\psi}(t-1)^T\varphi] \qquad (5)$$

The value of the parameters vector φ that minimizes the above cost function is computed sequentially from the adaptation algorithm given below[3]:

$$\hat{\phi}(t) = \hat{\phi}(t-1) + \mathbf{P}(t-2)\,\boldsymbol{\psi}(t-1)[\,\boldsymbol{\psi}(t-1)^T\mathbf{P}(t-2)\,\boldsymbol{\psi}(t-1)+\mathbf{R}]^{-1}[\mathbf{F}(t)-\boldsymbol{\psi}(t-1)^T\hat{\phi}(t-1)] \qquad (6)$$

$$\mathbf{P}(t-1)= P(t-2)P(t-2)\,\boldsymbol{\psi}(t-1)[\,\boldsymbol{\psi}(t-1)^T\mathbf{P}(t-2)\,\boldsymbol{\psi}(t-1)+\mathbf{R}]^{-1}[\mathbf{F}(t)-\boldsymbol{\psi}(t-1)^T\mathbf{P}(t-2)] \qquad (7)$$

Where $\mathbf{P}(-1) = \mathbf{P}_0$ and $\mathbf{R}$ are positive definite matrices, $\mathbf{P}_0$ is the initial estimate that can be interpreted as a measure of confidence and **R** is a weighting matrix for past errors. Generating the matrix $\boldsymbol{\psi}$ in an estimation algorithm, requires the knowledge of the joint position **q**, joint velocity $\dot{q}$, and joint acceleration $\ddot{q}$. A characteristic feature of the adaptive mechanism is that the control objective will be attained only after the adaptation period elapses. During the adaptation period which constitutes the learning phase of the system, the manipulator motion may deviate significantly from the desired trajectory. At the end of the learning process, however, the system performance will meet the specification until the identified parameters change.

IV. An Illustrated Example

In this section, we demonstrate the development of the paper through a simple two-dimensional example. We concentrate on the planar polar manipulator shown in Figure 2 with joint coordinates (θ, r)**.** We assume that the motion occurs on a plane perpendicular to the gravity field and ignore gravitational and frictional effects.

The dynamic model for this robot can be written as in (1):

$$\begin{bmatrix} F_1(t) \\ F_2(t) \end{bmatrix} = \begin{bmatrix} J+mr^2-mRr & 0 \\ 0 & m \end{bmatrix} \begin{bmatrix} d^2\theta/dt^2 \\ d^2r/dt^2 \end{bmatrix} + \begin{bmatrix} 2mrdr/dt\, d\theta/dt - mRdr/tdd\theta/dt \\ -mr\,(d\theta/dt)^2 + 1/2mR\,(d\theta/dt)^2 \end{bmatrix} \qquad (8)$$

where J is the inertia of the rotational link with respect to z axis; m is the mass of the translational link; mR is the first moment of the translational link with respect to the z axis. By defining the parameter vector as:

$$\varphi = [J, m, mR]^T \qquad (9)$$

we can rewrite the equations-of-motion in (8) as in (4):

$$\begin{bmatrix} F_1(t) \\ F_2(t) \end{bmatrix} = \begin{bmatrix} d^2\theta/dt^2 & r^2\, d^2\theta/dt^2 + 2rdr/dtd\theta/dt & -rd^2\theta/dt^2-dr/dtd\theta/dt \\ 0 & d^2r/dt^2-r(d\theta/dt)^2 & 1/2(d\theta/dt)^2 \end{bmatrix} \begin{bmatrix} J \\ m \\ mR \end{bmatrix} \qquad (10)$$

