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Research article

Adaptive fuzzy control of a class of nonaffine nonlinear system with input saturation based on passivity theorem

Ali Molavi, Aliakbar Jalali*, Mahdi Ghasemi Naraghi

Department of Electrical Engineering, Iran University of Science and Technology, Tehran, Iran

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ABSTRACT

In this paper, based on the passivity theorem, an adaptive fuzzy controller is designed for a class of unknown nonaffine nonlinear systems with arbitrary relative degree and saturation input nonlinearity to track the desired trajectory. The system equations are in normal form and its unforced dynamic may be unstable. As relative degree one is a structural obstacle in system passivation approach, in this paper, backstepping method is used to circumvent this obstacle and passivate the system step by step. Because of the existence of uncertainty and disturbance in the system, exact passivation and reference tracking cannot be tackled, so the approximate passivation or passivation with respect to a set is obtained to hold the tracking error in a neighborhood around zero. Furthermore, in order to overcome the non-smoothness of the saturation input nonlinearity, a parametric smooth nonlinear function with arbitrary approximation error is used to approximate the input saturation. Finally, the simulation results for the theoretical and practical examples are given to validate the proposed controller.

1. Introduction

Dissipativity concept and in its particular case, passivity have originally arisen from the electrical circuit theory and physical systems [1,2], and it was the main tool in network synthesis [3]. This concept has provided a useful tool for analyzing nonlinear systems. A dynamic system is dissipative or in the particular case, it is passive, if the amount of the energy stored by the system is less than which is supplied to the system. It means that the system does not generate energy internally, but it dissipates some energy. Typical examples of practical passive systems are the electrical circuits, with passive elements [4].

The dissipative systems have desirable stability properties which help to analyze and design the controller for the systems [5]. Use of passivity in nonlinear control systems has a long history of Willems's works in [6,7] and the connection of passivity and stability is considered in [6–9]. A significant feature of the passive systems is its asymptotic stability even by a pure linear feedback. The great tendency of utilizing the inherent properties of the passive system leads to develop feedback passivation approach. The first results of feedback passivation approach are given by Byrnes et al. [8]. They show that like the linear system, the nonlinear system can be rendered passive if and only if it has relative degree 1 and also is weakly minimum phase. But there are a lot of systems that do not have these conditions. As mentioned in [10], integrator back-stepping and forwarding method are methods which can be used to passivate those systems which their relative degree is not one or they are not weakly minimum phase respectively. Some efforts such as [11–13] have used feedback passification to passivate and control the considered systems, when they are not exactly known, owing to the uncertainties and external disturbances in a system. In this case, the problem of exact feedback passivation cannot be dealt with, and it must be substituted with approximate passivation i.e., passivation with respect to a defined set [14].

The vast majority of previous papers have considered affine in control systems, but there are numerous systems with non-affine in control structure such as chemical reactor [15], biochemical process, some aircraft dynamic, PH neutralization and magnetic levitation system [16]. As mentioned in [16], in the literature, there are some methods dealing with nonaffine nonlinear system, such as Dynamic inversion that satisfy the assumption of Thikhonov theorem from singular perturbation theory [17,18], and the other methods that convert system to an affine system such as (i) using Taylor series expansion to obtain an affine system like [19,20], (ii) by using implicit function theorem like [21], (iii) by exploiting mean value theorem in order to obtain affine form like [22], (iv) by using prescribed performance method [23] and neural-approximation-based back-stepping control methodology [24] to control an air-breathing hypersonic vehicle which it has the longitudinal dynamics that are nonaffine in control input. These mentioned

* Corresponding author.
E-mail addresses: ali_molavi@alumni.iust.ac.ir (A. Molavi), ajalali@iust.ac.ir, drjalali@gmail.com (A. Jalali), naraghi@iust.ac.ir (M. Ghasemi Naraghi).

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papers have used Lyapunov theorem in order to analyze the stability and design the proper control law. But to the best of authors' knowledge, there are few works in control literature, which had considered the control of non-affine system used passivity theorem. Like affine system, the most important question that must be answered about non-affine systems is, when they are passive. There are some researchers that paid attention to this problem. Lin in [25] has obtained necessary conditions of non-affine nonlinear system passivation, and Narang et al. in [26] have derived the sufficient conditions. Lin in [27] has considered the global stabilization of nonlinear nonaffine systems with stable free dynamic. Navarro-López et al. in [5] have developed the KYP Lemma for a nonaffine discrete time single-input single-output (SISO) system, and used it in [28] to obtain the sufficient conditions, in order to render a multiple-input multiple-output (MIMO) system passive by means of static state feedback. Almost the aforementioned works required the perfect knowledge of the nominal system. Like affine system, when a system that must be controlled is not exactly known, the problem of exact feedback passivation cannot be dealt with, and it must be substituted with approximate passivation i.e., passivation with respect to a defined set.

