Adaptive Force-Position Control for Teleoperated Manipulators

A.J. Koivo
Purdue University
Lafayette, IN 47907

Abstract

An adaptive controller with self-tuning can be designed for teleoperated robotic manipulators by determining a time-series model for the function of the teleoperator. Specifically, the position and force exerted by the operator are modelled for determining the derived values for the trajectory of the end-effector of the manipulator. Thus, the adaptive controller can be designed by following the steps which have previously been presented for the controller design of the gross motion.

1. Introduction

A teleoperated robotic manipulator refers usually to a system in which an operator equipped with sufficient sensors, effectors and computer intelligence can make the manipulator perform complex tasks either under human supervision or autonomously. The human operator supervises the robotic system which is performing low-level tasks by intermittently monitoring and/or reprogramming the computer. Thus, the teleoperator can increase the level of intelligence of the overall system.

The teleoperator functions in the system as the "master" and the manipulator as the "slave". The teleoperator is mainly interested in the motion of the end-effector, and not so much in the motion of the intervening segments. Although the control of manipulator motion is commonly performed in the joint space, it can also be accomplished directly in the Cartesian coordinate system [5]. If the motion of the master (the teleoperator) is described in the Cartesian world coordinate system, the slave can be made to follow the motion of the master by controlling the motion of the slave (manipulator) in the Cartesian base coordinate system. In the preliminary work described here, we will use this approach to control the force exerted by the end-effector of the manipulator, and its gross motion. We will construct an adaptive self-tuning controller for the control of the force and position of the end-effector.

The overall system is first described briefly, and the problem formulation is given. A time-series model for the motion of the teleoperator is then developed. This model is used to predict the desired motion of the manipulator. An adaptive controller is then designed to make the manipulator follow the desired motion without the supervision of the operator.

2. Teleoperated Robotic Manipulator System and Problem Statement

The overall system consists of a robotic manipulator with an end-effector, computer, and a teleoperator, whose arm and hand are constrained to have the same configuration as the manipulator. The hand is assumed to possess two (jaw-like) fingers. It will be assumed in this preliminary study that the position of the hand as well as the force and moments exerted by the hand can be measured.

The measurements of the position of the hand and the forces (moments) exerted by the hand on the object will be described as a multivariate discrete time-series model. The parameters of this model are estimated recursively by the least squares error method on-line. The resulting model will be used to predict the desired values of the variables for controlling the manipulator, and its end-effector.

The dynamics of the manipulator will also be modelled by means of a multivariate stochastic discrete time-series equation with unknown parameters. This vector difference equation is used as the basis in designing an adaptive self-tuning controller for the manipulator motion.

The problems to be considered in the following consist of constructing (i) a discrete time-series model for the desired values of the position and forces for the end-effector; (ii) a multivariate auto-regressive (ARX) model with external inputs for designing an adaptive self-tuning controller for the dynamics of the manipulator. The difference equation model for the desired values of the position and force are based on the measurements which become available when the teleoperator performs a task (i.e., teach-by-doing). The ARX-model is determined on the basis of the measurements available from the position sensors and the force sensors of the manipulator. We will assume that the forces exerted by the end-effector on the object are "soft", i.e., that they can be modelled by linear springs.

3. Mathematical Model for Teleoperated Manipulator System

In order to make the end-effector follow the path determined by the teleoperator, and exert the force (torque) specified by the same operator, the values of these variables will be measured as a function of time. The future values of these variables can be predicted by using a time-series model constructed on the basis of the measurements. Suppose that the teleoperator exerts a force $f^d(k)$ at time kT (T=sampling period) on an object, while following a trajectory passing through the points $p^d(k)$ expressed relative to a chosen Cartesian world coordinate system. These values can be modelled by time-series models:

$$f^d(k) = A_o^d + \sum_{i=1}^{n} A_i^d\, f^d(k-i) + \xi^d(k) \tag{1}$$

$$p^d(k) = B_o^d + \sum_{i=1}^{n} B_i^d\, p^d(k-i) + \eta^d(k) \tag{2}$$

where the equation error is signified by $\xi^d(k)$, and $\eta^d(k)$; the unknown parameters in the matrices A_j^d, and B_j^d, j = 0,1,...,n are estimated by the least squares error method on the basis of the measurements.

