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Research article

A solution for enhancement of transient performance in nonlinear adaptive control: Optimal adaptive reset based on barrier Lyapunov function

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A B S T R A C T

In this paper, an adaptive controller based on barrier Lyapunov function combined with an optimal reset rule is devised in order to improve the transient performance of nonlinear adaptive control. A novel reset rule is designed such that the estimated parameters of the adaptive controller jump to the optimal values in a way that optimizes a cost function representing the transient performance index. It is proved that asymptotic tracking is achieved and the output remains in a desired bound by ensuring boundedness of the barrier Lyapunov function. Besides, the convergence rate is increased by resetting the estimated parameters to optimal values. A regularly referred example is simulated to demonstrate the effectiveness of the proposed method and the results are compared with the existing investigations.

1. Introduction

Adaptive control as a popular method for systems with parametric uncertainties, could mostly achieve the asymptotic performance of the error signals, as in Refs. [1,2]. However, the transient performance in adaptive control systems has remained an open problem. Large transient error may occur at the beginning of a control process and especially when there is a time-varying parameter. Therefore, in order to have satisfactory results, both steady state and transient responses must be considered in the design procedure. It is important to note that, in adaptive control systems, poor transient performance may occur although the asymptotic performance can be achieved perfectly.

Some improvements in the transient performance of adaptive control have been made which most of them are only applicable to the linear systems [3]. In Ref. [4], an approach called L1 adaptive control was proposed in order to have fast adaptation by inserting a low pass filter in the feedback loop. However, as it was deeply discussed in Ref. [5], this filter deteriorates the performance and robust stability bounds compared to the standard Model Reference Adaptive Control (MRAC). On the other hand, intelligent methods such as fuzzy systems have also been noticed these days [6]. The authors in Refs. [7,8] have claimed that using fuzzy logic and genetic algorithm may improve the transient response of MRAC. They have illustrated some simulations but the results suffer from the lack of analytical support. Some efforts have also been done by applying the projection mechanism to improve the transient response as in Refs. [9,10]. Even though the projection algorithm is capable of avoiding the estimated parameter from going outside of a predetermined range, it needs to have a priori knowledge of the scope of the unknown parameter.

Among these methods, the multiple model adaptive control (MMAC) is the most famous one [11–13]. MMAC includes multiple estimators and controllers in which a supervisor selects the controller whose estimator has the best estimation error. Even though the superiority of MMAC over the traditional adaptive control has been shown in the literature, it suffers from some drawbacks. Firstly, the existence of multiple estimators makes the overall closed-loop system too complex in the structure. In MMAC, each estimator has different initial value distributed on the span of uncertainty. A better estimation needs more models which in turn increases the complexity of the structure. Secondly, in MMAC some basic performance indices, such as the overshoot and the rise time have not been discussed clearly.

In addition to the previously mentioned methods, some researchers have tried to introduce some bounds on the output of the closed loop system. Trajectory initialization [14], Prescribed Performance Bound [15,16] and Barrier Lyapunov Functions (BLF) [17,18] are some of them. The BLF which was first proposed in Ref. [19] is a function that goes to infinity when the states of the system approach some limits. Unlike the usual quadratic Lyapunov function, the BLF can handle the control problems including the output constraint.

Recently, reset control design has attracted researchers due to its

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capability of improving transient behavior [20,21]. In such controllers, the states of the controller reset according to a specific principle. Due to the capability of reset control in improving transient behavior, using this mechanism in adaptive control was suggested in Refs. [22,23], in which the estimated parameters were reset based on MMAC. It means that a number of models with fixed parameters are checked online for selecting the parameter that causes a negative jump in the control Lyapunov function. The drawbacks of MMAC were mentioned earlier. In Ref. [24], in order to have a suitable steady state and transient responses simultaneously, a logic-based switching and resetting mechanism was presented for the adaptation law. In that work, when the supervisor detects that parameter estimation is going to be far away from its range, the resetting action will occur. However, besides detecting a proper moment for resetting, what is so important in the reset control is finding a suitable point for the after reset value. In Ref. [24], the parameter estimation would be reset to a predetermined value. This procedure could only avoid the parameter estimation from going so far away, not lead to an optimal point.

In this paper, an Optimal Adaptive Reset Control (OARC) based on the BLF has been proposed to overcome the above mentioned problems in the nonlinear adaptive control of strict feedback form systems.

The first novelty of this paper is designing an optimal reset rule to improve the transient performance of nonlinear adaptive control systems. In fact what makes it difficult to reach at the suitable transient and steady state response simultaneously, is the counteraction between the control error and the parameter estimation error. This difficulty is more prominent at the beginning of the process when the control error is large. Therefore, even if the adaptation starts with an appropriate initial estimation, the large control error will cause the parameter estimation to be far regarding its real value. This, in turn causes the control error deviate from its right direction. Here, the reset mechanism corrects the controller when the control error is probably going beyond its predetermined threshold. After determining the appropriate time to reset the parameter estimation, the critical question is where it should be reset. This is an essential question that researchers have not considered implicitly, till now. Actually, resetting phenomenon without having a plan capable of directing the closed loop system to a proper situation, may deteriorate the performance and even place the closed loop system in the risk of instability. For this reason, here an optimal mechanism has been applied to find a target point that the parameter estimation should be reset to. At the reset time, an online gradient based optimization calculates the after reset values by minimizing a cost function which includes an index for the transient performance. The estimated parameter may reset to its optimal value if there is also a negative jump in the Lyapunov function. This procedure makes the system capable of governing both the asymptotic and the transient performance of the system.

