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Fully state constraint impulsive control for non-autonomous delayed nonlinear dynamic systems

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ABSTRACT

This paper investigates the problem of exponential stabilization criterion for non-autonomous delayed dynamic systems via state constraint impulsive control. It is fundamentally different from the traditional impulsive feedback control, and it has a good adaptation to different actual situations. Combining with convex analysis, inductive method and matrix measure theory, some sufficient conditions are obtained to ensure exponential stabilization for delayed system by using the linear feedback constraint impulsive controllers. Meanwhile, several examples with simulations are given to validate the effectiveness of the proposed criteria.

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1. Introduction

Many real systems suffer from the subpar effect of the constraints in conventionally configured aircraft, such as the lack of proportionality of the vertical velocity or climb rate to the attack angle of the aircraft. The internal state of the system model must be bound below the stall angle of the aircraft to avoid catastrophic failure of the closed-loop system. Based on actual demand and theoretical challenges, the rigorous handling of constraints in a control design has become an important research topic [1–8]. There are various techniques to solve the constraint control problem based on set invariance, model predictive control, adaptive variable structure control and so on. In order to avoid disturbance, it is important to know if there is a bounded invariant set such that all the state trajectories starting from inside of it will remain inside. Set invariance can be applied by estimating the attraction domain from the system origin under a saturated linear feedback [2,6]. In recent years, a barrier function has been proposed [7,9] to deal with the problem of stabilization for feedback linear systems with multiple state constraints. The authors [6] designed a controller for a single input–output nonlinear system with an output constraint. The construction of a time-variance barrier with positive defined functions solved the control problem of output time [10]. The authors [11] proposed an adaptive control technique for a class of uncertain nonlinear parametric systems. Additionally, some application results have been obtained for real systems with output constraints. An adaptive control was framed [12] for an uncertain robot system using full-state constraints by using the barrier Lyapunov function. However, although the aforementioned results account for the state constraints, the approaches cannot cope with the problem of the unknown control direction. This key point motivates us to solve the problem of the full state constraints and partial state constraints control of nonlinear systems.

As we know, qualitative analysis of non-autonomous systems is very complicated [13,14]. For example, the results demonstrated that even though the real parts of the eigenvalues of the linear system matrix are negative for every t, the

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system might not be stable. However, there is a linear non-autonomous system, which is stable even though it has positive eigenvalues [15]. Furthermore, it is more complicated for nonlinear systems. Time delay is another important source of instability for dynamic systems [16]. In many applications, time delays are introduced in physical system models due to transport lags, computational delays, or the various dynamics of the system components. The problems of stability and control of time-delay systems have attracted the attention of several researchers in recent years. There is an important and effective method using impulse control [17–22]. In control theory, the impulses are removed from the state variables in the controlled system at discrete moments. However, the impulse control for delay systems is very complicated [23,24]. In general, however, there are two common methods. One method is a simple quadratic Lyapunov function combined with a delayed equation. However, most of these methods assume that the continuous part is stable, yet there are results when the continuous part is unstable. The second method is a Lyapunov function, which contains time delay parts. Although the delay terms can be wiped out, it is complicated to deal with impulse times using the Lyapunov function. This article constructs a generalized delayed equation, which uses the impulse control for the state constraints.

In conclusion, a major obstacle in the application scope is that the output and state constraints are not considered in the design. Some researchers have attempted to solve the control problem of constraint systems because the constraints appear in most physical systems. There are many results concerning state constraint systems [1,2,4–6,10,11]. The control problem for delayed dynamic networks via constrained control systems has not been fully investigated yet, many challenging questions remain. Based on this, this paper proposes a special type of state constraint impulse controller, which addresses the state constraints problem. So far, there have been many studies on impulse control, but the impulses are basically unconstrained. In this paper, the full state control constraint is considered as a design, in which the controller engages the feedback control laws and analyzes the stability of the closed loop. The matrix measure theory and convex analysis method show that the state track for the closed loop delayed nonlinear dynamic systems are exponentially stable. Finally, two instances with numerical simulations are offered to demonstrate the availability of our results.

