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Brief paper

Composite adaptive posicast control for a class of LTI plants with known delay[☆]

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ABSTRACT

Many potential applications of adaptive control, such as adaptive flight control systems, require that the controller have high performance, stability guarantees, and robustness to time delays. These requirements typically lead to engineering trade-offs, such as a trade-off between performance and robustness. In this paper, a new Composite Adaptive Posicast Control (CAPC) framework is proposed for linear time-invariant (LTI) plants with input-matched parametric uncertainties and known delay. The CAPC architecture uses a combination of several modifications to the typical direct model reference adaptive control (MRAC). The described approach is a nonlinear controller design that explicitly accounts for known time delay. The stability of the overall closed-loop system can be guaranteed using nonlinear analysis tools. The benefits of the CAPC approach are explored using a simulation of the longitudinal dynamics of a fixed-wing aircraft. Comparison studies are presented for 80 ms and 250 ms time delay cases.

1. Introduction

Adaptive control was developed primarily to contend with control in the presence of parametric uncertainties, see Ioannou and Sun (1996), Krstic, Kokotovic, and Kanellakopoulos (1995), Khalil and Grizzle (1996), Narendra and Annaswamy (1989) and has matured into a well-established field. Due to its direct ability to cope with parametric uncertainties, guarantees of robustness margins to gains are immediate. However, a robust behavior of an adaptive system in the presence of a delay is quite difficult to guarantee. This paper addresses the development of a new adaptive controller in the presence of delays that are not necessarily small.

Past work in the area of adaptive control in the presence of time-delay can be broadly grouped into three categories. The first of these pertains to adaptive control design and analysis assuming that no delays are present and appeal to the robustness of the controller. Examples of this category include Annaswamy, Jang, and Lavretsky (2008) and Cao and Hovakimyan (2010). The second category assumes the presence of a delay and develops a controller assuming that neither the plant parameters nor the time-delay is known (see for example, Fernandez, Ortega, & Begovich, 1988, Ge, Hong, & Lee, 2005, Krstic, 2010 and Zhang & Ge, 2007). The third category accommodates the presence of a delay, assumes that it is known, and incorporates this knowledge in a suitable manner in the control design. Examples of this category include Chou and Cheng (2003), Niculescu and Annaswamy (2003), Ortega and Lozano (1988) and Yildiz, Annaswamy, Kolmanovsky, and Yanakiev (2010). The contribution in this paper pertains to the third category, and combines the elements of a combined/composite model reference adaptive controller (CMRAC) proposed in Duarte and Narendra (1989), Duarte-Mermoud, Rioseco, and Gonzalez (2005), Lavretsky (2009a) and Slotine and Li (1989) and an adaptive Posicast controller (APC) proposed in Yildiz et al. (2010).

The CMRAC is a unique adaptive controller that combines elements of both identification and control into parameter estimation by making use of both estimation and tracking errors in the adaptive law. While CMRAC has been proven to establish only stability, extensive simulation studies have shown significantly improved transients across the board, due perhaps to the parameter estimation being carried out in a different manifold than in a standard MRAC. Since improved transients, with attenuated high-frequency content, can directly lead to a better accommodation of delays and unmodeled dynamics, we include CMRAC as one of the main ingredients of our proposed design. The APC approach in Yildiz et al. (2010) is an adaptive extension of the Smith Predictor, which uses a plant model to predict the future outputs of the plant and then

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uses this prediction to cancel the effect of delay on the system. This methodology is included in our control design, due to its ability to accommodate large delays, as demonstrated in Yildiz, Annaswamy, Yanakiev, and Kolmanovsky (2007, 2008) with a successful validation in several applications with improved performance. We also incorporate the use of time-varying adaptive gains via a bounded forgetting factor (see Chapter 4 in Slotine & Li, 1991 and Narendra & Annaswamy, 1989), which has also been observed to lead to improved transients and therefore a better accommodation of delays.

A composite adaptive posicast controller (CAPC) incorporating CMRAC, APC, and bounded-gain-forgetting (BGF) adaptive gains is proposed in this paper and is shown to have a time delay margin that is bounded away from zero. The advantage of the proposed CAPC is then illustrated using a full-scale simulation study using a model of the F-16 short period dynamics. This study demonstrates that the CAPC is able to withstand a significantly larger delay than that with the classical MRAC. The fact that the delay is explicitly included in the control design suggests that the delay that can be accommodated by this design may be significantly larger than those in category 1. While adaptive controllers designed to accommodate unknown parameters and unknown delay such as in Krstic (2010) are more general, the controller structure can become overly complex, and for many problems the time delay in the system can be easily measured. As mentioned earlier, other approaches such as Ge et al. (2005) and Zhang and Ge (2007) have been suggested in the past as well, where a known upper bound on the time-delay is used in the control design. While the CAPC described here requires the knowledge of the actual delay, unlike the above papers, it does not require high gains or discrete switching, both of which may lead to chattering and excite unmodeled dynamics. It should also be pointed out that no assumptions are made regarding the norm of the delayed state with respect to the actual state as in Chou and Cheng (2003).

