



Global smooth stabilization of a class of feedforward systems under the framework of generalized homogeneity with monotone degrees

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Abstract

In this paper, based on the concept of generalized homogeneity with monotone degrees (HWMD), we develop a new design procedure to explicitly construct global stabilizers for a class of feedforward systems. The proposed controller design strategy has several new features. First, a series of positive constant gains instead of function gains are employed for a simpler controller construction. Second, the flexibility of HWMD provides a general framework to unify several existing results. Third, it is now possible to design continuously differentiable stabilizers for some feedforward systems, for which only continuous stabilizers were previously designed. Moreover, for feedforward systems with decreasing powers, the proposed approach will enable us to design a locally linear saturation control law which is easier to be implemented in practical applications.

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1. Introduction

In this paper we consider a class of feedforward (also known as upper-triangular) systems described by

$$\begin{aligned}\dot{x}_1 &= x_2^{p_1} + f_1(x_2, x_3, \dots, x_n) \\ \dot{x}_2 &= x_3^{p_2} + f_2(x_3, \dots, x_n) \\ &\vdots\end{aligned}$$

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$$\begin{aligned}\dot{x}_{n-1} &= x_n^{p_{n-1}} + f_{n-1}(x_n) \\ \dot{x}_n &= u^{p_n},\end{aligned}\tag{1.1}$$

where $x = (x_1, \dots, x_n)^T \in \mathbb{R}^n$ and $u \in \mathbb{R}$ are the system state and input, respectively. Moreover, $f_i(\cdot)$'s are nonlinear continuous functions and $p_i \in \mathbb{R}_{\text{odd}}^+$, $i = 1, 2, \dots, n$ are ratios of positive odd integers. System (1.1) represents a general class of nonlinear systems in the upper-triangular form. In the case when $p_i = 1$, $i = 1, \dots, n$, system (1.1) reduces to a class of well-known feedforward systems including some practical systems such as the cart-pendulum system [6], the ball and beam system [1], the TORA system [14], etc. In the higher-order case (i.e., $p_i \geq 1$, $i = 1, \dots, n$), system (1.1) can be regarded as the upper-triangular counter-part of a class of higher-order lower-triangular systems including the mechanical system with a nonlinear spring studied in [13]. However, compared with the global stabilization results for lower-triangular nonlinear systems, fewer results exist in the literature for solving the global stabilization problem of upper-triangular systems (1.1), especially in the higher-order case. As a matter of fact, the global stabilization problem of higher-order upper-triangular systems is very challenging and has only been considered in very few works, e.g., [5,16,2,3].

In the existing literature, the nested saturation control method [1,15–17,2,3], the forwarding method based on Lyapunov functions [7,8] and the homogeneous domination approach [9,11] are the main strategies to solve the control problems for these upper-triangular systems. In a recent work [3], the authors proposed a new design method to solve the global stabilization problem of Eq. (1.1) under a weaker condition. First, by integrating the adding a power integrator approach [12] with the homogeneous domination method [9], a local stabilizer for Eq. (1.1) was first designed. Then, combining with a series of nested saturation functions, a global stabilizer was achieved to render the feedforward system asymptotically stable or finite-time stable. However, it is worth pointing out that for some special systems, e.g., Example 1 in Section 4, the previous approach can only design a non-smooth stabilizer. A natural question is if we can design a continuously differentiable (C^1) or smooth (C^∞) stabilizer for these systems.

Recently in [10], a novel generalized homogeneous conception called homogeneity with monotone degrees (HWMD) was first introduced to unify some existing results under one framework, and to improve the smoothness of stabilizers. In this paper, to design stabilizers with better smoothness for feedforward system (1.1), the HWMD concept will be integrated with the adding a power integrator technique to overcome certain limitations of the existing approaches. However, a drawback of HWMD design method is that the gains in the stabilizer will be nonlinear functions rather than constant gains due to the use of the monotone degrees [10]. These nonlinear gain functions in general are quite complicated and will pose difficulties in practical implementation. In this paper, inspired by [16,2,3], the nested saturation functions [15] will be utilized to overcome the drawback of nonlinear gain functions brought by using the HWMD approach.

Compared with the existing results obtained for feedforward systems, the controller design methodology proposed in this paper has several new features. First, now it is possible to design continuously differentiable (C^1) stabilizers for some systems for which only continuous stabilizers were previously designed. Compared to non-smooth controllers, the continuously differentiable controllers can guarantee uniqueness of the solution and are always easier to be implemented. Second, for a class of feedforward systems, our approach can be applied to design smooth (C^∞) controllers. Moreover, some locally linear saturation controllers can be directly obtained for systems with decreasing powers, thus are easier to be implemented in practical applications.

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