The one-step ahead predicted values for the force f^d and p^d are computed by the following equations:

$$f^d(k+1|k) = \hat{A}_o^d + \sum_{i=1}^{n} \hat{A}_i^d\, f^d(k-i+1) \tag{3}$$

$$p^d(k+1|k) = B_o^d + \sum_{i=1}^{n} \hat{B}_i^d\, p^d(k-i+1) \tag{4}$$

where the terms on the right are known from the measurements and the calculations of the parameter estimates.

To construct a controller for the manipulator, an ARX-model is used as the basis of the design. If the position of the end-effector relative to the Cartesian base coordinate system p(k) at time kT is measured (e.g., encoder readings), while it exerts a force f(k) on an object, then an ARX-model for the measurements can be written as:

$$p(k) = C_o + \sum_{i=1}^{m} C_i p(k-i) + G_1 u(k-1) + e_1(k) \tag{5}$$

$$f(k) = D_o + \sum_{i=1}^{m} D_i f(k-i) + E_1 u(k-1) + e_2(k) \tag{6}$$

where the modelling errors are denoted by $e_1(k)$ and $e_2(k)$; the unknown parameters in the matrices C_j, and j, j = 0,...,m are estimated recursively on line by the least squares error method on the basis of the available measurements.

The desired values for the position and force are related to the values $p^d(k)$ and $f^d(k)$ determined by equations (1) through (4) for the teleoperator. By applying appropriate coordinate transformation, which relates the Cartesian world coordinate system used in describing $\{p^d(k)\}$ and $\{f^d(k)\}$, to the Cartesian base coordinate system, the desired values $\{\bar{p}^d(k)\}$ and $\{\bar{f}^d(k)\}$ expressed in the base coordinate system can be determined.

Having obtained the desired values for the manipulator motion, an adaptive self-tuning controller can next be designed. It is determined by minimizing the following performance criterion:

$$I_k[u] = E\{\|p(k+1)-\bar{p}^d(k+1|k)\|^2_{(I-S)} + \|f(k+1)-\bar{f}^d(k+1|k)\|^2_S + \|u(k)\|^2_R\} \tag{7}$$

where the matrix S represents the selection matrix for determining when the force-servoing or position-servoing will be used. The norm refers to the usual generalized Euclidean norm. The expectation operation is conditioned on the available measurements.

The problem is solved by minimizing $I_k[u]$ in equation (7) subject to the plant equation constraints given by equations (5) and (6).

The minimizing controller $u^*(k)$ is specified by the following equation:

$$\hat{G}_1'(I-S)[\hat{C}_o+\sum_{i=1}^{m}\hat{C}_i p(k+1-i)+\hat{G}_1 u^*(k)-\bar{p}^d(k+1|k)]+$$

$$+\hat{E}_1' S[\hat{D}_o+\sum_{i=1}^{m}\hat{D}_i f(k-i)+\hat{E}_1 u^*(k)-\bar{f}^d(k+1|k)]+R u^*(k) = 0 \tag{8}$$

Equation (8) can be solved for the control input $u^*(k)$ in the feedback form. It should be observed that the desired trajectory must also be updated according to equations (1) through (4), with the model parameters.

Simulations studies are currently being conducted to demonstrate for the feasibility of the approach.

4. Conclusions

An adaptive self-tuning controller design has been presented for the operation of teleoperated manipulators. The approach is first to model the function of the teleoperator. Then, the controller design is performed on the basis of the desired trajectory determined. Simulation studies are currently being conducted using the approach.

Acknowledgement

This work has been supported in part by National Science Foundation Grant CDR 8500022.

5. References

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