Notations: Throughout this paper, $\mathbb{R}^n$ and $\mathbb{R}^{n\times m}$ denote the n-dimensional Euclidean space and the set of $n \times m$ matrices, respectively. $\mathbb{R}^+ = (0, +\infty)$. $\mathbb{N} = \{1, 2, \ldots\}$. $\mathbb{M}_m \triangleq \{1, 2, 3, \ldots, 2^m\}$. $C(\mathbb{X}, \mathbb{Y})$ denotes the space of continuous mappings from the topological space $\mathbb{X}$ to the topological space $\mathbb{Y}$. The notation A^{T} and A^{-1} mean the transpose of A and the inverse of a square matrix A, respectively. $X > 0 (X \geq 0)$ means that X is a real symmetric and positive definite(positive semi-definite) matrix. Denote $\|u\|$ as a vector norm of the vector $u \in \mathbb{R}^n$. $\|A\|$ is the matrix norm of $A = (a_{ij})_{n\times n}$ induced by the vector norm, and $\|u\|_1 = \sum_{i=1}^n |u_i|$, $\|u\|_\infty = \max_j\{|u_j|\}$, $\|A\|_1 = \max_j \sum_{i=1}^n |a_{ij}|$. I stands for an identity matrix of appropriate dimension. $\lambda_{\max}(P)$ and $\lambda_{\min}(P)$ represent maximal and minimal eigenvalue of matrix P, respectively. co$\{\cdot\}$ denotes the convex hull of group of vectors. Let $\mathcal{D}$ be the set of $m \times m$ diagonal matrices whose diagonal elements are either 1 or 0. Each element of $\mathcal{D}$ is labeled as D_i, $i \in \mathbb{M}_m \triangleq \{1, 2, 3, \ldots, 2^m\}$.

2. Model description and some preliminaries

We consider a class of non-autonomous delayed nonlinear dynamic systems described by the following measure differential equations:

$$\dot{x}_i(t) = c_i(t)x_i(t) + \sum_{j=1}^{n} a_{ij}(t)f_j(x_j(t)) + \sum_{j=1}^{n} b_{ij}(t)g_j(x_j(t-\tau_j)) + U_i(t), \tag{1}$$

where $i = 1, 2, \ldots, n$, $x_i(t) \in \mathbb{R}$ corresponds to the ith state at time t, $c_i(t)$ is the connection weight of linear part, $a_{ij}(t)$ and $b_{ij}(t)$ are connection weights of nonlinear part related to the states without and with delays, respectively. Nonlinear functions $f_j(\cdot), g_j(\cdot) \in C(\mathbb{R}, \mathbb{R})$, τ_j is the time delay. $U_i(t)$ is an external input of the ith state. For system (1), its initial conditions are given by $x_i(s) = \phi_i(s) \in C([-\tau, 0], \mathbb{R})$, where $\tau = \max_j\{\tau_j\}$.

Compared to traditional results, which suggest that the control input is unconstrained, the control input variables can also be arranged arbitrarily. However, there are artificial constraints or physical constraints inherent in the actual engineering system. The phenomenon of saturation property is widely available in the reality control system. Meanwhile, there are no relevant results on impulse constraints. The typical saturation nonlinearity is depicted in Fig. 1. In this paper, we consider the following impulsive controller:

$$U_i(t) = \sum_{k=1}^{\infty} \mathrm{Sat}(u_i(t))\delta(t - t_k), \quad i = 1, 2, \ldots, n, \tag{2}$$

where

$$\mathrm{Sat}(u_i(t)) = \begin{cases} 1, & u_i(t) > 1, \\ u_i(t), & -1 \leq u_i(t) \leq 1, \ \forall\, i = 1, 2, \ldots, n, \\ -1, & u_i(t) < -1. \end{cases} \tag{3}$$

The time sequence $\{t_k\}$ satisfies $0 < t_0 < t_1 < \cdots < t_k < t_{k+1} < \cdots$ and $\lim_{k\to+\infty} t_k = +\infty$. $\delta(t - t_k)$ is the Dirac function. At time instants t_k, jumps in the state variable x_i are denoted by $\triangle x_i(t_k) = x_i(t_k^+) - x_i(t_k^-)$, $x_i(t_k^+) = x_i(t_k)$ and $x_i(t_k^-) = \lim_{t\to t_k^-} x_i(t)$. Let $C(t) = \mathrm{diag}(c_1(t), c_2(t), \ldots, c_n(t))$, $A = (a_{ij}(t))_{n\times n}$, $B = (b_{ij}(t))_{n\times n}$, $f(\cdot) = (f_1(\cdot), f_2(\cdot), \ldots, f_n(\cdot))^{\mathrm{T}}$,

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