The outline of the paper is as follows. Section 1 gives some introduction and background references. In Section 2, we state the problem for a multi-input multi-output (MIMO), state variables accessible plant with input-matched uncertainties. Section 3 describes the modifications to MRAC in detail and how those modifications can be combined to generate the composite adaptive posicast controller. Section 4 gives simulation results for the longitudinal dynamics of a fixed-wing aircraft. A summary is given in Section 5. In the Appendix we present proofs of results used throughout the paper.

2. Problem statement

Consider a MIMO, state variables accessible system of the form

$$\dot{x}_p(t) = A_p x_p(t) + B_p \Lambda u(t-\tau), \tag{1}$$

where $A_p \in \Re^{n\times n}$ is constant and *unknown*, $x_p \in \Re^n$, $u \in \Re^m$, and the following assumptions hold:

Assumption 1. The matrix $B_p \in \Re^{n\times m}$ is constant, *known*, and full-rank,

Assumption 2. The matrix $\Lambda \in \Re^{m\times m}$ is *unknown*, diagonal, constant, and has positive elements,

Assumption 3. The time delay τ is *known*.

Assumptions 1 and 2 suggest that the uncertainty in actuation is limited to a scaling of components of the control input u. This uncertainty can be thought of as a loss of control effectiveness when the diagonal terms of $\Lambda, \lambda_{ii} \in (0, 1]$. Matched linear-in-parameters uncertainties of the form $\Theta_l^T \Phi(x_p)$ can also be accommodated by the methods described below, but will not be addressed in this paper. The goal is to track a reference command $r(t)$ in the presence of the unknown A_p, Λ, and the known τ. The system output is given by

$$y(t) = C_p x_p(t), \tag{2}$$

where $C_p \in \Re^{m\times n}$ is a constant known matrix and the output tracking error is given by $e_y(t) = y(t) - r(t-\tau)$, where $e_y(t)$, $y(t)$, and $r(t) \in \Re^m$. Augmenting (1) with the integrated output tracking error $e_{y_I}(t) \in \Re^m$, where $\dot{e}_{y_I}(t) = e_y(t)$, leads to the extended open-loop dynamics

$$\dot{x}(t) = Ax(t) + B\Lambda u(t-\tau) + B_c r(t-\tau), \tag{3}$$

where the extended system state vector $x(t) \in \Re^N$, where $x(t) = \begin{bmatrix} x_p^T(t) & e_{y_I}^T(t)\end{bmatrix}^T$ and thus $N = n + m$. The extended open-loop system matrices are given by

$$A = \begin{bmatrix} A_p & 0 \\ C_p & 0 \end{bmatrix}, \qquad B = \begin{bmatrix} B_p \\ 0 \end{bmatrix}, \qquad B_c = \begin{bmatrix} 0 \\ -I \end{bmatrix}, \tag{4}$$

and the extended system output

$$y(t) = \begin{bmatrix} C_p & 0 \end{bmatrix} x(t) = Cx(t), \tag{5}$$

where $A \in \Re^{N\times N}$, B and $B_c \in \Re^{N\times m}$, and $C \in \Re^{m\times N}$.

Assumption 4. There exists a constant, possibly unknown gain matrix θ_τ such that $A_m = A - B\Lambda\theta_\tau^T$ and A_m is Hurwitz.

One can translate these matching conditions into conditions involving A_p, B_p, and C_p by breaking up A_m into a block matrix with a definition similar to that of A in (4).

The reference model is given by

$$\dot{x}_m(t) = A_m x_m(t) + B_c r(t-\tau), \tag{6}$$

where $x_m \in \Re^N$ and $A_m \in \Re^{N\times N}$. Note that the known time delay is included in the reference model. Then the system dynamics can be rewritten as

$$\dot{x}(t) = A_m x(t) + B\Lambda\left(u(t-\tau) + \theta_\tau^T x(t)\right) + B_c r(t-\tau). \tag{7}$$

The goal is to design a suitable control input $u(t)$ so that the output $y(t)$ tracks the reference model output $y_m(t) = Cx_m$ or equivalently, the convergence of the model-tracking error to 0. Note that this implies that $y(t)$ tracks $r(t-\tau)$ whenever $r(t-\tau)$ is asymptotically constant.

3. Modifications to MRAC

The CAPC approach comprises several modifications to a standard MRAC approach. The overall control structure is that of a linear quadratic regulator (LQR) baseline controller augmented by a direct adaptive posicast controller as well as an indirect adaptive controller. In both the direct and indirect adaptive parts, time-varying adaptive gains are utilized. In this section, the design of each of these modifications is described in detail.

3.1. Direct adaptive posicast controller

The APC is an adaptive extension of the Smith Predictor, an approach that originated as a method to deal with systems with large delays. The APC method also brings in ideas from finite spectrum assignment, see Manitius and Olbrot (1979). The main idea in this approach is to predict the future output of the plant using a plant model, and then use this prediction to cancel the effect of the time delay on the system. It does this by adding another set of adaptive parameters, which leads to an additional term in the control law.

Consider a control input of the form

$$u(t) = -\hat{\theta}_\tau^T(t) x(t+\tau), \tag{8}$$

where $\hat{\theta}_\tau(t)$ are time-varying adaptive parameter estimates, and $x(t+\tau)$ is the system state positively forecasted (hence "posicast")