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Novel sliding surface design for nonlinear singular systems

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ABSTRACT

This paper proposes a novel nonlinear sliding surface and investigates the sliding mode control problem for nonlinear singular systems. Because of the existence of nonlinear dynamics, the Differential Mean Value Theorem is used to transform the nonlinear singular system into a singular linear parameter varying system. Since the robustness to the uncertainties of the sliding mode, we can deal with the singular linear parameter varying system by applying the sliding mode control strategy. In some published papers people always design the sliding surface based on algebraic type or integral type, however, in this paper we propose a novel nonlinear sliding surface and the sliding surface contains a matrix exponent part, which can be used in both singular system and normal system. Finally, four examples are shown to illustrate the effectiveness and the advantages of the proposed method.
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1. Introduction

Singular systems, also referred to as descriptor systems, generalized state-space systems, differential-algebraic systems or semi-state systems has draw more and more attention in recent years. The singular systems have been used to described a large amount of physical systems because the normal system models can not reflect some of the physical systems for example the economic systems, biological systems, circuit systems or the power systems which contain the algebraic constraint, however, the singular systems can better reflect the physical systems due to the existence of both differential equations and algebraic equations [1,2].

In the past years, singular systems has been extensively studied and a lot of concepts and results in normal systems have been extended to the singular systems [3–10], for example, [3] analyzed the stability problem of switched linear singular systems, [4] studied the input–output decoupling of singular systems, in [5], the author introduced the singular system to improve the traditional complex networks to describe the singular dynamics behaviors of nodes, [6] investigated the observability and detectability of singular linear systems with unknown inputs, [9] considered the robust H_∞ filtering design for uncertain discrete-time singular systems under the interval time-varying delay. However, most of the existence results are derived under the condition that the singular systems are linear systems. Inevitably, the physical systems in the real life are not totally linear, for example, when we consider the power systems, biological systems or the mechanism systems, these kinds of systems often exhibit strong nonlinear dynamics, thus, the linear singular system models can not meet the demand when we want to analyze or control these systems. So, people started to study the nonlinear singular systems in order to better reflect the truth of the physical systems. In the past decades, several results on nonlinear singular systems have been published [11–15]. In [11], the author designed the H_∞ observers for a class of nonlinear singular systems, [12] considered the finite-time stabilization and finite-time H_∞ control problem of a nonlinear Hamiltonian descriptor systems with an appropriate state feedback, [13] studied the fault robust estimation and fault-tolerant control of a class of nonlinear descriptor systems, in [14], the authors designed H_∞ filter for a class of singular biological systems, in [15], authors analyzed the positivity characteristic of continuous time descriptor systems with time delays, a set of necessary and sufficient conditions is presented to check the property. Although nonlinear singular systems have been regarded as a topic with rapidly increasing interesting since the nonlinear singular system models can be used to describe the power systems, biological systems, mechanical systems and so forth, compared with the linear singular systems or the normal nonlinear systems, the analysis method and theoretical results aren't mature enough, some issues such as impulse definition and impulse elimination in nonlinear singular systems; positivity analysis in nonlinear singular systems still need further research. Thus, in this paper we will investigate a kind of nonlinear singular systems in order to cover a wider scope of physical systems.

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Control will be a necessary method if the systems can not reach the desired states. Several control methods have been used in the singular systems to achieve the desired objective, lots of existed results have been published. [16,17] investigated the H_∞ control problem in singular Markovian jump systems and nonlinear singular Markovian jump systems respectively. In [18], the author considered the reliable passive control for singular systems under the time-varying condition, [19,20] studied the feedback control problem of the singular systems. Considering the nonlinear dynamics in the singular systems, we will apply the sliding mode control to the nonlinear singular systems in order to better suppress the effect which is caused by the treatment of the nonlinear dynamics. Sliding mode control(SMC) is one of the robust control techniques that has drawn interest among control communities since the last four decades due to its ability to reject the disturbance completely, invariance property etc. The sliding mode control method alters the dynamics of a given dynamical system (linear or nonlinear) by applying a discontinuous control input that forces the system to slide along a cross-section(manifold) of the system normal behaviour. The merits of sliding mode control (SMC) are robustness against disturbances and parameter variation, reduced-order system design, and simple control structure. Some of the key technical problems associated with sliding mode control are chattering, matched and mismatched uncertainties, unmodeled dynamics, etc. Many new approaches have been developed in the last decade to address these problems[21–26]. In [21,22] the authors designed the sliding mode controller which could suppress the chattering effect, [23] studied the second order sliding mode control to drive a knee joint, [24] investigated the nonlinear observer for PEM fuel cell power systems via second order sliding mode method, [25] considered load frequency control by neural-network-based integral sliding mode control, [26] investigated the applications of robust sliding mode control on tracking of multi-objective PSO.

In this paper, we investigate a nonlinear singular system, considering the nonlinear dynamics in the system, we will use the Differential Mean Value Theorem[27] to deal with the nonlinear system in order to transform the nonlinear system into a singular linear parameter varying system[28,29], then, we proposed a novel nonlinear sliding surface and design a sliding mode controller to apply to the singular system. Compared with the sliding mode controller proposed in [32], the method proposed by us is faster and the chattering effect is suppressed well.

