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Research article

Adaptive integral robust control and application to electromechanical servo systems☆

Wenxiang Deng[a], Jianyong Yao[a,b,*]

[a] School of Mechanical Engineering, Nanjing University of Science and Technology, Nanjing 210094, China
[b] Hebei Provincial Key Laboratory of Heavy Machinery Fluid Power Transmission and Control, Qinhuangdao 066004, China

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ABSTRACT

This paper proposes a continuous adaptive integral robust control with robust integral of the sign of the error (RISE) feedback for a class of uncertain nonlinear systems, in which the RISE feedback gain is adapted online to ensure the robustness against disturbances without the prior bound knowledge of the additive disturbances. In addition, an adaptive compensation integrated with the proposed adaptive RISE feedback term is also constructed to further reduce design conservatism when the system also exists parametric uncertainties. Lyapunov analysis reveals the proposed controllers could guarantee the tracking errors are asymptotically converging to zero with continuous control efforts. To illustrate the high performance nature of the developed controllers, numerical simulations are provided. At the end, an application case of an actual electromechanical servo system driven by motor is also studied, with some specific design consideration, and comparative experimental results are obtained to verify the effectiveness of the proposed controllers.

1. INTRODUCTION

HIGH performance tracking controller design for uncertain nonlinear system is an unending pursuit in control community. How to handle various modelling uncertainties, which can be categorized into parametric uncertainties and additive disturbances [1,2], is the research hotspot that continues to challenge control theoreticians and engineers, since these uncertainties are always bring undesirable influence on the performance specification. To name a few, see hydraulic motion platforms [3,4], suspension vehicles [5,6], motor drive systems [7–10]. To deal with this troublesome problem, lots of design methods have been proposed and integrated during the last three decades for various classes of uncertain nonlinear systems. For example, adaptive control [11,12] is often considered to be the prior choice if modelling uncertainty can be linearly parameterized (i.e., parametric uncertainty); nonlinear robust control, such as sliding mode control [13,14], on the other hand, has been widely concerned to be the method of choice to handle additive disturbance (i.e., unstructured disturbance) with assuming that the disturbance can be upper bounded by a prior known norm-based inequality. These two fundamental methodologies can both theoretically achieve asymptotic tracking performance in their corresponding circumstances. However, in many practical systems, the mathematical model is poorly known or heavily uncertain, that is to say, the uncertain nonlinear system both exists considerable parametric uncertainties and unstructured disturbances, which makes matters even more difficult and complicated. Specifically, additive disturbances may cause adaptive system unstable and widely discussed solutions are various robust adaptive controls [10,15–17] which however, can only ensure the tracking error be driven into a residual bounded set with size of the order of the disturbance magnitude, and the excellent asymptotic tracking performance will disappear in this case; on the other hand, parametric uncertainties may lead to large design conservatism of nonlinear sliding mode control, even the design prerequisite, i.e., a prior known bound of uncertainty, no longer exists. Moreover, although sliding mode control could achieve excellent asymptotic tracking control, it typically results in a discontinuous control effort, which may cause chattering problem in physical systems. In addition, sliding mode controllers are often hard to tune, and may waste energy and cause unnecessary machine wear due to their aggressive nature, and may not be robust in the face of time-varying system parameters. To avoid these disadvantages, the authors in [18] proposed a judicious robust

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[*] Corresponding author at: School of Mechanical Engineering, Nanjing University of Science and Technology, Nanjing 210094, China
E-mail addresses: wxdeng_njust@163.com (W. Deng), jerryyao.buaa@gmail.com (J. Yao).

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feedback control strategy called the robust integral of the sign of the error (RISE) to accommodate for sufficiently smooth bounded disturbances. As long as the matched additive disturbance is smooth enough with known bounds of its time derivatives, the RISE feedback control can achieve asymptotic tracking performance. More important, the resulting control effort is always keeping continuous, and thus the chattering problem is greatly alleviated. In recent years, the RISE feedback control methodology has been greatly developed. In [2,19], gradient adaptive and modular adaptive extension of RISE control were developed respectively. The authors in [20] proposed a RISE-based adaptive backstepping design method for uncertain nonlinear systems with mismatched parametric uncertainties, and the authors in [21] gave an integration of direct adaptive and indirect adaptive control with RISE feedback. Above adaptive designs with RISE feedback control reveal that the inclusion of an adaptive feed-forward term can reduce the need for high-gain feedback and improve the tracking performance compared with the traditional RISE feedback controller [18]. In addition, RISE-based control was also successfully applied to various physical nonlinear systems [22–26]. For a more in depth review of RISE-based control approaches of uncertain nonlinear systems, the reader is referred to the related references in the aforementioned literatures.

