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Adaptive backstepping control for an engine cooling system with guaranteed parameter convergence under mismatched parameter uncertainties

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A B S T R A C T

This paper proposes a novel adaptive backstepping control for a special class of nonlinear systems with both matched and mismatched unknown parameters. The parameter update laws resemble a nonlinear reduced-order disturbance observer. Thus, the convergence of the estimated parameter values to the true ones is guaranteed. In each recursive design step, only single parameter update law is required in comparison to the existing standard adaptive backstepping techniques based on overparametrization and tuning functions. To make a fair comparison with the overparametrization and tuning function methods, a second-order nonlinear engine cooling system is taken as a benchmark problem. This system is subject to both matched and mismatched state-dependent lumped disturbances. Moreover, the proposed model-based controllers are compared with a classical PI control by using performance metrics, i.e., root-mean-square error and control effort. The comparative analysis based on these performance metrics, simulations as well as experiments highlights the effectiveness of the proposed novel adaptive backstepping control in terms of asymptotic tracking, global stability and guaranteed parameter convergence.

1. Introduction

Backstepping is one of the most popular design methods that not only guarantees global stability but also excellent tracking performance for a broad class of strict-feedback systems. This is achieved by defining a Lyapunov function at each design step in a recursive fashion, cf. Isidori (1995), Krstic, Kanellakopoulos, and Kokotovic (1995), Khalil (2002), Zhou and Wen (2008), Ioannou (2006). Backstepping control offers the advantage to design control laws for the system under the influence of mismatched uncertainties too. In adaptive backstepping control, the underlying idea is to design a dynamic part of the feedback that serves primarily as a parameter update law with which the static part is continuously updated, see Isidori (1995), Krstic et al. (1995), Khalil (2002), Zhou and Wen (2008), Ioannou (2006), Aschemann and Schindele (2014), Zhou and Wang (2005). A perfect tracking behavior and robustness can be addressed with the inclusion of unknown parameters and lumped disturbances in the control law. These lumped disturbances include parameter uncertainty, modeling errors and other immeasurable effects. In observer-based control, a disturbance observer is employed to estimate external disturbances. Examples in different control applications, where a disturbance observer estimates external disturbances, can be found in the works of Kim (2002), Chen, Ballance, Gawthrop, and O'Reilly (2000), Huang and Messner (1998), Chen (2003). For a strict feedback nonlinear system, an adaptive neural network control, adaptive fuzzy backstepping control and disturbance observer based RBF neural network using backstepping design are proposed in Zhang, Ge, and Hang (2000), Hou and Fei (2015) and Rong, QingXian, and ChangSheng (2010), respectively. Likewise, in Ge and Wang (2003), the robust adaptive backstepping tracking for time-varying uncertain nonlinear systems is investigated using unknown control coefficients. For matched disturbances, a control design based on adaptive backstepping control has attracted ever increasing interest, cf. Aschemann and Schindele (2014), Huang and Ching (2009), Uddin and Nam (2009), Morishita and Souza (2014). Nonetheless, systems with mismatched lumped disturbances are commonly encountered in everyday life. For example, immeasurable drift in the velocity component of helicopters, cf. Yue, Hai, Hong, and Tai (2013), crane systems, see Vázquez, Fridman, Collado, and Castillo (2015), and immeasurable state-dependent as well as ambient temperature dependent heat transfers into and out of the engine cooling system, see Aschemann et al. (2011), Butt et al. (2015), Wang and Wagner (2015).

One of the biggest advantage of an adaptive backstepping control is guaranteed asymptotic stability in spite of the speed of

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convergence of estimated lumped disturbances to their true values. However, the question of speed of convergence of the unknown parameters as well as the lumped disturbances to their true values is always a concern, cf. Lin and Kanellakopoulos (1999). Usually parameter update laws are governed by the error dynamics only, which could either lead to slow convergence or it may lead to non-physical values of the parameters when the input signal is not sufficiently excited, cf. Lin and Kanellakopoulos (1999), Slotine and Li (1991). Although the control aim is achieved, the estimated values of the unknown parameters may lead to a misinterpretation of the influence of parameters on the overall system behavior. Therefore, in this paper the choice of the parameter update laws for unknown matched and mismatched parameters are addressed. The parameter update laws are similar to a nonlinear reduced-order disturbance observer and allow to estimate both the matched and mismatched parameters with an excellent accuracy.

Although an observer-like parameter update law is proposed in Yue et al. (2013) for a helicopter system, the parameter update law for both the matched as well as mismatched lumped disturbances is designed in the last step of the adaptive backstepping control. Furthermore, no systematic procedure related to the asymptotic convergence of the closed-loop dynamics is addressed therein. In this work, on the contrary, the parameter update law is proposed at the first occurrence of the unknown parameter in each design step and the closed-loop stability is thoroughly analyzed.

This paper is structured as follows: In Section 2, a novel adaptive backstepping control is presented for a special class of nonlinear systems under the influence of both matched and mismatched unknown parameters. In Section 3, the approach is applied to an engine cooling system as a benchmark problem. In an engine cooling system, the parameter uncertainties appear in the form of state-dependent lumped disturbances. To make a fair comparison, the performance of the proposed adaptive backstepping control in terms of trajectory tracking and parameter convergence is compared with the standard overparametrization, tuning function methods and a classical PI-controller. Furthermore, the simulation analysis and experimental results on a dedicated test-rig are presented as well. Finally, conclusions are drawn in Section 4.