The second novelty of this paper is ensuring a certain transient bound on the output signal in the adaptive reset control problem. This purpose has been achieved using the BLF idea. A function called BLF is selected which goes to infinity when the error signal approaches some limits. Then adaptive backstepping procedure has been employed based on this Lyapunov function. As long as the initial condition satisfies some limit, the output signal will remain in a desired bound.

The proposed BLF-based OARC is verified using the simulation. The results illustrate the superiority of the method in improving the transient performance and ensuring the transient bound of nonlinear adaptive control.

This paper is organized as follows: Section 2 covers the problem formulation and preliminaries. The complete design of BLF based OARC is given in Section 3. Section 4 is allocated to simulation results, and finally, Section 5 presents conclusions of the paper.

2. Problem statement and preliminary

Consider the following uncertain nonlinear system in the strict-feedback form:

$$\begin{aligned}
\dot{x}_1 &= x_2 + \varphi_1(x_1)^T\theta \\
\dot{x}_2 &= x_3 + \varphi_2(x_1, x_2)^T\theta \\
&\vdots \\
\dot{x}_{n-1} &= x_n + \varphi_{n-1}(x_1, x_2, \ldots, x_{n-1})^T\theta \\
\dot{x}_n &= \beta(x)u + \varphi_n(x)^T\theta
\end{aligned} \tag{1}$$

where $x = [x_1,\ x_2,\ \ldots,\ x_n] \in R^n$ and $u \in R$ are the state vector of the system and the control input, respectively. $\theta \in R^m$ is the unknown constant parameters vector, $\varphi_1,\ \varphi_2,\ \ldots,\ \varphi_n$ and β are known nonlinear smooth functions. Besides, it is assumed that $\beta(x) \neq 0\ \ \forall x$. The following adaptive backstepping controller would stabilize this system [25]:

$$u = \frac{\alpha_n(x, \hat{\theta}) + x_{1desired}^{(n)}}{\beta(x)} \tag{2}$$

$$\dot{\hat{\theta}} = \Gamma\tau_n(x, \hat{\theta}) \tag{3}$$

where $\Gamma>0$ is the adaptation gain matrix, $\hat{\theta}$ is the estimate of θ. The error variable z_i, the stabilizing functions α_i and tuning functions τ_i in adaptive backstepping technique are given by

$$z_1 = x_1 - x_{1desired}, \quad z_i = x_i - x_{1desired}^{(i-1)} - \alpha_{i-1} \tag{4}$$

$$\alpha_i = -c_i z_i - z_{i-1} - w_i^T\hat{\theta} + \sum_{k=1}^{i-1}\left(\frac{\partial\alpha_{i-1}}{\partial x_k}x_{k+1} + \frac{\partial\alpha_{i-1}}{\partial x_{1desire}^{(k-1)}}x_{1desired}^{(k)}\right) + \frac{\partial\alpha_{i-1}}{\partial\hat{\theta}}\Gamma\tau_i + \sum_{k=2}^{i-1}\frac{\partial\alpha_{k-1}}{\partial\hat{\theta}}\Gamma w_i z_k \tag{5}$$

$$\tau_i = \tau_{i-1} + w_i z_i \tag{6}$$

$$w_i = \varphi_i - \sum_{k=1}^{i-1}\frac{\partial\alpha_{i-1}}{\partial x_k}\varphi_k \tag{7}$$

$$i = 1,\ \ldots,\ n$$

Theorem 1. [25] The closed loop adaptive system consisting of plant (1) and controller (2)–(3) has a globally uniformly stable equilibrium and $\lim_{t\to\infty} z(t) = 0$.

Assumption 1. Suppose that x_1 is required to remain in the set $|x_1| \le k_c\ \ \forall\ t \ge 0$, where k_c is a positive constant. For any given k_c, there exist positive constant A such that $|x_{1desired}| \le A < k_c$, $|\dot{x}_{1desired}| \le A_1, \ldots, |x_{1desired}^{(n)}| \le A_2$.

Definition 1. A Barrier Lyapunov Function is a function $V(x)$ defined on an open region $\mathscr{D}$, that has the following properties [19]:

- It is continuous and positive definite.
- It has continuous first order partial derivatives at every point in $\mathscr{D}$.
- $V(x) \to \infty$ as x approaches the boundary of $\mathscr{D}$.
- $V(x(t)) \le b \quad \forall\ t \ge 0$ along the solution of the system for $x(0) \in \mathscr{D}$ and some positive constant b.

The control objectives are as follows:

1) All the closed loop signals are bounded and tracking error defined as $e = x_1 - x_{1desired}$ converges asymptotically to zero.
2) Transient performance is improved in terms of the convergence rate.
3) The desired constraint on x_1 in Assumption 1 is satisfied.

3. BLF based OARC design and stability analysis

The control objectives have been pursued in this section. Firstly, an adaptive backstepping design based on barrier Lyapunov function has been designed in order to satisfy the first and the third items of the control objectives. Secondly, an optimal reset law has been designed for applying to the calculated adaptive controller to improve the transient