However, all above RISE feedback designs are based on a common assumption that the matched additive disturbances are C^2 with bounded time derivatives, and the bounds have to be definitely known [2,18–26]. A significant outcome of this assumption is that one can use the bound information to build a unique continuous term with a judicious RISE feedback gain, which can perfectly accommodate for sufficiently smooth disturbances to result in asymptotic tracking performance. The prior known bounds on the time derivatives of disturbances are the basis of the choice of RISE feedback gain and an important clue to guarantee the stability of the closed-loop system. However, this specific assumption of known bounds imposes a strong restriction on the considered additive disturbance, which is often not satisfied with physical systems. Assuming uncertain disturbance be C^2 with bounded time derivatives is acceptable, but how does one investigate the definite bounds of its time derivatives in practice? Typically, the additive disturbance is poorly known, to seek exact bounds of its time derivatives is thus very difficult and complicated, even impossible in practice, due to the complexity of structure of the disturbance. Even if the bounds can sometimes be obtained, they are usually very conservative. Previous RISE-based controller just utilized a fixed RISE feedback gain. However, too large selection of the RISE feedback gain will lead to severe design conservatism while too small selection may cause performance deterioration and even instability.

In this paper, we present a new development of RISE feedback control for a class of uncertain nonlinear systems in which the RISE feedback gain is adopted online via an appealing adaptation method. With this design, the prior needs for knowing the upper bounds of the time derivatives of the additive disturbances is eliminated. Asymptotically stable feature of the closed-loop system has been proved via Lyapunov analysis. The resulting controller possesses the advantages of continuous control effort, automated gain tuning without the loath and conservative investigation on the disturbances, and asymptotic tracking capability, all these features are the pressing demands of industrial applications. Comparing with the traditional RISE feedback design, the contributions can be summarized as: the proposed method greatly reduces the design conservatism, and is more feasible for physical systems. In addition, motivated by the desire to reduce the need for high-gain feedback, we also consider the case that the uncertain nonlinear system both exists parametric uncertainties and additive disturbances, and propose an adaptive compensation integrated with the proposed adaptive RISE feedback control to further reduce the design conservatism. Here, the adaptation is used to compensate for parametric uncertainties and the proposed adaptive RISE feedback is taken as a robustifying mechanism to compensate for additive disturbances, hence recovering the asymptotic tracking property of the traditional adaptive controller when disturbance-free. With the help of adaptive compensation, the lumped disturbance is reduced and thus the need for high-gain RISE feedback is alleviated. A Lyapunov-type stability analysis is also present to prove the proposed robust adaptive controller yields semi-global asymptotic tracking.

To illustrate the effectiveness of the proposed controllers, an application to electromechanical servo system driven by electrical motor is investigated. Electromechanical servo is widely employed in industrials, examples can be found in [8,10]. Various modelling uncertainties are the main obstacle of developing advanced controllers for electromechanical servo systems. The methods in [9,10] are a combination of adaptive compensation and nonlinear robust control, which can only guarantee the tracking error be bounded. Although the controllers in [8] achieved asymptotic tracking performance with the help of RISE feedback, the bound information of the additive disturbance should be known. How to handle various uncertainties and disturbances for electromechanical servo systems with as weak as possible assumptions is still an open issue in control community. In this application, the comparative experimental results show that the proposed controllers are effective and suitable choices to complete this control mission.

This paper is organized as follows. Section II gives the problem statement. Section III constructs the adaptive RISE feedback design procedure and its theoretical results. Section IV presents an adaptive extension when system exists parametric uncertainties. Section V carries out the comparative simulation and experimental certification. And some conclusions can be found in section VI.

2. Problem statement

In this paper, we first consider a class of nth-order, single-input–single-output (SISO) nonlinear systems having the general form:

$$\begin{aligned} &\dot{x}_i = x_{i+1},\ i = 1, \dots, n-1, \\ &\dot{x}_n = u - F(x, t) + d \\ &y = x_1 \end{aligned} \tag{1}$$

where $x(t) := [x_1(t), x_2(t), \dots, x_n(t)]^T \in R^n$ denotes the system state, $y(t) \in R$ is the output, $u \in R$ is the control input, $F(x, t)$ is a smooth nonlinear function, and $d(t)$ represents the lumped additive disturbances. We make the following assumption regarding the considered uncertain nonlinear system.

Assumption 1. $d(t) \in C^2$, $|\dot{d}(t)| \le \delta_1$ and $|\ddot{d}(t)| \le \delta_2$, where δ_1 and δ_2 are unknown positive constants.

Remark 1. This assumption is very common in traditional RISE based design. However, in previous RISE feedback control, δ_1 and δ_2 have to be known for controller design and stability analysis. This prerequisite may lay a strong restriction on the considered nonlinear systems and be not suitable for physical applications. In this paper, we just need the time derivatives of $d(t)$ to be bounded, and this greatly release the strength of assumption.

Given the desired smooth motion trajectory $y_d = x_{1d}(t)$, the objective is to synthesize a continuous control input u such that the output $x_1 \to x_{1d}(t)$ as $t \to \infty$.

Assumption 2. The desired position trajectory $y_d \in R$ is smooth