2. Adaptive backstepping control

In this paper, a new design approach is presented for nonlinear systems transformable into the following form

$$\begin{aligned} \dot{x}_i &= f_i(\boldsymbol{x}) + \Phi_i(x_i)\theta_i, \quad 1 \le i \le n-1, \\ \dot{x}_n &= f_n(\boldsymbol{x}) + g(\boldsymbol{x})u + \Phi_n(x_n)\theta_n, \end{aligned} \tag{1}$$

where $\boldsymbol{x} = [x_1, \ldots, x_n]^T \in \mathbb{R}^n$ denotes the state vector of the nonlinear system, $u \in \mathbb{R}$ is the control input, and $f_i(\cdot) \in \mathbb{R}$ and $g(\cdot) \in \mathbb{R}$ are smooth nonlinear functions. Furthermore, the nonlinear functions $\Phi_i(\cdot)(1 \le i \le n)$ are assumed to be continuously differentiable and unequal to zero. The parameter $\theta_i(1 \le i \le n)$ is unknown, and θ_i, $i < n$ and θ_n represent mismatched parameter uncertainties as well as a matched parameter uncertainty, respectively. To proceed with the design of the novel adaptive backstepping control, the following assumptions are introduced:

Assumption 1. All states $x_i(t)$ of the nonlinear system (1) are measurable.

Assumption 2. The nonlinear functions $\Phi_i(x_i)$ and $g(\boldsymbol{x})$ are known and not equal to zero for any $x(t)$.

To illustrate the idea of the novel adaptive backstepping, the analysis is confined to a second-order system under the influence of both mismatched θ_1 and matched θ_2 parametric uncertainties

$$\begin{aligned} \dot{x}_1 &= x_2 + \Phi_1(x_1)\theta_1, \\ \dot{x}_2 &= f(\boldsymbol{x}) + g(\boldsymbol{x})u + \Phi_2(x_2)\theta_2, \end{aligned} \tag{2}$$

where $\boldsymbol{\theta} = \left[\theta_1, \theta_2\right]^T \in \mathbb{R}^2$ is a constant unknown vector and $\Phi_i(\cdot) \in \mathbb{R}$ are known continuously differentiable nonlinear functions. As the novel approach involves parameter update laws similar to a nonlinear reduced-order disturbance observer, integrator disturbance models are introduced for θ_1 and θ_2

$$\dot{\theta}_1 = 0, \quad \text{and} \quad \dot{\theta}_2 = 0. \tag{3}$$

Note that these disturbance variables are affected within the parameter update laws by the tracking errors. In the following, the adaptive backstepping design procedure for the system (2) is elaborated.

*Step-1:*The tracking error e_1 and its corresponding first time derivative are defined as follows

$$e_1 = x_1 - x_d, \quad \text{and} \quad \dot{e}_1 = \dot{x}_1 - \dot{x}_d, \tag{4}$$

where x_d denotes the desired trajectory. Since the mismatched parameter θ_1 is unknown, a quadratic control Lyapunov function can be chosen as

$$V_1 = \frac{1}{2}e_1^2 + \frac{1}{2}\gamma_1^{-1}\tilde{\theta}_1^2 > 0, \tag{5}$$

with $\tilde{\theta}_1 = \theta_1 - \hat{\theta}_1$. Here, $\hat{\theta}_1$ represents the estimated value of the parameter θ_1. Furthermore, a strictly positive adaptation gain is denoted by γ_1. The corresponding first time derivative of V_1 becomes

$$\dot{V}_1 = e_1(\dot{x}_1 - \dot{x}_d) + \gamma_1^{-1}\tilde{\theta}_1\frac{d}{dt}\tilde{\theta}_1. \tag{6}$$

According to the standard backstepping control procedure, a virtual control input x_{2d}, an error function e_2 and a time derivative of the parameter $\tilde{\theta}_1$ are introduced, i.e.,

$$\begin{aligned} x_{2d} &= \alpha + \dot{x}_d, \\ e_2 &= x_2 - x_{2d}, \\ \dot{\tilde{\theta}}_1 &= \dot{\theta}_1 - \dot{\hat{\theta}}_1 = -\dot{\hat{\theta}}_1. \end{aligned} \tag{7}$$

Here, the virtual control input x_{2d} comprises a stabilizing function α and the first time derivative of the desired trajectory. Substitution of (2) and (7) in (6) results in

$$\dot{V}_1 = e_1\underbrace{\left(\alpha + \Phi_1(x_1)\hat{\theta}_1\right)}_{-k_1e_1} + e_1e_2 + \underbrace{\left(e_1\Phi_1(x_1) - \gamma_1^{-1}\dot{\hat{\theta}}_1\right)}_{-k_2\tilde{\theta}_1}\tilde{\theta}_1. \tag{8}$$

With the following choice of the stabilizing function α and the parameter update law $\dot{\hat{\theta}}_1$

$$\alpha = -k_1e_1 - \Phi_1(x_1)\hat{\theta}_1, \tag{9}$$

$$\dot{\hat{\theta}}_1 = \gamma_1 e_1 \Phi_1(x_1) + \gamma_1 k_2(\theta_1 - \hat{\theta}_1), \tag{10}$$

the time derivative of the Lyapunov function becomes

$$\dot{V}_1 = -k_1e_1^2 - k_2\tilde{\theta}_1^2 + e_1e_2 \le 0. \tag{11}$$

Herein, e_1e_2 will be eliminated in the next step of the design procedure. After this elimination, the time derivative of the Lyapunov function turns out to be

$$\dot{V}_1 = -k_1e_1^2 - k_2\tilde{\theta}_1^2 < 0. \tag{12}$$