The aim of this paper is to passivate a non-affine nonlinear system and use the feature of asymptotic stability of the passive systems to control and stabilize a class of non-affine systems. Because of the existence of uncertainty and disturbance in the system, exact passivation and reference tracking cannot be tackled, so the passivation with respect to a set is obtained and as mentioned in [14], the zero state detectability assumption to check stability of the passive system is not required and tracking error remains in a neighborhood around zero. To overcome these uncertainties in the system, this paper utilizes the approximation capability of fuzzy systems, which has been very useful in system identification and control design [29–38]. Some works which have worked on non-affine systems with passivity theorem usually assumed that the system has relative degree one and its unforced dynamic is stable [26,27]. But these assumptions are restrictive and there exist some systems which have unknown dynamics or their unforced dynamics are unstable. This paper studies the problem of reference tracking for a non-affine nonlinear system with arbitrary relative degree and unstable unforced dynamic nominal dynamic. In this way, the problem is solved by using back-stepping method.

As the explosion of terms is a negative feature of back-stepping method, some researchers have used a filter to eliminate this phenomenon, like [39,40] and some of them have taken the time derivative of the virtual control inputs as a part of uncertainty and estimated it online [41,42]. In this paper, the system is in the canonical form. So we have encountered with a lumped term of error and its time derivatives, which are known because of using the normal form, as the fuzzy system input. Then it does not need to calculate the time derivatives of the virtual control signal and we do not have the “explosion of term” phenomenon. In addition, there is not any constraint on unforced dynamic of system and it can be unstable. To overcome the non-affine problem, this paper uses the mean value theorem to convert the non-affine system to an affine form. The main contributions of this paper are listed as follows:

(1) This paper uses the passivity theorem and uses the feature of asymptotic stability of the passive systems to control an unknown non-affine nonlinear system.
(2) The system has relative degree more than one, then back-stepping method is used in order to passivate the system step by step and because of using the normal form the explosion of term phenomenon does not exist.
(3) The system considered here has unstable unforced dynamic, however in other works [27,25] they usually assumed that the unforced dynamic is stable.
(4) The uncertainties owing to the non-smooth input saturation nonlinearity i.e., $sat(v)$ are approximated by a parametric smooth nonlinear function of the control input signal that can reduce the approximation error, in comparison with the proposed function in [43], which has a fixed approximation error.

This paper is organized as follows: after introduction, the preliminary and necessary definitions are given in Section 2, and then the problem statement is introduced in Section 3. Section 4 is devoted to design the adaptive fuzzy passivation controller, furthermore passivity analyzing and obtaining a passivation set and stability analyzing and convergence area are discussed. The simulation results are presented in Section 5 and finally, the conclusion is included in Section 6.

2. Definition and preliminary

In this section, we introduce some preliminaries and results that are necessary for the subsequent analysis.

2.1. Notation

Through the paper let $\|x\| = \sqrt{x^T x}$ be the Euclidean norm. A function is said to be C^r when it is continuously differentiable r times, and a smooth function implies C^∞ function. Consider the nonlinear system as follows:

$$\begin{cases} \dot{x} = f(x, u) \\ y = h(x, u) \end{cases} \tag{1}$$

where $x \in \mathbb{R}^n$ is the state variable of the system, $u \in \mathbb{R}^m$ is the control input and $y \in \mathbb{R}^m$ is the output of the system respectively. It is assumed that the vector fields $f(x, u)$ and $h(x, u)$ are smooth mapping and origin is the equilibrium point of the system, that is $f(0, 0) = 0$ and $h(0, 0) = 0$.

Definition 1 (*[44]*). The system (1) is said to be dissipative, if there exists continuous and non-negative real value C^1 function $V(x)$ with $V(0) = 0$, called the storage function, such that for all admissible inputs $u, \forall x(0) = x_0 \in R^n, \forall t \ge 0$ the following inequality holds:

$$V(x(t)) - V(x(0)) \le \int_0^t w(u(\tau), y(\tau), x(\tau))d\tau \tag{2}$$

where the $w(\cdot)$ is called a supply rate. When the $w(u(\tau), y(\tau), x(\tau)) = y^T u$, the system is said to be passive. In the specific state, the system (1) is called the C^r-passive, $r \ge 1$, if the function $V(x)$ is C^r. When the system is passive, Eq. (2) is converted to

$$V(x(t)) - V(x(0)) \le \int_0^t y^T u d\tau. \tag{3}$$

Remark 1. If the storage function $V(x)$ is C^1 function, Eq. (3) can be written as:

$$\dot{V}(x) \le y^T u \tag{4}$$

Definition 2 (*[45], Local Existence and Uniqueness*). Let $F(t, x)$ be piecewise continuous in t and satisfy the locally Lipschitz condition:

$$\|F(t, x) - F(t, y)\| \le L\|x - y\| \tag{5}$$

$\forall x, y \in \mathrm{B} = \{x \in \mathbb{R}^n \,|\, \|x - x_0\| \le r\}, \quad \forall t \in [t_0, t_1]$. Then there exist some $\delta > 0$ such that the state equation $\dot{x} = F(t, x)$ with $x(t_0) = x_0$

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