Analytical Controller Design Strategy for Remotely Operated Systems with Long Time Delays

Ya-Dung Pan

Dept. of Elect. & Comp. Engr.
University of Arizona
Tucson, Arizona, 85721
U.S.A.
YPan@Helios.ECE.Arizona.Edu

François E. Cellier

Dept. of Elect. & Comp. Engr.
University of Arizona
Tucson, Arizona, 85721
U.S.A.
Cellier@ECE.Arizona.Edu

Abstract

This paper presents a new analytical controller design strategy for remotely operated systems, emphasizing on the stability of closed-loop control systems involving long time delays. A model-predictive control loop is constructed and implemented inside a digital controller to provide predictive state information, and an efficient model reduction method is applied to yield a reduced-order digital controller. This reduced-order digital controller is a model-reference adaptive controller that can control closed-loop systems with long time delays by following a specified performance. The Stanford arm is chosen as a simulation example.[1]

Keywords: time delay; teleoperation; model reduction; Smith predictor; Stanford arm.

1 Introduction

Processes need often to be controlled in a hostile environment. Examples include nuclear power plants, deep undersea exploration, and space research. For such operations, a remotely-controlled mechanical manipulator may be the right answer. However, the control problems to be mastered in remote mechanical manipulator control are formidable. One of the most serious problems is concerned with control loop stability due to time delays in the loop.

In practice, time delays are encountered in every type of system. They can be as short as a few nanoseconds, e.g. in electric transistor switching circuits; they can also be as long as several days, e.g. measurement delays in environmental pollution control. Other representative systems that include delays are mechanical systems with hydraulic or pneumatic transmission, computer-controlled systems with calculating or sampling operation, chemical processes involving thermal or distillatory processes, and control systems with remote or manual control.

Time delays can be caused by three different phenomena: the control algorithm, the measurement technique, and finally the plant itself. This paper mostly concerns itself with time delays caused by signal transmission. When a remotely controlled, human-operated robot arm is located aboard the forthcoming international Space Station Freedom in low Earth orbit, control is affected by a 2 *sec* time delay of the control and telemetry signals between the operator and the robot arm via the White Sands up-link facility and a geostationary satellite. Time delays can make the closed-loop system unstable when operated at high frequencies. It is therefore essential to study the stability of closed-loop mechanical manipulator control systems involving time delay, and to develop an effective controller strategy for such systems.

2 Controller Design

Because of the exponential term describing pure time delays in the overall transfer function of a closed-loop system, the standard state-space representation cannot be directly applied, and modern control design strategies cannot be immediately used. Yet, it is desirable to preserve the advantages of existing control strategies for delay-free systems.

Smith [4] proposed a second feedback loop to be constructed around the conventional controller. With this feedback structure, the time delay can be eliminated from the characteristic equation of the closed-loop system. The controller design for a system with time delay can then be based on the same system without delay. The overall transfer function

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of the closed-loop becomes

$$T(s) = \frac{C(s)G(s)}{1 + C(s)G(s)} \cdot e^{-sT_d} \qquad (1)$$

The detailed design strategy for the digital controller of a remotely operated system with time delay is then as follows:

1. Design an analog controller for the continuous system without delay.

2. Discretize the continuous system with a sample-and-hold device applied to all input signals.

3. Apply digital redesign to obtain modified feedback gains according to Kuo [3].

4. Approximate the pure time delay through multiples of the sampling time: The z-transform of a signal x(t) with delay time $T_d = n \cdot T_s$ is $\mathcal{Z}\{x(t - nT_s)\} = z^{-n}X(z)$. In the discrete system, it is thus easy to use state equations to represent time delays.

5. Reduce the controller order: Representing time delays in the above manner leads to high discrete system orders. To reduce the computational burden for the controller, model reduction methods have been developed to derive an adequate low-order controller model that preserves the main properties of the high-order model for the purpose of control. Eitelberg [1] proposed a suitable unbiased model reduction method based on minimizing the model error. This method works particulary well for situations with clusters of eigenvalues with similar real parts and different imaginary parts (e.g. problems with eigenvalues all spread along the imaginary axis).

3 Simulation Results

The Standford arm is chosen as the plant to be controlled with 0.4 *sec* signal delay time in each communiction path. A position control scheme is used around the non-linear continuous-time robot arm as a local control loop using the method proposed in [2]. A reduced-order discrete controller model developed in accordance with the method described in the previous section is applied. A program was written in ACSL to simulate the sampled-data non-linear control system. Fig. 1 shows the simulation results for joint 6 with unit step reference input with and without this controller. From the result, it can be seen that this model reference adaptive controller is well geared to control the closed-loop system with long time delay.

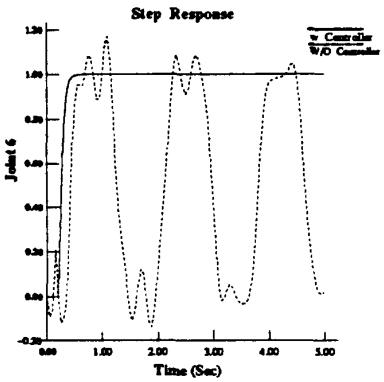

Figure 1: Step Response for Joint 6

4 Conclusions

For telescience experiments to be performed aboard the forthcoming Space Station Freedom, remotely controlled robot arms are needed since the astronauts' time is too precious for wasting it on routine operations. A major problem in this context are the inevitable time delays caused by relaying the transmitted control and telemetry signals via geostationary satellites. The long time delay can make the closed-loop system unstable when operated at high frequencies. In this paper, a simple but effective controller design strategy was proposed that allows us to apply comparatively high input frequencies to closed-loop systems with long time delays.

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