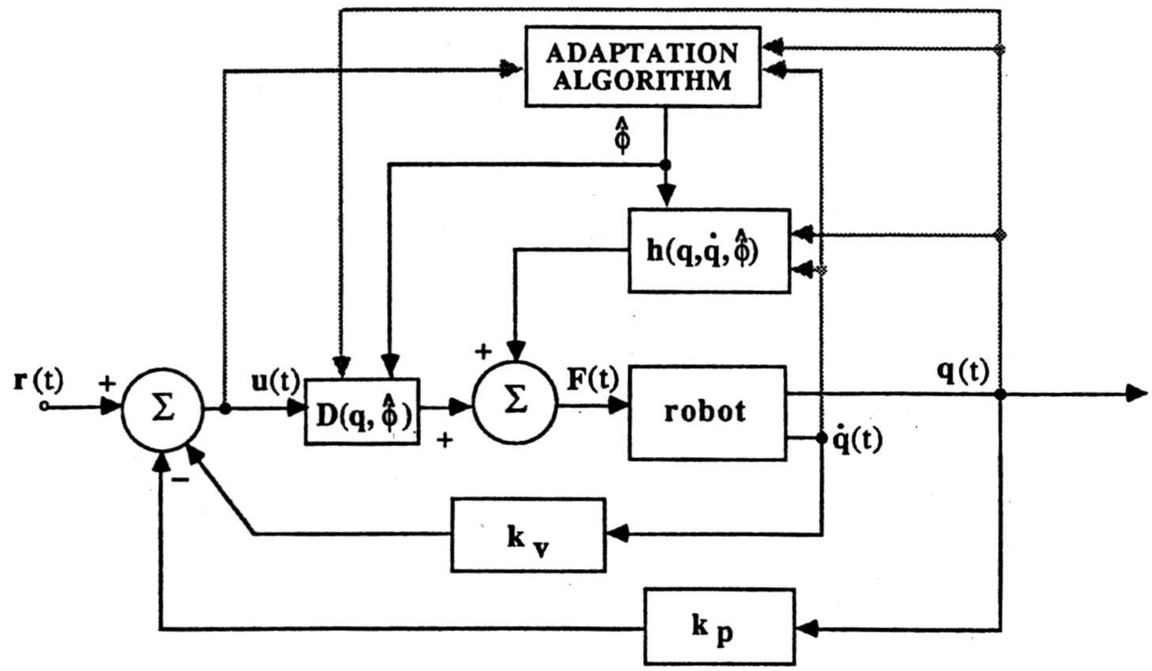

Figure 1. Adaptive Algorithm Block Diagram

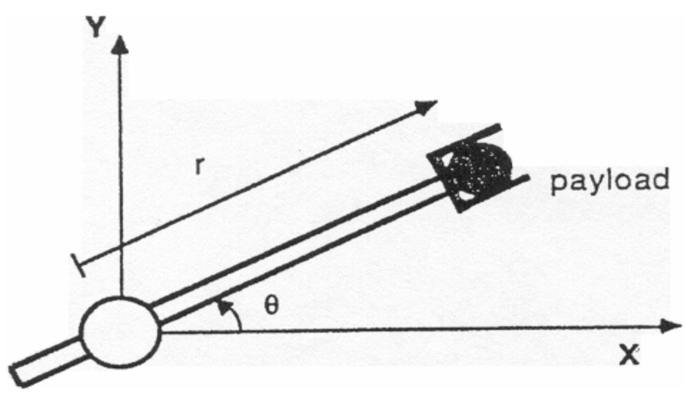

Figure 2. Two-joint Planar Robot

We implemented the adaptation mechanism with P(t) = Po = R = I for a fifth-order polynomial trajectory sampled at 5 ms. In Table 1, we highlight the initial, final, and true values of the dynamics parameters after 20 recursive steps. The robustness of our procedure is clearly observed from the fact that the algorithm converged in spite of large initial errors.

Table 1. Simulation Results

parameter	Initial Value	Final Value	True Value
J(kg-m$^{2)}$	1.0	1.7523	1.75
m(kg)	1.0	2.4988	2.5
MR(kg.m)	1.0	1.4879	1.5

V. Results

Model-based robot control is sensitive to modeling and parameter errors. We developed a solution to this problem by augmenting the standard controller with an adaptation mechanism. The proposed design incorporates an on-line identifier to eliminate parameter errors and individual joint controllers to compensate for unmodeled dynamics. Our approach is particularly appealing because it retains the basic structure of model-based robot control.

References

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