The rest of the paper is organized as follows. A problem to be considered is provided and the Differential Mean Value Theorem method is applied to the problem to derive a singular linear parameter varying system in Section 2. In Section 3 we propose a novel nonlinear sliding surface and design a sliding mode controller for the system. In Section 4, the simulation results will show the effectiveness and the advantages of the proposed method. Finally, some conclusions and future works are made in Section 5.

Notations: Let $\|x\| = \sqrt{x^T x}$ denote the Euclidean norm of a finite dimensional vector x. Let $diag\{\cdots\}$ denote the block diagonal matrix, $P>0(\geq 0)$ means that P is real symmetric and positive definite(semi-definite). R denotes the set of real numbers. R^n denotes the n-dimensional Euclidean space. $\mathcal{C}$ denotes the set of complex number. $R^{n\times m}$ denotes the set of all $n\times m$ matrices.

2. Preliminary

The nonlinear singular system is described as follows:

$$E\dot{x}(t) = f(x(t),t) + Ax(t) + Bu(t) \tag{1}$$

where matrix $E \in R^{n\times n}$ may be singular, and $rank(E) = r \leq n$. $f: R^n \to R^n$, is a continuous differentiable vector function and $f(0,0)=0$, for this nonlinear singular system, $x(t)$ is the state of the system, and $A \in R^{n\times n}$ is a constant matrix. $B \in R^{n\times 1}$ is a vector with full column rank. $u(t)\in R$ is the sliding mode input applied to the system.

Definition 1. [27] Let x,y be two elements in R^n. We define by $Co(x,y)$ the convex hull of the set $\{x,y\}$, i.e.

$$Co(x,y) = \{\lambda x + (1-\lambda)y, \lambda \in [0,1]\}$$

In addition, the following standing assumption and some useful lemmas will be made on the system. If we consider the nonlinear singular system as follows:

$$E\dot{x}(t) = F(x(t),t) \tag{2}$$

where $F(x(t),t) = f(x(t),t) + Ax(t)$ then we give out the following assumption.

Assumption 1. Let $\overline{x} \in R^n$, $\overline{A} = \frac{\partial F}{\partial x}(\overline{x})$. Then, the system (2) is admissible implies the following hold:

1. the system is locally regular at each $\overline{x} \in R^n$ and hence locally solvable, i.e., $det(sE-\overline{A}) \not\equiv 0$;
2. the system is locally asymptotically stable, i.e., $(E,\overline{A})$ is Hurwitz at each $\overline{x}\in R^n$.

Lemma 1 (*[27]*). *Let $a,b \in R^n$. We assume that f is differentiable on $Co(a,b)$. Then, there are constant vectors $c_1,\cdots,c_q \in Co(a,b), c_i \neq a, c_i \neq b$ for $i=1,\cdots,q$ such that*

$$f(a)-f(b) = \left(\sum_{i,j=1}^{q,n} e_q(i)e_n^T(j)\frac{\partial f_i}{\partial x_j}(c_i)\right)(a-b) \tag{3}$$

where $e_q(i)$ and $e_n(j)$ refer to the canonical basis of the vectorial space R^n which take the form of $E_n = \{e_n(j) | e_n(j) = \left(0,\cdots,0,\underbrace{1}_{j},0,\cdots,0\right)^T, j=1,\cdots,n\}$, where E_n represents the collection of the canonical basis.

Lemma 2 (*[30]*). *Let X,Y,F be real matrices of appropriate dimensions with $F^T(t)F(t)\leq I$ then*

$$XFY + T^TF^TX^T \leq XX^T + Y^TY$$

In order to deal with the nonlinear dynamics by using Differential Mean Value Theorem, we can rewrite the nonlinear singular system as:

$$E\dot{x}(t) = f(x(t),t) - f(0,0) + Ax(t) + Bu(t) \tag{4}$$

By using Lemma 1, there exists an element $z(t) \in Co(0,x(t))$ such that we can derive the following equations:

$$f(x(t)) - f(0) = \frac{\partial f}{\partial x}(z(t))(x(t)-0) \tag{5}$$

Since $\left(\frac{\partial f}{\partial x}\right) \in R^{n\times n}$, we can derive that:

$$\frac{\partial f}{\partial x}(z(t)) = \sum_{j=1}^{n} e_n^T(j)\frac{\partial f_i}{\partial x_j}(z(t)) \tag{6}$$

with the notation $h_{ij}(t) = \frac{\partial f_i}{\partial x_j}(z(t))$ we let $H(t) = [h_1(t),\cdots,h_n(t)]^T$, where $h_i(t) = [h_{i1}(t),\cdots,h_{in}(t)]^T$. The function $h_{ij}(t)$ is bounded, which means $\underline{h}_{ij} \leq h_{ij}(t) \leq \overline{h}_{ij}$, $\underline{h}_{ij}$ and $\overline{h}_{ij}$ are constant. Let $\tilde{H}(t) = \frac{1}{\sqrt{\gamma}}H(t)$, then we can derive $\tilde{H}^T(t)\tilde{H}(t) \leq I$, where $\gamma = \max\{l_{ij} | l_{ij} = \overline{h}_{ij} - \underline{h}_{ij}\}$, l_{ij} represents the length of the interval. With the above presentation we can derive the following equation:

$$f(x(t)) - f(0) = \sum_{j=1}^{n} e_n^T(j)h_j(t)x(t) \tag{7}$$

If we substitute (7) to (4) we can transfer the original nonlinear singular system to a linear singular system with parameter varying,

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